

Future of Venus Research and Exploration

Lori S. Glaze¹ · Colin F. Wilson² · Liudmila V. Zasova³ ·
Masato Nakamura⁴ · Sanjay Limaye⁵

Received: 5 September 2017 / Accepted: 10 July 2018 / Published online: 23 July 2018
© The Author(s) 2018

Abstract Despite the tremendous progress that has been made since the publication of the Venus II book in 1997, many fundamental questions remain concerning Venus' history, evolution and current geologic and atmospheric processes. The international science community has taken several approaches to prioritizing these questions, either through formal processes like the Planetary Decadal Survey in the United States and the Cosmic Vision in Europe, or informally through science definition teams utilized by Japan, Russia, and India. These questions are left to future investigators to address through a broad range of research approaches that include Earth-based observations, laboratory and modeling studies that are based on existing data, and new space flight missions. Many of the highest priority questions for Venus can be answered with new measurements acquired by orbiting or *in situ* missions that use current technologies, and several plausible implementation concepts have

Venus III

Edited by Bruno Bézard, Christopher T. Russell, Takehiko Satoh, Suzanne E. Smrekar and Colin F. Wilson

✉ L.S. Glaze
Lori.S.Glaze@nasa.gov
C.F. Wilson
Colin.Wilson@physics.ox.ac.uk
L.V. Zasova
lzasova@gmail.com
M. Nakamura
nakamura.masato@me.com
S. Limaye
SanjayL@ssec.wisc.edu

¹ NASA Goddard Space Flight Center, Greenbelt, MD, USA

² Oxford University, Oxford, UK

³ Space Research Institute, IKI RAS, Moscow, Russia

⁴ Institute of Space and Astronautical Science, JAXA, Sagamihara, Japan

⁵ University of Wisconsin, Madison, Madison, USA

been studied and proposed for flight. However, observations needed to address some science questions pose substantial technological challenges, for example, long term survival on the surface of Venus and missions that require surface or controlled aerial mobility. Missions enabled by investments in these technologies will open the door to completely new ways of exploring Venus to provide unique insights into Venus's past and the processes at work today.

Keywords Venus · Exploration · Space missions · Technology development

Abbreviations

ALMA:	Atacama Large millimeter/submillimeter Array;
APXS:	Alpha-Particle X-ray Spectrometer;
CNES:	Centre National d'Études Spatiales;
COSPAR:	Committee on Space Research;
CUVE:	Cubesat UV Experiment;
DAVINCI:	Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging;
ESA:	European Space Agency;
ESPaDOnS:	Echelle SpectroPolarimetric Device for the Observation of Stars;
EVE:	European Venus Explorer;
GC-MS:	Gas Chromatograph-Mass Spectrometer;
GCM:	General Circulation Model;
HIPWAC:	Heterodyne Instrument for Planetary Wind and Composition;
HOT Tech:	Hot Operating Temperature Technology;
JMARS:	Java Mission-planning and Analysis for Remote Sensing
InSAR:	Interferometric Synthetic Aperture Radar;
IR:	Infrared;
ISRO:	Indian Space Research Organization;
IVEWG:	International Venus Exploration Working Group;
JAXA:	Japanese Aerospace Exploration Agency;
JCMT:	James Clerk Maxwell Telescope;
JMARS:	Java Mission-planning and Analysis for Remote Sensing;
JSDT:	Joint Science Definition Team;
LAC:	Lightning and Airglow Camera;
LIBS:	Laser Induced Breakdown Spectroscopy;
LIR:	Longwave Infrared Camera;
MARSIS:	Mars Advanced Radar for Subsurface and Ionosphere Sounding;
MESSENGER:	Mercury Surface, Space Environment, Geochemistry, and Ranging;
MM:	Millimeter;
MMRTG:	Multi-Mission Radioisotope Thermoelectric Generator;
MOM:	Mangalyaan Orbiter Mission to Mars;
MTLas:	Multichannel Tunable Laser;
NASA:	National Aeronautics and Space Administration;
NIR:	Near Infrared;
NOEMA:	Northern Extended Millimeter Array;
NRC:	National Research Council;
OME:	Orbital Maneuver Engine;
OSIRIS-REx:	Origins-Spectral Interpretation-Resource Identification-Security-Regolith Explorer;

RCS:	Reaction Control System;
RFSP:	Russian Federal Space Program;
RS:	Radio Science;
SAGE:	Surface and Atmosphere Geochemical Explorer;
SAR:	Synthetic Aperture Radar;
SHARAD:	Shallow Radar;
SIMPLEx:	Small Innovative Missions for Planetary Exploration;
THIS:	Tuneable Heterodyne Infrared Spectrometer;
TIR:	Thermal Infrared;
US:	United States;
UV:	Ultraviolet;
UVI:	Ultraviolet Imager;
VALOR:	Venus Aerostatic-Lift Observatories for in-situ Research;
VAMP:	Venus Atmospheric Maneuverable Platform;
VCM:	Venus Climate Mission;
Venera-D:	Venera-Dolgozhivushaya;
VEx:	Venus Express;
VERITAS:	Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy;
VEXAG:	Venus Exploration Analysis Group;
VIRTIS:	Visible and Infrared Thermal Imaging Spectrometer;
WISE:	Venus In Situ Explorer;
VITaL:	Venus Intrepid Tessera Lander;
VME:	Venus Mobile Explorer;

1 Outstanding Science Questions

Despite the emphasis on Venus of early space exploration (Mariner, Venera, Vega, & Pioneer), and the more recent Magellan, Venus Express, and Akatsuki Missions, Venus remains a mystery. Sitting in our own back yard, Venus represents an unusual example of terrestrial planet formation and evolution that differs substantially from Earth and the other solid planets of the inner solar system. Many fundamental questions remain unanswered. For example (see Sect. 2 for more detailed discussion), what was the original composition of the Venus atmosphere, did Venus have oceans, how has that atmosphere evolved over time, and when and why did the runaway greenhouse begin (Taylor et al. 2017, this issue)? How does Venus lose its heat, how volcanically and tectonically active has Venus been over the last billion years, and has Venus always had a “stagnant-lid”, or was a plate tectonics regime ever present earlier in her history (Sotin et al. 2017, this issue)? What is the composition of the highland tessera terrain, are these regions the oldest rocks exposed on the Venus surface, and do these surfaces retain evidence of an earlier time when water was more prevalent (Gilmore et al. 2017, this issue)? What are the thermal structure and circulation of the deep atmosphere (Limaye et al. 2017; Sanchez-Lavega et al. 2017, this issue)? What drives the atmospheric super-rotation observed in the upper cloud layer (Sanchez-Lavega et al. 2017, this issue)? What is the composition of the atmosphere above the cloud layers and what chemical cycles drive the variability observed in some species at these altitudes in particular sulfur species (Marcq et al. 2018, this issue)? What are the chemical cycles operating below the clouds and to what extent do surface-atmosphere exchange or possible active volcanism play a role (Marcq et al. 2018, this issue)? What are the unknown chemical species that absorb incident ultraviolet

(UV) radiation near the cloud tops (Titov et al. 2018, this issue)? What is the impact of solar wind and space weather “storms” on ion escape processes and rates (Futaana et al. 2017, this issue)? What are the sources of the variability observed in air glow emissions on the night side (Gerard et al. 2017, this issue).

Several international science communities have assessed these questions and placed priorities for future research and exploration efforts. The European Space Agency’s (ESA’s) Cosmic Vision is the result of discussions between scientific advisory committees, working groups, and members of the scientific community. “Cosmic Vision 2015–2025” (Bignami et al. 2005; Clavel 2009) was designed to address four main questions that are high on the agenda of research across Europe concerning the Universe and our place in it:

1. What are the conditions for planet formation and the emergence of life?
2. How does the Solar System work?
3. What are the fundamental physical laws of the Universe?
4. How did the Universe originate and what is it made of?

The most recent United States (US) National Research Council (NRC) Planetary Decadal Survey, “Visions and Voyages for Planetary Science in the Decade 2013–2022” (Squires 2011), identifies ten priority science questions to be addressed by the National Aeronautics and Space Administration (NASA) in the decade 2013–2022. Understanding the formation and evolution of the inner planets within our solar system is critical to understanding how and why Earth evolved the way it did and for interpreting information about newly discovered exo-solar planets. Specifically, the 2013 Planetary Decadal Survey identifies three scientific goals for exploration of the inner planets:

1. Understand the origin and diversity of terrestrial planets,
2. Understand how the evolution of terrestrial planets enables and limits the origin and evolution of life, and
3. Understand the processes that control climate on Earth-like planets.

Venus is a key example within our family of terrestrial planets required to fully address these goals.

Building on the scientific goals established by the NRC Planetary Decadal Surveys of the last two decades, the Venus Exploration Analysis Group (VEXAG) has developed and maintained a priority listing of Goals, Objectives, and Investigations that are specific to Venus exploration. This document represents a community-based consensus on science priorities, and is periodically updated and maintained by VEXAG. As of this writing, the document was most recently updated in May 2014, with minor modifications in August 2016 (VEXAG 2016). In this document, VEXAG has identified three top level Goals that are of equal priority: (1) Understand atmospheric formation, evolution, and climate history on Venus, (2) Determine the evolution of the surface and interior of Venus, and (3) Understand the nature of interior-surface-atmosphere interactions over time, including whether liquid water was ever present. Within each of these goals, VEXAG has defined two to three prioritized science objectives, as well as several prioritized investigations that are needed to address each objective. The highest priority science investigations within each goal are to measure the noble gas abundances and their isotopic ratios within the atmosphere, assess the evolution of volcanism, tectonism, and other geologic processes that construct and modify the crust, and measure the D/H ratio within the atmosphere to place constraints on the history of water.

Table 1 VEXAG Roadmap for Venus Exploration

Near term	Mid term	Far-term
Orbiter with Active Remote Sensing (Radar, Altimetry, emissivity, gravity)	Deep atmosphere multi-probes	Surface (or near surface) platform with regional mobility
Sustained Aerial Platform	Short Duration tessera lander	Long lived lander network for seismic studies
Deep atmosphere probe Multiple probes/dropsondes Passive remote sensing orbiter or multiple fly-bys	Long-lived geophysical lander	Venus surface sample return

VEXAG also developed a roadmap and a technology plan that augment the Goals, Objectives, and Investigations for future exploration. The “*Roadmap for Venus Exploration*” adopted by VEXAG in May 2014 lays out a framework for investigating the planet’s atmosphere, surface, and interior (VEXAG 2014a). The Roadmap recognizes that a much-improved understanding of Venus is possible only by a combination of small, medium and large missions and deployment of optimum observing platforms that are either available or can be developed and flown at affordable costs. The key areas for exploration are Atmospheric Composition, Surface Composition and Morphology, Atmospheric Structure and Circulation, and Interior Structure and Dynamics. For each theme, missions can be developed and implemented in a logical sequence based on engineering capability and affordability, while realizing maximum science return. The relative priority of missions is guided by the science priorities in each theme. The roadmap document provides a nominal choice of near term, mid-term and long-term (decadal scale) exploration of Venus shown Table 1.

The “*Venus Technology Plan*” (VEXAG 2014b), also adopted by VEXAG in May 2014, assesses the technologies required to implement the Near, Mid, and Far-term missions identified in the VEXAG Roadmap for Venus Exploration. The document indicates that there are several scientifically important missions that can be accomplished by using currently existing technology. However, missions that are enabled by extended operations in the near-surface or surface environments still require substantial technology investments. Key areas identified as benefiting from technology development are (1) thermal protection systems for missions that require atmospheric entry, (2) high-temperature subsystems and components for surface operations beyond a few hours, (3) guided aerial platforms (e.g., airplanes or dirigibles) with carrying capacities greater than balloons and lifetimes beyond 30 days, (4) instrumentation specifically designed to operate and possibly withstand the surface environment, (5) deep space optical communication systems that can enhance science return from missions requiring transmission of large data volumes, (6) advanced power and cooling technologies for long-duration (> 24 hour) on the Venus surface, and (7) advanced descent and landing systems that would improve targeting and precision landing (e.g., hazard avoidance) in rough terrains such as the highland tesserae.

It should be pointed out that although the VEXAG documents are directed toward NASA investigations, they represent a consensus of the larger international community of Venus scientists that have participated regularly in the VEXAG deliberations since its inception in 2005. Further, the roadmap implicitly assumes and encourages international collaboration, participation and coordination of efforts by the interested space agencies (see Sect. 3).

2 Venus Research Focus Areas

Improved understanding of Venus is essential to better appreciate the full range of terrestrial planet origin and evolution present in our own solar system and to interpret observations of new earth-sized planets being discovered around other stars. The prior articles in this issue have each identified key open issues as well as the measurements or approaches that are needed to resolve them. These approaches can be broadly categorized as (1) earth-based observations, (2) laboratory studies, (3) modeling studies, or (4) new spaceflight missions.

2.1 Earth-Based Observations

Venus is our closest neighbor and is very well suited to observation from Earth (or from near-Earth observatories in space). These observations are complementary to Venus spacecraft observations in a number of fields, from geology to atmospheric composition and dynamics (Fig. 1).

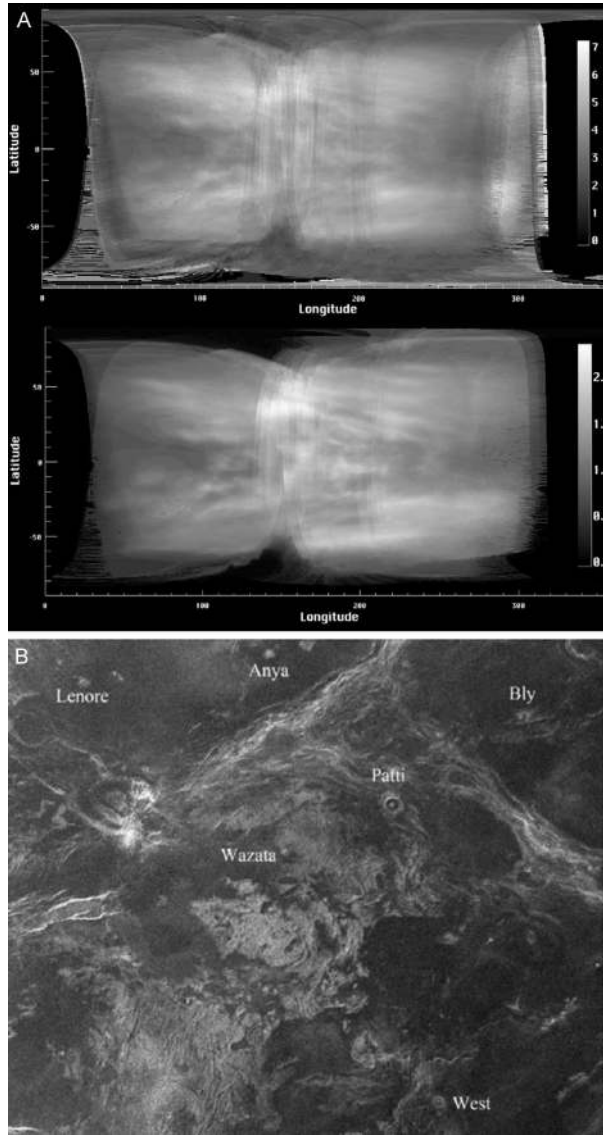
For atmospheric composition, ground-based observatories can provide a broad range of spectral coverage: including regions of the spectrum for which instrumentation has not yet flown on Venus orbital missions. For example, ground-based observations by Allen and Crawford (1984) provided the discovery of near-infrared spectral windows at 1–2.5 μm , which allowed mapping of tropospheric gases on the night-side of Venus; it was then over 20 years before an orbital instrument observing in this spectral range reached Venus. The best spectral resolutions reachable in ground-based facilities are also highly complementary to those achievable in Venus orbit; for example, tropospheric HF (Bézard et al. 1990) and mesospheric ClO (Sander and Clancy 2018) have been measured from the ground but not from orbit. Further atmospheric species may be detected as new facilities become available, thus providing important drivers to develop new orbital instrumentation capabilities.

Spatial mapping from ground-based observations provides viewing geometries different, and complementary, to those achieved from Venus spacecraft. Encrenaz et al. (2012, 2016) has mapped HDO and SO₂ abundances across the full disk of Venus, and has tracked their variation on timescales ranging from minutes to years. The full disk measurements of horizontal distribution are complementary to the point measurements and vertical profiles measured from Venus Express (Marcq et al. 2018, this issue).

Ground-based observatories can also provide monitoring over long periods of time, particularly times when no spacecraft are at Venus. The stand-out example of this is long-term monitoring of mesospheric sulphur dioxide; in addition to measurements by Pioneer Venus (1978–1992), Venera 15 (1983–1984), and Venus Express (2006–2014), mesospheric SO₂ was monitored in the UV from sounding rockets and from the Hubble space telescope (Esposito et al. 1997); it has also been measured in the thermal infrared (IR), as discussed above, and now also in sub-mm ranges from observatories such as JCMT and ALMA. Continuing these observations in the coming decade, when no Venus missions are planned, will help constrain SO₂ (and, by extension, perhaps volcanic activity) in this period.

High spectral resolution also allows direct measurement of winds through Doppler velocimetry, and detection of trace chemicals. To be scientifically valuable, Doppler velocimetry must achieve accuracies on the order of 10 m/s or better, which requires spectral resolutions of $\lambda/d\lambda > 3 \times 10^7$ or higher, depending on viewing geometry. This is now achievable in a range of earth-based telescopes, from sub-millimetre (ALMA, NOEMA, JCMT) to visible-near-IR (HIPWAC, THIS, ESPaDOnS)—all of these have been used to measure winds, at altitudes ranging from 60–110 km, depending on the spectral feature observed (Sanchez-Lavega et al. 2017, this issue). Of particular interest is the 90–120 km altitude region, which marks a transition from the retrograde zonal circulation in the mesosphere to a

Fig. 1 Earth-based observations are useful for increasing our understanding of Venus in a wide range of scientific areas. (A) Global average lower cloud cover as determined by Tavenner et al. (2008) using Earth-based observations from the IRTF. (B) Polarized radar image of Hyndla Regio and Zirka Tessera can be used to identify the extent of fine-grained deposits (Campbell et al. 2015)



subsolar-to-antisolar circulation in the thermosphere—there are scarcely any clouds in this rarefied portion of the atmosphere, so the only wind velocities measured in this highly variable region come from ground-based Doppler velocimetry. Further observation campaigns, from observatories offering ever more spatial and spectral resolution, will help to understand this variability.

Wind fields at cloud level can also be measured from Earth using feature tracking. Single-station observations have tracked meridional profiles of zonal winds, using observation sequences a few hours long; longer durations can be obtained either by co-ordinating observatories distributed in longitude, or by using observatories at polar latitudes. Of particular note is the possibility of telescopes carried by stratospheric balloons; at 35 km altitude these are

above most atmospheric turbulence and water vapor, offering observing conditions intermediate in spatial resolution and temporal duration between ground-based and Venus satellite observations (Young et al. 2008), providing a unique dataset to study large-scale atmospheric variability on day- to week-long timescales.

While the above observations all discuss the atmosphere, the surface of Venus can be observed from Earth, too. The highest resolution ground-based radar images of Venus, from the Arecibo observatory, reach spatial resolutions of 1–2 km; while this is an order of magnitude poorer than Magellan radar images, 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. For example, polarimetric information has been effectively used to map impact crater ejecta that mantle tessera terrain. This information is important for selecting potential landing sites that are not covered by materials derived from other surface locations (Campbell et al. 2015). Polarimetric information has also been demonstrated to be helpful for identifying deposits of granular material (few cm in diameter) that have been interpreted as pyroclastic material from explosive volcanic eruptions (Campbell et al. 2017). Future ground-based radars, such as the Square Kilometer Array (SKA) could provide an increase in collecting area of two orders of magnitude compared to current radio telescopes (e.g., Carilli and Rawlings 2004) and may be useful for mapping Venus surface properties and for identifying any changes due to volcanism or tectonism. The SKA is expected to begin preliminary science observations as early as 2020 using a partial array.

Earth-based radar can also be used for monitoring of Venus' spin. Previous measurements of Venus' spin rate from ground- and space-based radar have varied by around 1 part in 10^5 , equivalent to uncertainties of about three minutes in Venus' sidereal day. Some variation in the spin rate is expected as a result of momentum exchange between the planet and its massive atmosphere, as well as due to solar tidal forcing and possible mantle-core interactions (Cottureau et al. 2011; Navarro et al. 2018); measuring variations in the spin state therefore would help constrain these parameters. Radio signals reflected from the surface of Venus exhibit spatial inhomogeneities, or speckles; a cross-correlation between observations of these speckle patterns from different observatories on Earth allows measurement of the instantaneous spin rate of Venus. The accuracy achievable in this spin rate measurement is estimated to be $\Delta\lambda/\lambda \sim 10^{-6}$ for a single-frequency measurement using two receiving stations on Earth, or $\Delta\lambda/\lambda \sim 10^{-8}$ using multiple frequencies and arrays of receivers (Karatekin and Holin 2016). These measurements are logistically demanding, due to the use of multiple observatories, but may lead to valuable constraints on interior structure not achievable from an orbiter.

“Amateur” astronomical observations—i.e. those outside academic or research institutions—have shown their worth in other fields of planetary observation, most spectacularly in the observation and even video recording of impacts on Jupiter (Sanchez-Lavega et al. 2010): could they be similarly useful at Venus? Amateur observers typically collect images in visible, UV or near-IR wavelengths with telescopes of < 0.5 m primary aperture (Barentsen and Koschny 2008). At these wavelengths, almost all light is from the dayside and any contrasts observed at Venus tend to be associated with large-scale cloud features. Imaging of nightside IR emission has been demonstrated using occulting masks to block out light from the dayside of Venus (Mousis et al. 2014). Although this is an impressive achievement with amateur equipment, such maps have poor spatial resolution and have not yet proved useful for scientific analysis. Video capture of the nightside of Venus is novel, well-aligned with the observing equipment used by many amateurs, and potentially scientifically rewarding, as these observations could reveal lightning flashes and/or meteor impacts.

However, such emissions are likely to be very faint and difficult to observe in such proximity to the extremely bright dayside of Venus and may be beyond the reach of amateur observing equipment in the near future. On the other hand, participation by non-professional scientists (sometimes called “citizen scientists”) in the analysis of datasets obtained by Venus spacecraft is feasible. Enthusiastic participation in Mars spacecraft missions, with tools such as JMARS and Midnight Planets, has shown the public appetite for engaging in planetary scientific data analysis. Such public engagement should be harnessed in future Venus missions, particularly those such as high-resolution radar orbiters that will generate vast amounts of high resolution imagery.

2.2 Laboratory Studies

Laboratory work is absolutely fundamental to our ability to interpret observational and modeling results. There are still many areas where new lab work is needed in support of both studies of the rocky surface as well as of the atmosphere. In particular, recent results from Venus Express indicating possible emissivity anomalies in highland regions (Gilmore et al. 2017, this issue) have driven the need for new laboratory work to fully characterize complex temperature effects on the spectra of minerals and rocks in the near infrared wavelength range. Laboratory studies are also needed to better understand the unusual origin of surface features that may have formed through limited subduction driven by mantle plumes (Davaille et al. 2017). In addition, much is still unknown about the weathering environment at the Venus surface. To better constrain observations, it is important to calibrate the oxidation rate of basaltic glass that results in a thick (10 μm) coating of hematite. Assumptions that it would take less than 1 million years to form a weathered coating have led to the inferences that unweathered lava flows observed by VIRTIS (as high emissivity anomalies) are “young”. Additional laboratory work is also needed to determine reaction rates that can form sulfates in the Venus surface environment in order to better understand the interactions of the atmosphere with the surface. Finally, changes in radar emissivity as a function of altitude that were observed by Magellan remain unexplained. Additional laboratory work is still needed to identify plausible semiconductor and ferroelectric substances that could cause this effect.

In terms of better understanding chemical reactions and rates within the atmosphere, there is a strong need for laboratory studies that can place better constraints on chemical reactions occurring at a range of altitudes as well as to characterize the physical and chemical properties of the aerosols that make up the thick cloud layer. For example, because sulfur species play such an important role in Venus’ atmospheric chemistry, rate coefficients are needed for all expected sulfur reactions to constrain photochemical modeling efforts. Laboratory studies of cross sections of sulfur species are also required to constrain models and to assess their potential as candidates for the unknown UV absorber (Marcq et al. 2018, this issue). In addition, for cloud layer and lightning studies, assessment of mechanisms for faster production H_2SO_4 is needed as well as laboratory studies of reactions involving C_3O_2 , S_nO and negative ions. Finally, laboratory studies of aerosol chemistry and characterization of optical properties of particulate products are also needed. In particular, laboratory studies of sulfuric acid aerosols at high concentrations, including phase behavior, are required to better constrain the microphysical properties of the aerosols under Venus conditions (Titov et al. 2018, this issue).

In support of future remote sensing observations, laboratory measurements are needed to improve understanding of high-temperature, high-pressure spectra at near-infrared wavelengths of H_2O , HDO, and CO_2 (Marcq et al. 2018, this issue). Laboratory studies are also

needed to understand the mechanisms that convert SO_3 and OCS to CO , CO_2 and SO_2 , the rate coefficients for these reactions, and to identify appropriate wavelengths for observation. In addition, although it is known that both CO_2 and N_2 are each individually critical fluids at Venus surface temperature and pressures, the critical conditions for the mixture have not yet been identified either theoretically or experimentally (Limaye et al. 2017, this issue).

2.3 Modeling Studies

Similar to laboratory work, there is a very broad range of modeling work that needs to be completed to aid in interpretation of existing observational data and for planning future observations. The recent VEx and Akatsuki missions have provided important observational data that have driven a surge of progress in atmospheric modeling. Key areas that are very well suited to advancement through modeling work are radiative transfer models to better understand the greenhouse effect (e.g., Lee and Richardson 2011; Lebonnois et al. 2015), chemical kinetics models to better understand atmospheric chemistry (e.g., Zhang et al. 2012; Krasnopolsky 2012), cloud micro-physics (e.g., McGouldrick and Toon 2007), and general circulation models (e.g., Lebonnois et al. 2016). In addition, a great deal of progress has been made in recent years in the development of models to better understand planetary interior dynamics and the conditions under which mantle plumes can form (Smrekar and Sotin 2012).

There are several radiative transfer modeling advances needed that will improve understanding of energy balance in Venus' atmosphere and its influence on global circulation and climate (Limaye et al. 2017, this issue). In particular, the role of large-scale dynamics, chemical reactions, and cloud processes on the Venusian entropy budget still needs to be studied. The influence of clouds and cloud formation processes in climate models needs development and one of the most important open issues is the effect of variability of atmospheric properties such as the abundance of radiatively active gases, cloud microphysical and optical properties and total opacity. In addition, it is critical to understand how the distribution of sources and sinks of radiative energy drive the atmospheric dynamics and new studies are needed to understand the processes that most strongly influence Venus' climate. Finally, better understanding of radiative processes will provide insights into the role of radiation in Venus' atmospheric evolution, including the onset of greenhouse conditions and the loss of water.

An area where numerical modeling can be particularly effective is atmospheric dynamics (Sanchez-Lavega et al. 2017, this issue). Recent General Circulation Model (GCM) advances (e.g., Lebonnois et al. 2016) are capable of reproducing important features such as temperature structure, static stability and zonal winds. However, work is needed to understand the dynamics of key features (e.g., cold collar, large stationary gravity waves) and how they couple or not to the super-rotation. In addition, the role of eddy processes is crucial, but likely involves the complex interaction of a variety of different types of eddy, either forced directly by radiative heating and mechanical interactions with the surface or through various forms of instability. There is also a need for improved numerical models that are capable of spatially resolving the polar vortex morphology and accurately reproducing its dynamics, and the role of subgrid-scale processes in the angular momentum budget, especially small-scale gravity waves. Finally, the robustness of existing GCMs should be confirmed through inter-comparison between several models, with particular focus on the conservation of angular momentum.

Photochemical studies can also benefit greatly from new modeling work (Marcq et al. 2018, this issue). Detailed dynamical and photochemical studies of the Venus middle atmosphere (~ 70 – 110 km) can be used to understand the photochemistry, dynamics, heating,

and microphysics that drive the atmosphere at these altitudes. Existing validated models with updated photochemical schemes can be used for this type of study. Models can also be used to address major questions regarding dynamical exchange between the lower and upper atmosphere. Understanding of aerosols can be improved through new microphysical models of sulfuric acid aerosol formation, growth and decomposition (Titov et al. 2018, this issue). In addition, such studies need to be expanded to other species (e.g., elemental sulfur) that may be consistent with observations of unknown absorbers in the UV and other wavelengths. Incorporation of new microphysical models into regional scale and global scale circulation models can then be used to study feedbacks between microphysics, chemistry, and the momentum and energy balance.

2.4 New *In Situ* Observations

Although much can be learned from Earth-based observations, laboratory studies and modeling, there are many unanswered questions that can only be answered by new observations acquired by a space flight mission. Measurements made *in situ*, within the Venus atmosphere or from the surface, are critical for understanding Venus' evolution and for placing Venus into context with Earth and Mars. The last *in situ* Venus mission was Vega in 1985. The Vega balloons, combined with the earlier Pioneer Venus probes (flown in 1978), have stimulated numerous unresolved questions about the composition and structure of the atmosphere. Likewise, although the Venera and Vega landers measured bulk chemistry of the surface in several locations, surface mineralogy has never been measured, leaving many unanswered questions regarding the origin and evolution of the surface. Many of these questions cannot be fully addressed through remote sensing observations from orbit.

One of the fundamental measurements that is needed is the bulk elemental composition and mineralogy of the surface from key locations, especially tesserae (Gilmore et al. 2017, this issue). Tesserae are thought to be 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 regimes. Even the regional volcanic plains that are typical of ~40% of the Venus surface appear to exhibit significant variability as observed by multiple Soviet landers. Although Venera and Vega chemical analysis indicate overall basaltic composition (Fegley et al. 1997), details of the mineralogy can be used to understand the petrologic origin of the magmas and possibly even address hypotheses related to rates of volcanic resurfacing. There is also a need to characterize the oxidation state in the deepest atmosphere that interacts with the surface. Combined with measurements of surface mineralogy, knowledge of the oxidation state can constrain what minerals are stable at the surface. Likewise, the sulfur chemistry cycle (Zhang et al. 2012) needs to be constrained through measurements of rock mineralogy and atmosphere composition. Seismic measurements would be invaluable for studying tectonic and volcanic activity, and for constraining internal structure. A comprehensive seismological survey will require technically demanding long-lived surface stations, but precursor studies could be carried out using short-lived landers, infrasonic detectors from balloons or airglow imaging from orbital platforms (Stevenson et al. 2015; Lorenz and Panning 2018).

Substantially more data are needed on the thermal structure of the deep atmosphere (below 40 km). Very limited data exist for this important region (Limaye et al. 2017, this issue), which contains more than 75% of Venus' atmospheric mass. Only the Vega 2 lander made any reliable measurements of temperature in this region and those data are too sparse to resolve important structural characteristics, such as the extent of the planetary boundary layer. It is vital that the adiabatic lapse rate for the Venus atmosphere be measured accurately for

the conditions found from the Venusian surface to the minimum temperature region, found at about 125 km altitude. *In situ* platforms are required to secure data on thermal structure below about 35 km. Prior missions have also introduced questions that require new measurements to resolve, such as a possible unexplained gradient in N₂ reported by Oyama et al. (1979) and the as yet unidentified species that is absorbing UV in the upper clouds (58–65 km). Again, to constrain dynamics models, one of the most important open issues in this field is the abundance and variability of radiatively active gases as well as radiative heat fluxes. There is also a need to characterize the aerosol population (Titov et al. 2018, this issue), including number density, particle size distribution and optical properties as well as their chemical origin, in order to constrain micro-physical models of Venus' clouds.

Numerical models of atmospheric dynamics have achieved significant success (Sanchez-Lavega et al. 2017, this issue) but many uncertainties remain, especially in the deep atmosphere. Precise wind field retrieval below the upper clouds (surface to 60 km) as a function of location (long/lat) and local time is an essential ingredient required to derive the vertical distribution of the angular momentum, momentum transfer and super-rotation origin. In addition, observations of waves (e.g., gravity, Kelvin, Rossby and tidal) below the clouds are needed to better understand their role in the inertial forces caused by super-rotation. While *in situ* measurements are generally the most direct approach to measuring these parameters, they are limited by short lifetimes (hours to days) and small spatial coverage inherent to current *in situ* approaches. As remote sensing techniques are improved and *in situ* lifetimes are extended, there is ultimately a need for more detailed observations of the deep atmosphere that can match the coverage obtained by missions such as Venus Express in the middle atmosphere.

There are also many questions concerning the composition of the atmosphere that are needed to constrain models of chemical cycles, photochemistry, and radiative transfer (Marcq et al. 2018, this issue). *In situ* measurements are needed of trace gas species in the cloud region extending from 48–65 km. More importantly, measurements of trace gas abundances and possible gradients are sorely needed below the clouds, where only limited observations are available. Abundances and isotopic ratios of noble gases are of significant scientific interest in regard to Venus' atmospheric evolution in comparison with Earth and Mars. These gases are unique because they are inert. As such, they are fossil indicators of the earliest process that formed and modified the original atmosphere. The heaviest noble gases, krypton and xenon, are least susceptible to atmospheric escape and are particularly important. Pioneer Venus and Venera measurements of krypton are discrepant by a factor of four and xenon has never been quantified (Baines et al. 2013). However, because these species lack detectable spectral features, they can only be measured *in situ*. Measurements of D/H are also needed in order to quantify the volume of water in Venus' past as well as the timing and processes for water loss. Deep atmospheric measurements of D/H are needed for the bulk atmospheric value as well as to understand vertical profile uncertainties. Improved measurements of other important isotopic ratios, such as ¹³C/¹²C and ¹⁵N/¹⁴N, provide insights into how Venus' evolutionary history has been similar to or different from Earth. To better understand the coupling of the surface and atmosphere, and the degree to which buffering reactions produce trace gas species in the atmosphere, there is a need to measure trace species in the lowermost scale heights.

2.5 New Orbital Observations

There are many important new observations that are attainable using remote sensing techniques from Venus orbit. The two most recent Venus missions (VEx and Akatsuki) were primarily focused on understanding atmospheric chemistry and dynamics, and a new mission

focused on geologic and geophysical questions is needed. The only historic Venus mission that addressed questions of global surface and interior process was Magellan (1990–1994), with its 1970's era synthetic aperture radar which collected data in one sense of polarization. While Magellan revealed many interesting geologic features on the surface, numerous mysteries remain that require modern instrumentation to bring Venus up to the level of understanding of Mars. For example, Magellan imaging resolutions (100–200 m) are analogous to Viking images of Mars and Magellan altimetry with ~ 10 km posting is of insufficient precision to constrain models at geologic process scales. In addition, models of surface emissivity using near infrared remote sensing data (Gilmore et al. 2017, this issue) require surface topography with much better spatial and vertical resolution than possible using Magellan data, particularly in regions of substantial topographic variability (e.g., tesserae). To more fully understand the story of tessera formation and evolution, higher resolution imaging and complete coverage of the surface in the near infrared is also needed. To improve knowledge of temporal changes in atmospheric circulation, there is a need to establish the average albedo of Venus more accurately as well as to detect changes over annual and longer time scales (Limaye et al. 2017, this issue). More precise observations of zonal and meridional winds (Sanchez-Lavega et al. 2017, this issue) are needed to answer questions about polar vortex dynamics, the extent of the Hadley cell, and to reduce wind divergence uncertainty in order to better constrain cloud top sources and sinks.

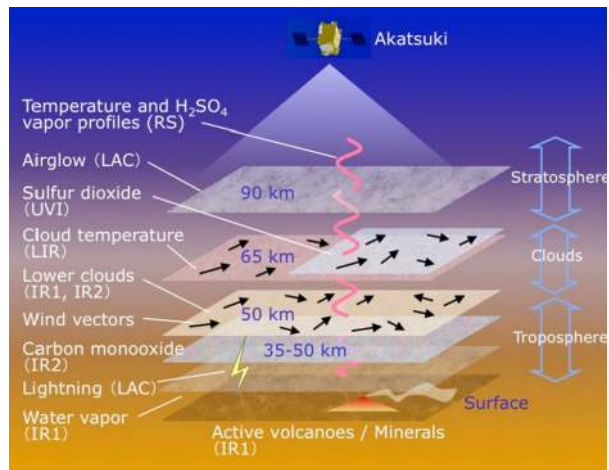
Synoptic imaging spectroscopy with sufficient spectral, spatial, and temporal resolution and sufficient duration to track variations in SO_2 and SO at the cloud tops across the few hours to few weeks time scales would be invaluable for sorting the relative contributions of photochemistry, dynamics and microphysics (Marcq et al. 2018, this issue). Longer term temporal variations in SO_2 abundance at the cloud tops that extend observations made by Pioneer Venus (Esposito 1984), Venera 15 (Zasova et al. 1993), and Venus Express (Marcq et al. 2012), combined with observations of SO_2 variability in the deeper atmosphere, would provide insights into possible mechanisms (e.g., active volcanism, climate variability, or other mechanisms) that drive observed variations. Optical, radio wave, and electric field monitoring are needed to characterize Venus lightning (Titov et al. 2018, this issue).

Orbiting remote sensing platforms are ideally suited to study the upper atmosphere. A dedicated aeronomy and solar wind interaction mission that can provide coverage of the north and south poles, noon and midnight sectors, and terminator regions, during the full solar cycle, would provide necessary data and allow comparisons with Earth and Mars (Futaana et al. 2017, this issue). Precise measurement of the magnetic field and currents in the ionosphere can provide insights into mantle conductivity, which has implications for crustal water content. In addition to dedicated missions, observations by fly-by spacecraft equipped with plasma and field instrumentation can also provide valuable new data (Coradini et al. 2015). Finally, sustained time-series observations of near-infrared molecular emissions in the mesosphere would increase understanding of observed spectral and spatial variability in airglow on the night side (Gerard et al. 2017, this issue).

3 International Collaboration for Venus Exploration

Thanks to the efforts of individual scientists and dialog between space agencies, exploration of Venus has become an international effort. To foster close collaborations, partnerships and coordination of missions, a grassroots International Venus Exploration Working Group (IVEWG) was formed under COSPAR in 2012. COSPAR has fostered international dialog

Fig. 2 Akatsuki's payload is designed to characterize physical and chemical processes that drive Venus' super-rotating cloud layer and runaway greenhouse climate that are unique in our solar system



and collaboration in space exploration since the beginning, even during less friendly relations between nations.

One very valuable and fruitful method for international collaboration has been through Participating Scientist Programs, originating through bi-lateral dialog between agencies. By mutual agreement, NASA and ESA selected individual scientists to formally work with the Venus Express science team. Japanese scientists have also worked similarly with NASA. Because the Venus Express and Akatsuki science is so complementary, the Japanese Akatsuki team has also established good relationships with the European Venus Express scientists. Although neither ESA nor JAXA had hardware roles on the other's missions, the science communities worked together to plan several workshops, including Venus sessions at COSPAR. In addition, Venus Express included one Japanese interdisciplinary scientist.

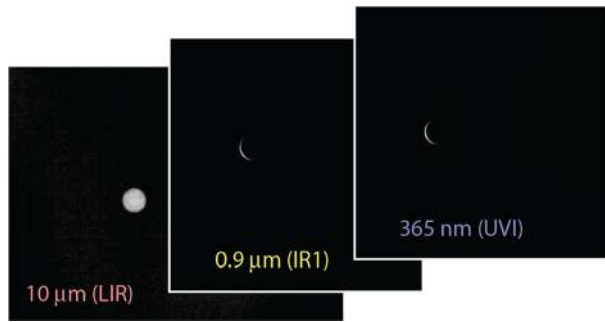
NASA and JAXA have also established a US Participating Scientist Program for Akatsuki. Six American scientists were selected by NASA Announcement of Opportunity with rights to access Akatsuki data just after the data acquisition as well as Japanese Venus scientists prior to the database being opened to the public (18 month after the data acquisition). Two of the six American scientists remained in residence in Japan after orbit insertion. Such cooperation should be more and more important in future international space development. These examples of international cooperation indicate a strong science community that is eager to work together to advance science through collaboration.

3.1 JAXA's Akatsuki

Akatsuki is currently the only active mission at Venus. Japanese interest in exploring Venus has been high for nearly two decades. Competing against other solar system targets, Venus' turn came up when the Planet-C mission was approved in 2001 (Nakamura et al. 2007). The mission was eventually named Akatsuki ("Morning Star") at the time of its launch in May 2010.

Akatsuki was designed to observe the atmospheric dynamics of Venus (Fig. 2), which is totally different from Earth. One of the most fundamental differences between the two planets is expressed by the extremely rapid wind speeds (more than 100 m/s) that have been observed at the Venus cloud tops, 70 km above the surface. The primary objective of the Akatsuki mission is to better understand this atmospheric super-rotation, where the planet is slowly rotating westward while its atmosphere is rotating around the planet 60

Fig. 3 Venus images acquired by the LIR, IR1, and UVI instruments two days after the failed orbit insertion. Images were taken looking back at Venus from 600,000 km away from the planet. All three cameras performed as expected, with the LIR image revealing characteristic features in Venus' night-side cloud-top temperature



times faster. To address the dynamics of the Venusian atmosphere Akatsuki has five cameras (Infrared 1 μm camera (IR1), Infrared 2 μm camera (IR2), Ultraviolet Imager (UVI), Longwave Infrared Camera (LIR), and Lightning and Airglow Camera (LAC)), which detect the atmospheric motion at different altitudes. Radio occultation (Radio Science: RS) studies the temperature, and the H_2SO_4 vapor component between 35 km and 100 km altitude. The original orbit design was optimized to maximize scientific results with a thirty-hour orbital period and 80,000 km periapsis. Such an orbit results in spacecraft motion that is synchronized with the super-rotation of the Venusian atmosphere for 20 hours, i.e., 10 hours prior and 10 hours after the periapsis.

Akatsuki reached Venus six months after launch on 7 December 2010. Unfortunately, the spacecraft suffered a technical failure of the main engine during the orbital insertion burn. Fortunately, the spacecraft computer shut down the burn, saving precious fuel, and putting the spacecraft in a solar orbit with a period slightly smaller than the orbital period of Venus. After investigation, it was learned that, in the propulsion system, salt was formed at the check valve on the fuel tank side that blocked the He gas pressure applied to the fuel tank (Nakamura et al. 2014). The burning condition at the Orbital Maneuver Engine (OME) became oxidizer rich, which caused higher temperatures in the engine and destroyed it. Other parts of the spacecraft, however, turned out to be in good shape and Venus was imaged with three cameras two days after the failed orbit insertion (Fig. 3).

Akatsuki successfully entered Venus orbit on the second attempt on 7 December 2015, using the reaction control system (RCS) thrusters (Nakamura et al. 2016). Akatsuki is currently in a highly elliptical, near equatorial orbit around Venus (orbit inclination is $\sim 166^\circ$ relative to the Venus equator). The periapsis achieved by the RCS thrusters (that are weaker than the OME) is 360,000 km. The spacecraft has survived severe thermal conditions that occurred at every perihelion during the five years of heliocentric orbit, about 1000 W/m^2 more solar flux than the spacecraft was designed for, and the temperature of several parts of the spacecraft have survived higher than the designed permission range. At present the spacecraft and most of the instruments are in good health and performing well. An orbital maneuver, to avoid a long umbra, is expected in December 2018.

In the first two years of orbital operations, Akatsuki has already provided many significant scientific results (e.g., Sanchez-Lavega et al. 2017, this issue). One of the most compelling results to come from Akatsuki to date is the discovery of large scale stationary gravity waves in the atmosphere (Fukuhara et al. 2017). These waves span thousands of kilometers and appear in the afternoon (local times) over high standing surface topography. The presence of such waves at the cloud tops indicates a strong coupling between the air masses flowing over the mountainous terrain and super-rotating clouds. It is possible that the coupling between the surface and the atmosphere is strong enough to change the rotation rate of the solid planet (Navarro et al. 2018).

3.2 What's Next in Venus Exploration?

There are currently no firm commitments to future Venus missions by any international space agency beyond Akatsuki. However, several international space agencies are considering future plans for Venus exploration. VEx and Akatsuki revealed many secrets of Venus' atmosphere, but have also left many questions unanswered (Table 2). Questions regarding the surface and interior have been left unresolved since Venera, Vega, and Magellan. Venus mission concepts developed in recent years have built on existing capabilities and can be grouped into several common themes: orbiters, atmospheric balloons and probes, and landers (Fig. 4). Orbiter missions can be further subdivided into two fundamental types, those that are focused on chemical and dynamic atmospheric processes, and those that are focused on surface geology and geophysics. Orbiter missions focused on atmospheric processes generally include remote sensing payloads to address key questions about the current state of the atmosphere and climate. Orbiter missions focused on geology and geophysics generally include some type of radar system to characterize the surface morphology, topography, and gravity to address key questions about the interior structure and surface evolution. Atmospheric balloons and probes are generally designed to carry instrumentation capable of *in situ* measurements of noble and trace gases to address fundamental question of atmospheric origin and evolution, history of water, and chemical cycles below, within and above the clouds. Probes are capable of measuring chemical composition and atmospheric dynamics in the region where the surface interacts with the atmosphere, whereas current balloon designs generally are designed to float at about 55 km altitude and are capable of measuring the composition and dynamics within the cloud layer over several days. Landers are generally focused on surface chemistry and mineralogy to address key questions about the origin and evolution of the crust. Much larger Venus mission concepts have been considered by ESA, NASA and Russia that generally combine these various flight elements to achieve more comprehensive science objectives. For example, the Venus Flagship Design Reference Mission (Bullock et al. 2009) included an orbiter with a capable radar and instrumentation for atmospheric observations, as well as two balloons and two landers.

With the success of small-sats and cube-sats for Earth observations, there has been a surge of interest in possible planetary applications through competitive programs such as the NASA Small Innovative Missions for Planetary Exploration (SIMPLEx) program (Daou 2017). These small (typically < 100 kg), secondary payloads that can share a launch vehicle with a larger mission are becoming increasingly capable and can include a range of mission architectures including orbiters, probes, and small landers. Numerous small Venus mission concepts are under study. For example, the Cubesat UV Experiment (CUVE) is a small orbiter that could carry instrumentation to characterize the UV absorption (Cottini et al. 2017). Other concepts under development include small payloads to remotely detect seismic activity on Venus from orbit (Komjathy et al. 2018), long-lived surface landers to directly measure seismic activity (Kremic et al. 2018), and small probes to sample noble gases in the upper atmosphere (Sotin et al. 2018). With the increased interest in these small missions, there is an increase in the number of opportunities to deploy such missions at Venus as stand-alone missions, secondary payload elements on a larger Venus mission, or as a payload that can be deployed by other spacecraft performing Venus gravity assist flybys (Coradini et al. 2015). Because there is limited public information available about these concepts at the present time and due to the dynamic nature of evolving capabilities in this field, these concepts are not reviewed in detail in this paper.

The science community and general public have become accustomed to the presence of long-term landers and rovers on other planetary surfaces. In particular, rovers such as Sojourner, Spirit, Opportunity, and Curiosity seem routine for Mars exploration. However, it is

Table 2 Examples of top level science questions identified in Section 1 can be addressed individually or in combination in an effort to more fully understand the differences in Earth's and Venus' evolution. This table shows the primary types of measurements that are required to address these questions and the types of observation platforms that provide an appropriate vantage point for those measurements. Very small and focused missions (e.g., single small instrument), can be flown as a cubesat or a smallsat, riding along with other larger missions that are not necessarily bound for Venus. Slightly larger missions with focused science objectives addressed by a small suite of instruments on a single platform (either in situ or orbital) fit well within a Discovery class mission. Individual components can be combined to form more synergistic missions of larger scope that can range from M-Class and New Frontiers to L-Class and Flagship. All of the mission architectures described are technically ready to fly in the near-term with the exception of the long-lived lander, which still requires some development

	Science question	Primary measurement	Mission element
Surface & Interior	How does Venus lose its heat?	Surface geology, topography, and gravity	Geophysical orbiter
	How volcanically and tectonically active has Venus been over the last billion years	Surface geology, topography, and gravity Seismicity	Geophysical orbiter Long-lived Lander
	Has Venus always been in a stagnant lid regime or was a plate tectonics regime present in the past?	Surface geology, topography, and gravity	Geophysical orbiter
	What is the composition of the highland tessera terrain?	Surface bulk chemistry and mineralogy	Lander, remotely from orbiter, aerial platform
	Do the tessera retain evidence of a time prior to volcanic plains emplacement when water was more prevalent?	Surface bulk chemistry and mineralogy	Lander, geophysical orbiter
	Atmosphere	What are the thermal structure and circulation of the deep atmosphere?	Temperature, pressure, and winds from within the atmosphere
What drives the atmospheric super-rotation observed in the upper cloud layer?		Composition of cloud layer gases and aerosols from within the atmosphere	<i>In situ</i> (e.g., aerial platform, long-lived lander) orbiter
What chemical cycles drive the variability observed in some species above the cloud layers, in particular sulfur species?		Global time dependent measurements of composition above the clouds	Atmospheric composition orbiter
What are the chemical cycles operating below the clouds and to what extent do surface-atmosphere exchange or possible active volcanism play a role?		Relative abundances and gradients of reactive gases below the clouds from within the atmosphere	<i>In situ</i> (e.g., probe, deep-atmosphere aerial platform, lander)
What are the unknown absorbers at the cloud tops?		Composition measurements from within the atmosphere and remotely (spectra and distribution)	<i>In situ</i> (e.g., aerial platform) Remotely from orbiter

Table 2 (Continued)

	Science question	Primary measurement	Mission element
Aeronomy & Escape	What is the impact of solar wind and space weather “storms” on ion escape processes and rates?	Ion & neutral particles, magnetic fields	Aeronomy orbiter
	What causes the observed variability in NO, O ₂ , and OH emissions on the night side? (circulation at mesopause and thermosphere)	Airglows & nightglows	Aeronomy orbiter
	How much water is contained in Venus’ crust	Magnetic fields and current in the ionosphere	Aeronomy orbiter
Evolution/ Geochemistry	What was the original composition of the Venus atmosphere?	Noble gas abundance and isotopic measurements from within the atmosphere	<i>In situ</i> (e.g., probe, aerial platform)
	Did Venus have oceans and did life evolve?	Isotopic abundances in atmosphere; Geological history	<i>In situ</i> platform, lander Geophysical orbiter
	How has the atmosphere evolved over time?	Isotopic abundances in atmosphere; escape processes	<i>In situ</i> platform; aeronomy orbiter
	When and why did the runaway greenhouse begin?		<i>In situ</i> (e.g., probe, aerial platform)

important to keep the Venus environment in mind when planning future mission concepts. While the Venus environment does place some limitations on the types of missions that can currently be envisioned, the majority of high priority science objectives can be achieved with current, existing technology capabilities.

All past Venus orbiter missions have chosen highly elliptical orbits, driven in part by the large amount of fuel required to circularize the orbit. However, science objectives such as high-resolution global topography and improved gravity models, benefit greatly from circular orbits. NASA’s Magellan mission was the first orbiter to effectively demonstrate aerobraking, where multiple deep dips into the planet’s atmosphere were used to slow the spacecraft, and effectively circularize the orbit (Doody 1995; Lyons et al. 1995). Since that time, aerobraking has been used successfully on several NASA Mars missions (Lyons et al. 1999; Smith and Bell 2005; Spencer and Tolson 2007). More recently, ESA also successfully implemented aerobraking toward the end of the Venus Express mission (Svedhem 2014). Another option that has been proposed is the use of Solar Electric Propulsion to directly insert a spacecraft into a circular orbit.

Cloud level balloons are subject to fairly benign temperatures and pressures (at 55 km altitude, the temperature is 30 °C and atmospheric pressure is 0.5 bar), however, sulphuric acid aerosol particles are strongly corrosive. Thus, balloon materials and instrument payloads must be resistant to corrosion. In addition, supplying power to an instrument payload within the cloud layer is a challenge. Because of the dense clouds, solar power is not an efficient option. Many balloon concepts have relied on batteries, but to supply sufficient power for extended duration can increase the mass of the payload that needs to be carried by the bal-

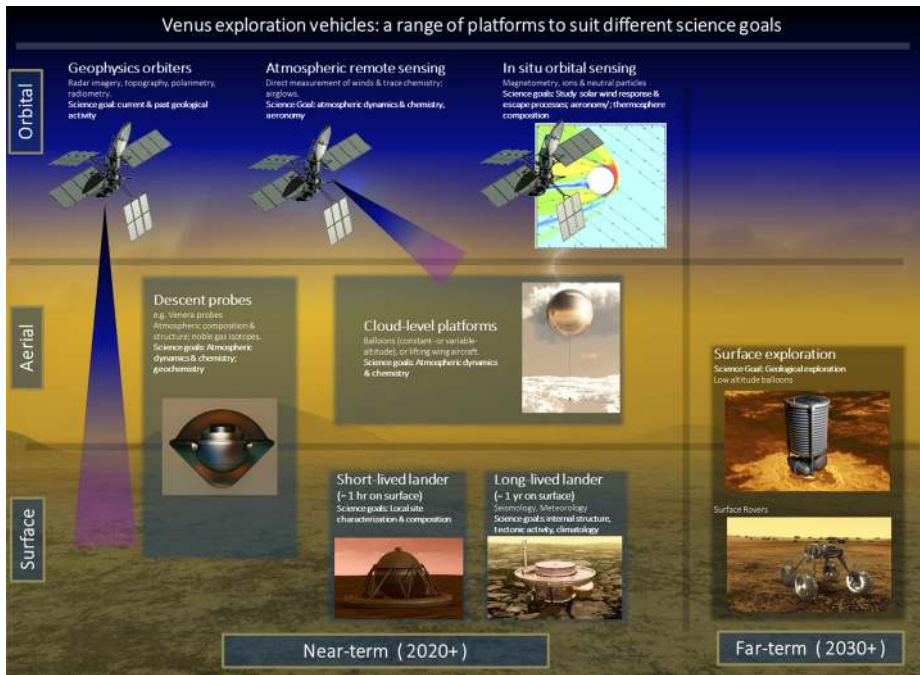


Fig. 4 High priority Venus questions can be addressed by a broad range of mission concepts using surface, aerial, and orbital platforms. While many missions can be implemented in the near-term using existing capabilities, investments in new technologies will enable long term surface science as well as missions that take advantage of mobility in the surface, near-surface, and atmospheric environments

loon. An alternative to traditional batteries is the use of radioisotope power systems (Balint and Baines 2008). However, current systems, such as the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) that is carried on the Curiosity rover, are very large and heavy for balloon applications. In addition, the availability of plutonium needed to power these systems can be challenging for space agencies to secure. The two Vega balloons that flew in 1985 each survived approximately two days at an altitude of 54 km altitude. More recent concepts, such as the Venus Climate Mission study (Grinspoon et al. 2010) include balloons that are designed to survive for up to three weeks.

Deep atmospheric probes and landers pass through the cloud layer relatively quickly (the Venera landers and Pioneer Venus probes all completed their atmospheric descents in about one hour) but must survive the near-surface environment which includes highly-corrosive supercritical carbon dioxide at average surface temperatures of 462 °C and 92 bar atmospheric pressure. The surface pressure is equivalent to water pressure at depths of about 1 km in the ocean, requiring robust pressure vessels to protect instrumentation. In addition, the high temperatures require thermal control systems within the pressure vessel to maintain an environment required for the instrument payload to function. Passive thermal control systems, such as the use of phase change materials, can keep a payload cool for a few hours. However, after all the material has changed phase, temperatures within the pressure vessel will rise quickly. As with balloons, power supply is also an issue. Again, current designs for solar power are not an option, and sufficient battery power for long-term operations increase the total payload mass and must be balanced against the mass of the science payload.

Radioisotope power technology requires future developments to improve efficiency in order to provide Venus surface power. The Venera landers and the Pioneer Venus probes all carried battery systems to supply power. The Venera 9–14 landers were able to survive on the surface for a minimum of 53 minutes (Venera 9) and a maximum of 127 minutes (Venera 13). More recent concepts, e.g., the Venus Flagship Design Reference Mission (Bullock et al. 2009), include lander designs that can survive one hour of descent plus an additional two-five hours of operation on the surface.

Both ESA and NASA offer periodic competitive opportunities to propose innovative missions to planetary destinations, including Venus. Within ESA, there are M-class (medium cost range) and L-class (larger cost) mission opportunities to address high priority science goals of the Cosmic Vision (Bignami et al. 2005). Within NASA, mission concepts can be proposed to the Discovery (medium cost range) and New Frontiers (larger cost) programs to address high priority science within the Planetary Decadal Survey (Squyres 2011). Recent experience has demonstrated a strong interest by the international Venus science community in a wide range of mission concepts in each of these competed categories.

3.2.1 ESA

ESA launched the Venus Express orbiter in November 2005 to end a long hiatus in exploration of the planet after the end of the Magellan mission in October 1994. Thus, the arrival of Venus Express in April 2006 was noteworthy for more than eight years of observations (see other articles in this issue for key Venus Express results). The large scientific output has been due to the high level of interest shown by the European and international scientific community. The mission also enabled training of many young scientists who are eager to address the new questions raised by Venus Express about the planet. Several Venus mission (balloon and orbiter) proposals have been considered or submitted to ESA's Cosmic Vision M-2, M-3, and M-4 opportunities. However, despite significant interest from the science community, none of these concepts has yet been selected for flight. At the time of this writing, Venus is under consideration for M-5 with launch no earlier than 2029.

European Venus scientists have considered two main Venus mission concepts to follow after Venus Express: a cloud-level balloon mission and an orbiter mission focusing on geological activity. These were proposed separately to ESA as M-class missions in 2010 under the names “European Venus Explorer (EVE)” (Chassefière et al. 2009; Wilson et al. 2012) for the balloon mission (Fig. 5), and “EnVision” (Ghail et al. 2012) for the orbiter mission. They were also proposed together as a combined L-class mission in 2013 (Wilson et al. 2013).

France has a long history of scientific ballooning and, crucially, worked with their counterparts in the Soviet Union to develop the two Vega balloons which would eventually be deployed in the clouds of Venus in 1985 (Kremnev et al. 1986; Sagdeev et al. 1986). The Vega balloons were helium superpressure balloons; this balloon type provides a nearly constant float altitude and offers the potential of a long lifetime (superpressure balloons on Earth often achieve lifetimes in excess of 100 days). The Vega balloons were deployed at an altitude of 55 km, which offers the significant advantage of having ambient temperatures of around 30 °C. The Vega balloons carried only simple meteorological sensors and a transponder, but a new Venus mission would seek to carry a much more capable scientific payload.

Proposed to the M-2 and M-3 calls in 2007 and 2010, the EVE balloon mission would have used, like Vega, a helium superpressure balloon deployed at 55 km altitude (Chassefière et al. 2009; Wilson et al. 2012). There were two main scientific goals proposed for

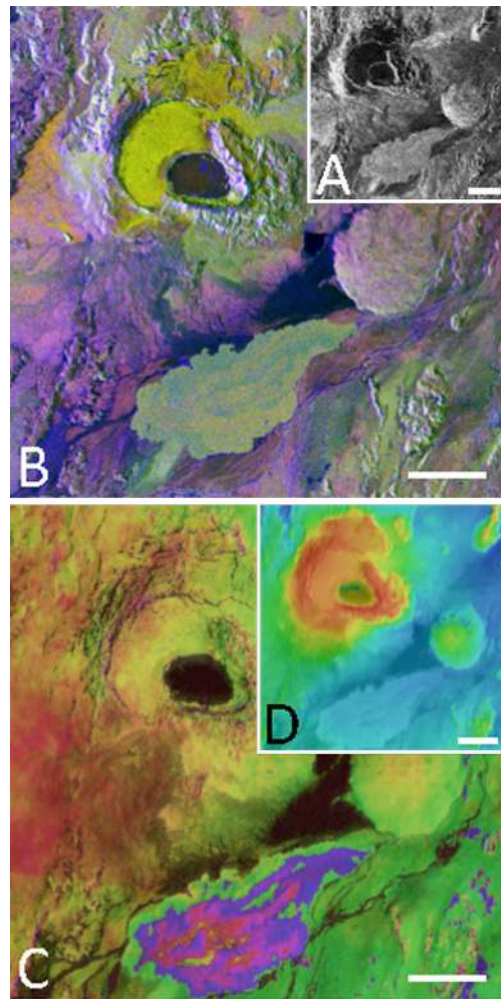
Fig. 5 Artist's impression of the European Venus Explorer (EVE) balloon mission (credit: T. Balint/EVE team)



this mission. Firstly, it would measure the abundances of noble gas and light element isotopes which, as discussed in Crisp et al. (2002), provide constraints on the formation and evolution of Venus and its volatile history. These abundances would be measured by a mass spectrometer equipped with chemical and cryogenic traps to concentrate trace gases to allow more sensitive measurement. A second goal for the balloon mission would be to characterize chemical, dynamical, and radiative processes at work in the cloud layer. The float altitude of 55 km puts this balloon in the heart of the main convective layer, which the Vega balloons revealed to have updrafts and downdrafts of typically 1–2 m/s. A cloud-level balloon would seek to characterize compositional, microphysical and radiative differences between regions of updrafts, as well as seeing how these parameters vary as a function of local solar time as the balloon gets carried around the planet. The viability of small balloon-deployed probes, with masses ranging from 0.1 to 2 kg, was studied as a valuable way of accessing the lower atmosphere and possibly even the surface from a cloud-level balloon mission (Wilson and Wells 2007)—but this option was not retained in the final EVE proposals.

The most recent concept developed by European scientists and submitted for consideration to the M-5 opportunity is an orbiter, EnVision. Following the primarily atmospheric discoveries made by Venus Express and Akatsuki, EnVision focuses on the planetary surface and interior and their relationship with the atmosphere. Proposed in 2010, 2014, and 2016, the central goal of the mission is to study the current and past rates and styles of geological activity (Ghail et al. 2012). In 2018, EnVision was down selected by ESA for an in-depth concept design study. A search for active volcanism is high on the list of intended investigations, but a history of volcanic and tectonic activity, as well as establishment of weathering rates, would all contribute to a better understanding of Venus' history. The payload comprises a state-of-the-art S-band radar, with image spatial resolutions of 1–30 m, 3-band polarimetry, and differential interferometry capability to measure cm-scale deformation (Ghail et al. 2017); this is complemented by subsurface radar, and an IR emission mapper with IR and UV spectrometers to map volcanic gases, and geodetic investigations through Ka/X-

Fig. 6 Simulation of data types to be acquired by VenSAR on EnVision: (A) simulated image with Magellan resolution and single polarization; (B) VV-VH-HH 30 m polarimetric image; (C) 30 m Interferometric Synthetic Aperture Radar (InSAR) image, showing subsidence of a 2-year old lava flow; (D) 60 m stereo and InSAR-derived topography. VenSAR will also obtain 6 m HiRes and 1 m resolution Spotlight images. All images derived from ESA/EU Sentinel-1 data of the Askja caldera and Holuhraun flow, Iceland



band tracking (Fig. 6). Complementary science payloads to study the surface include a multi-channel Venus Emissivity Mapper to map thermal emission and surface emissivity at 0.8–1.1 μm spectral windows (Helbert et al. 2017), to look for composition variations as well as thermal anomalies of active volcanic activity. The payload also includes measuring tropospheric H_2O and SO_2 (using IR nightside spectral windows) and mesospheric SO_2 (using dayside UV spectroscopy) to track volcanogenic gases. The subsurface radar sounder, similar to MARSIS, and SHARAD, will determine the depth of weathering, sediments, and lava flows on Venus.

The European science community has the necessary expertise to realize both of these mission types: the balloon mission takes advantage of CNES experience with scientific ballooning on Earth and with the Vega Venus balloons, as well as heritage from *in situ* instrumentation from missions including Huygens, Rosetta and ExoMars. A radar-equipped orbiter would exploit experience gained from radars including Sentinel-1 and NovaSAR. As discussed above, the European Venus community have concentrated their efforts on orbiter and balloon proposals—but probe/lander missions have also been studied, both by ESA (e.g.

PEP 2010) and by others (e.g. Chassefière et al. 2002). Recently, there has been a renewed interest in long-lived surface stations, exploiting developments in high temperature SiC electronics which might permit uncooled surface stations suitable for seismology (Wilson et al. 2016); though promising, these developments are (at the time of writing) still at a very low level of technology readiness.

3.2.2 NASA

NASA has not had a mission to Venus since Magellan, which ended in 1994, and currently has no plan to fly a Venus mission. The 2013 NRC Planetary Decadal Survey (hereafter referred to as *Visions and Voyages*, Squyres 2011) clearly recognized the importance of Venus exploration to comparative planetology by recommending two specific missions to Venus that address high priority science questions. The two missions include one in the New Frontiers class and one Flagship-class mission. The New Frontiers program, established in 2003, historically selects missions that cost less than \$1B and are led by a scientific Principal Investigator. New Frontiers missions, e.g., New Horizons, Juno, and OSIRIS-REx, are solicited by NASA on a periodic basis (approximately two per decade), with the most recent New Frontiers competition in 2017. Flagship-class missions are directed to a specific NASA center for leadership and cost more than \$1B. In addition to these mission classes with prescribed science requirements, *Visions and Voyages* also recommends that NASA continue the highly successful Discovery Program (e.g., Dawn, MESSENGER, InSight, Lucy, Psyche) with a two-year launch cadence. The Discovery Program is a competed category of NASA Principal Investigator-led missions that are smaller in scope than New Frontiers. *Visions and Voyages* suggest that there are multiple Venus missions that can be conducted within the Discovery Program.

Since its inception in 1992, at least 24 Venus mission concepts have been submitted to the Discovery program. Of those, six have been awarded Phase A study funding; yet, none have ultimately been selected for flight. The Venus concepts considered within Discovery have included balloons (e.g., VALOR, Baines et al. 2009), atmospheric-focused orbiters (e.g., Vesper, Allen and Chin 1998; Chin 2011), surface-focused orbiters (e.g., VERITAS, Smrekar et al. 2016), and probes (e.g., DAVINCI, Glaze et al. 2016). VERITAS and DAVINCI, both submitted to the 2014 round of Discovery, accounted for two of the five concepts selected for Phase A funding in 2015. However, again, neither were selected for flight. These two highly complementary concepts both addressed the major question of how and why Venus' evolution was so different from Earth (Smrekar et al. 2016; Glaze et al. 2016), one through orbital remote sensing of the surface and the other through *in situ* measurements of the atmosphere. VERITAS was focused on providing a global digital elevation model, high resolution (30 m) imaging, near-infrared emissivity, and gravity. The VERITAS spacecraft would have carried an X-band SAR, capable of single-pass interferometry and a 6-band near-infrared spectrometer. DAVINCI was focused on measuring noble gases and deep atmosphere vertical profiles of trace gases and isotopes, including precise measurements of D/H. DAVINCI would also have characterized atmospheric structure along the descent path and would have imaged a tessera unit prior to touchdown. The DAVINCI probe carried a mass spectrometer, a tunable laser spectrometer, an imager, and an atmospheric structure package.

The New Frontiers-class mission recommended by *Visions and Voyages* is the Venus In Situ Explorer (VISE) (Squyres 2011). This mission was also recommended in the prior Planetary Decadal Survey ("New Frontiers in the Solar System", Belton et al. 2003; Beebe et al. 2008). Despite several proposed concepts, including three submitted to the 2017

Table 3 Venus is one of several targets identified by the Visions and Voyages Planetary Decadal Survey for NASA's New Frontiers. The Venus In Situ Explorer (VISE) New Frontiers mission theme has six scientific objectives prescribed by the Decadal Survey

VISE scientific objectives

Understand the physics and chemistry of Venus's atmosphere through measurements of its composition, especially the abundances of sulfur, trace gases, light stable isotopes, and noble gas isotopes

Constrain the coupling of thermochemical, photochemical, and dynamical processes in Venus's atmosphere and between the surface and atmosphere to understand radiative balance, climate, dynamics, and chemical cycles

Understand the physics and chemistry of Venus's crust

Understand the properties of Venus's atmosphere down to the surface and improve our understanding of Venus's zonal cloud-level winds

Search for evidence of past hydrological cycles, oceans, and life and constraints on the evolution of the atmosphere of Venus

New Frontiers solicitation (VOX: Venus Origins eXplorer, Smrekar et al. 2018; VICI: Venus In situ Composition Investigations, Glaze et al. 2017; VISAGE: Venus In Situ Atmospheric Geochemical Explorer, Esposito et al. 2017), NASA has selected no VISE mission for flight to date. The overarching goal of the VISE mission is to deliver measurements of the atmosphere and surface that cannot be achieved from orbit (Table 3). As noted in Visions and Voyages, a mission that can fully address all of these objectives would likely fall into a Flagship-class cost. Thus, a proposed New Frontiers mission must address a preponderance of these objectives. Venus mission concepts have been submitted to the New Frontiers opportunities in 2004, 2009, and 2017 (at least five proposals across the three calls). Most of these concepts have utilized a lander that could make *in situ* measurements of the atmosphere during descent as well as measurements of rock composition at the landing site. The Surface and Atmosphere Geochemical Explorer (SAGE) concept, selected for Phase A funding from the 2009 call (Esposito 2011), was a lander proposed to land on the flanks of a volcano. Over a period of at least three hours, the lander would take photographs and measure the chemistry and mineralogy of the surface.

Visions and Voyages also recommended the Venus Climate Mission (VCM) as a possible Flagship-class (>\$1B) mission (Grinspoon et al. 2010). Although the VCM concept is substantially less costly than other Flagship-class missions, three recommended flagship missions (Mars, Europa or Uranus) have higher priority than VCM. Thus, the likelihood of NASA commitment to fly VCM during the 2013–2022 Decadal period is very low. The VCM builds on the Venus Flagship Design Reference Mission (Bullock et al. 2009), which is a comprehensive mission that addresses a broad range of Venus science objectives that can be either shared by international partners, or split into multiple smaller missions. The VCM focuses on understanding the current climate of Venus and includes an orbiter, a balloon, a mini-probe, and two dropsonde observational platforms (Table 4).

In addition to the VISE and VCM mission concepts described in Visions and Voyages, the Inner Planets Panel of the Planetary Decadal Survey also explored two additional concepts, both of which build on the six science objectives for VISE (Table 3). The Venus Mobile Explorer (VME) (Glaze et al. 2009) includes an additional requirement for surface chemistry and mineralogy measurements at a second location (Fig. 7), as well as optical surface images along a linear transect between the two surface measurement locations. The VME implements a metallic balloon concept that lifts the lander from the initial landing site location and then enables the balloon to float ~ 5 km above the surface for a distance of

Table 4 The key to the science objectives for VCM is that all measurements are acquired synergistically

VCM scientific objectives

Characterize the strong carbon dioxide greenhouse atmosphere of Venus, including variability over longitude, solar zenith angle, altitude and time of the radiative balance, cloud properties, and dynamics and chemistry of Venus' atmosphere

Characterize the nature and variability of Venus' super-rotating atmospheric dynamics, to improve the ability of terrestrial general circulation models to accurately predict climate change due to changing atmospheric composition and clouds

Constrain surface/atmosphere chemical exchange in the lower atmosphere

Determine the origin of Venus' atmosphere

Search for atmospheric evidence of recent climate change on Venus

Understand implications of Venus' climate evolution for the long-term fate of Earth's climate, including if and why Venus went through radical climate change from a more Earth-like climate in the distant past, and when Earth might go through a similar transition

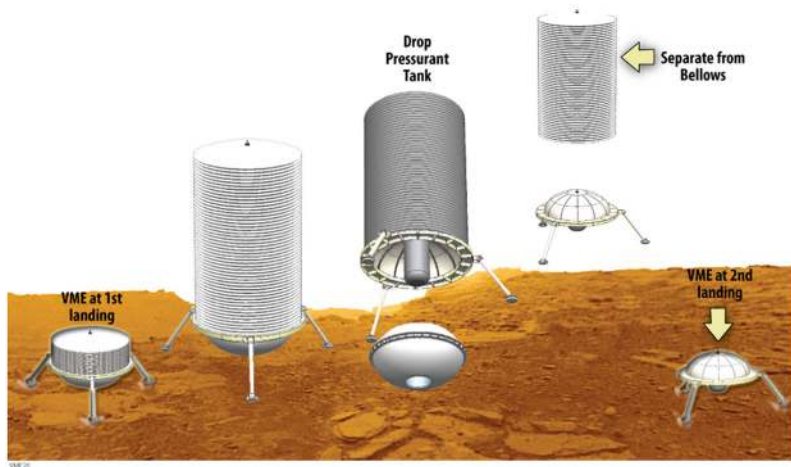
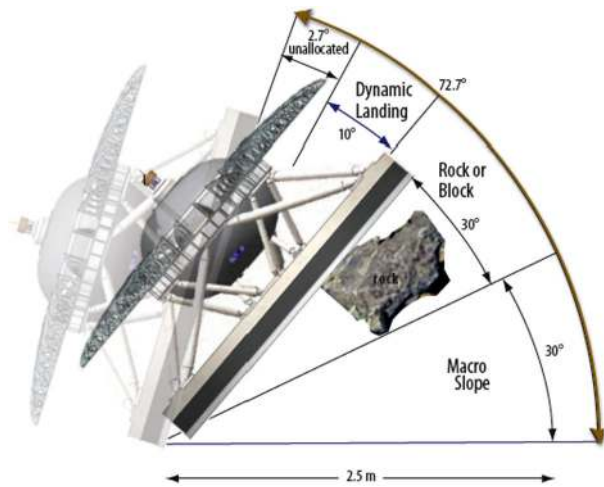


Fig. 7 Venus Mobile Explorer studied by NASA's Planetary Decadal Survey uses a metallic bellows concept to float between two landing locations separated by ~ 8 km (Glaze et al. 2009)

~ 8 km. The total lifetime of the VME lander, including science data collection and relay is 5 hours.

The Inner Planets Panel also explored the Venus Intrepid Tessera Lander (VITaL) concept (Gilmore et al. 2010). Again, the science objectives for VITaL are identical to those defined for VISE, but with the additional requirement that chemistry and mineralogy measurements must be made within a tessera region. Tesserae have been hypothesized to be the most ancient parts of the surface, where information about the epoch before global volcanic resurfacing one billion years ago may be found (Ivanov and Head 1996). Because current technology only supports uncontrolled landing, because tesserae are generally much more rugged than the smooth volcanic plains, and because knowledge of detailed topography and roughness are not available, the VITaL lander concept is designed to safely land on slopes up to 72.7° (Fig. 8).

Fig. 8 VITaL lander concept with very low center of gravity designed for stable landing in extremely rugged terrain (Gilmore et al. 2010)



3.2.3 Roscosmos

Planning efforts are under way in Russia for a potential new Venus mission named Venera-D (where “D” is for Dolgozhivushaya, or “Long Lived”). The last Soviet mission to Venus included the successful deployment of balloons (Kremnev et al. 1986) and landers on Venus in 1985 by Vega 1 and Vega 2. The Venera-D mission, proposed by Vasily Moroz to the Russian Academy of Sciences in 2003, was included in the Russian Federal Space Program (RFSP) 2006–2015 as the first mission to Venus in the post-Soviet era. Originally intended as a long-lived (30 days) lander on the surface of Venus, the current baseline mission concept includes a short-lived (2–3 hour) lander and an orbiter. Several possible contributed mission elements have also been studied, such as balloons, a sub-satellite, or a longer-lived (24 hours) surface station (Zasova et al. 2014). The current RFSP places the Venera-D launch after the launch of the collaborative ESA and Russian Federation Space Agency (Roscosmos) ExoMars mission. The mission launch is possible in the years 2026 (earliest), 2027 and beyond, with launch opportunity intervals of approximately 1.5 years.

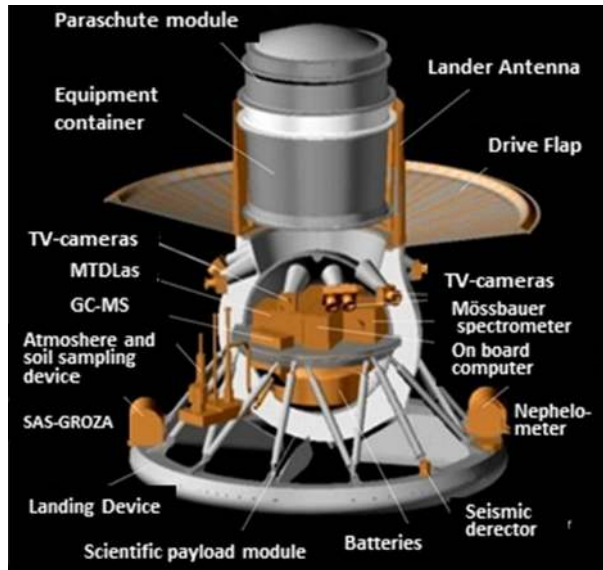
Although there are, as yet, no firm commitments to fly Venera-D, NASA and IKI/Roscosmos have established a Joint Science Definition Team (JSDT) to define the science goals and priorities, mission architecture, and technology needs of the Venera-D concept. A key task of the JSDT was to codify the synergy between the goals of Venera-D and those of NASA. To this end, the group established traceability to the NASA Planetary Decadal Survey (Squires 2011) and to VEXAG’s Goals, Objectives and Investigations (VEXAG 2016) (Senske et al. 2016, 2017a, 2017b). The JSDT also identified areas where science objectives of high priority to NASA may not be addressed by the baseline Venera-D concept, and have generated a list of potential contributed options, including both instruments and flight elements.

The scientific objectives of the Venera-D mission concept (Senske et al. 2017b) are focused on a complex study of the Venus atmosphere, surface and plasma environments, with an overall goal of better understanding why did Venus and Earth evolve so differently, as well as learning what Venus can teach us about the possible future evolution of Earth’s climate. To address these investigations, the Venera-D mission concept nominally includes three basic flight elements: a Lander with a required lifetime of 2–3 hours on the surface,

Table 5 The Venera-D baseline mission would address a wide array of scientific questions

Venera-D platform	Venera-D scientific goals
Orbiter	<p>Study of the dynamics and nature of super-rotation, radiative balance and nature of the greenhouse effect</p> <p>Characterize the thermal structure of the atmosphere, winds, thermal tides and solar locked structures</p> <p>Measure composition of the atmosphere; study the clouds, their structure, composition, and chemistry, nature of absorption features in the UV</p> <p>Investigate the upper atmosphere, ionosphere, electrical activity, magnetosphere, solar wind and dissipation of the atmospheric component</p>
Lander	<p>Perform chemical analysis of the surface material and study the elemental composition of the surface, including radiogenic elements</p> <p>Study of interaction between the surface and atmosphere</p> <p>Investigate the structure and chemical composition of the atmosphere down to the surface, including abundances and isotopic ratios of the trace and noble gases</p> <p>Perform direct chemical analysis of the cloud aerosols</p> <p>Characterize the geology of local landforms at different scales</p> <p>Search for lightning</p>

Fig. 9 Concept for Venera-D lander based on successful Venera and Vega landers flown in the 1970's and 1980's, with proposed payload assembly (Lavochkin Assoc.)



a long-lived surface station with a lifetime of 60–120 days, and an Orbiter. The science objectives of the mission would address key questions about the dynamics of the atmosphere with emphasis on the atmospheric super-rotation, its origin and evolution, the geological processes that have formed and modified the surface with emphasis on the mineralogical and elemental composition of surface materials, and the chemical processes related to the interaction of the surface and the atmosphere (Table 5).

The Lander (Fig. 9) is planned to be of the Venera-Vega type. This flight system has demonstrated 10 successful landings, proving its reliability for the delivery of landed scien-

Table 6 The Venera-D Lander carries instruments to assess the surface chemistry and geology

Venera-D lander: instrument payload

Active Gamma and Neutron Spectrometric Soil Analysis
 Gas-Chromatograph-Mass-Spectrometer (GC-MS)
 Mossbauer spectrometer
 Television cameras (landing, stereo, panoramic, micro-imaging)
 Multichannel tunable laser spectrometer (MTLAs)
 Nephelometer-particle counter
 Wave-, PTW-, Optical-packages
 Radio-science

Table 7 The Venera-D Orbiter carries instruments to study atmospheric chemistry and dynamics

Venera-D orbiter: instrument payload

Thermal Infrared (TIR) Fourier Spectrometer
 Millimeter (MM)-sounder
 Ultraviolet (UV)-mapping spectrometer
 Visible-near IR (VIS-NIR)-mapping spectrometer
 Solar and Star Occultation Experiment in UV and near IR (NIR)
 Radio science
 Plasma package that includes: (1) Magnetometer; (2) Wave instrument; (3) Electron spectrometer; (4) Mass spectrometer; (5) Solar wind monitor; (6) Neutral atom detector, and (7) High energy particle detector

tific payloads. The proposed baseline lander payload includes eight instruments (Table 6). Possible augmentation of the scientific payload to address high priority NASA science objectives could include a Raman spectrometer, Raman-Laser Induced Breakdown Spectrometer (LIBS), or Alpha-Particle X-ray Spectrometer APXS. With this instrument package, the Venera-D Lander would measure noble gases and trace gas elemental and isotopic ratios during descent. These instruments also measure chemical composition and microphysical properties of the clouds, and place constraints on the radiative balance within the atmosphere. At the surface, the Lander would measure elemental chemistry and mineralogy. The Lander will be sensitive to volcanic and electric activity, and will obtain surface images using several cameras. The atmospheric and soil samples will be delivered inside the pressure vessel for investigation by the GC-MS, MTLAs, Mossbauer, and APXS.

Potential Venera-D landing sites include volcanic plains that satisfy both safe landing and science priority requirements.

The Venera-D baseline Orbiter payload includes seven investigations (one of which includes multiple instruments) (Table 7). Augmentation of the orbiter payload could include cameras in the NIR (e.g., Helbert et al. 2017) and thermal infrared (TIR) spectral ranges for mapping of the surface emissivity in several atmospheric windows (NIR) and to study dynamics of the upper clouds (TIR).

The main goals for the orbital payload are atmospheric dynamics and super-rotation, unknown absorbers of incident sunlight, thermal structure from the lower atmosphere to the thermosphere, thermal tides, thermal balance, composition of the atmosphere, mapping of the cloud structure and winds, monitoring of surface emissivity to search for volcanic

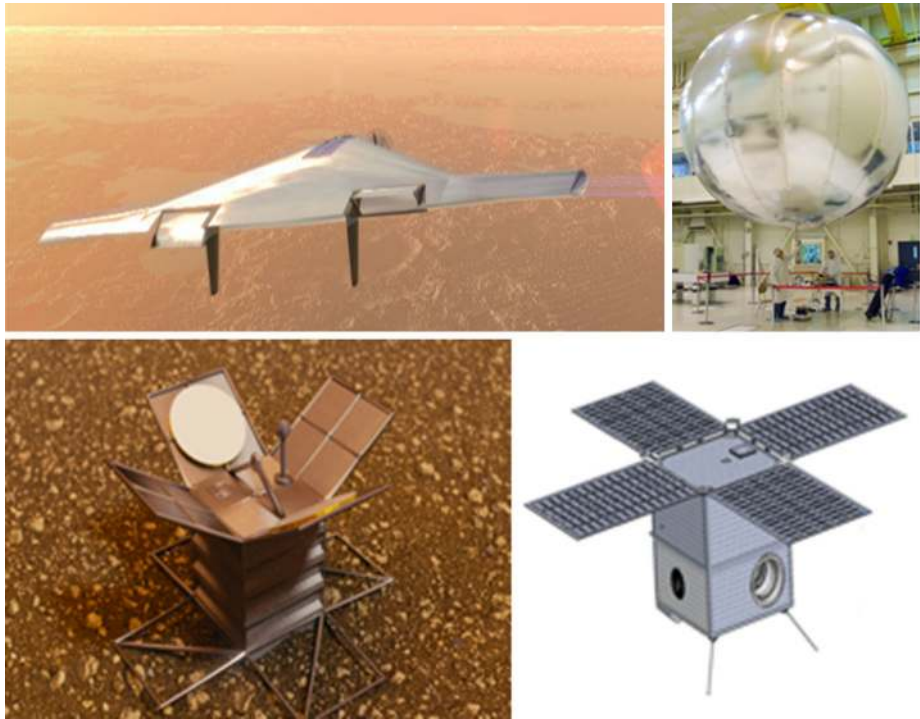


Fig. 10 Possible augmentation elements, proposed for Venera-D mission: VAMP, balloon, small long-lived station and sub-satellite

activity and seismic activity through airglow distribution, and interaction with the solar wind and escape rate.

A long-lived surface station (Kremic et al. 2016) is of particular interest. The Venera-Vega landers survived on the surface of Venus for two hours at best. However, to substantially increase knowledge of the surface environment, monitoring for periods of months to years is needed. Science goals of a long-lived station for Venera-D are the following:

- Monitor the amplitude and phase of diurnal tides, other planetary scale waves, and mesoscale turbulence;
- Characterize the exchange of the planet's solid body and air mass, which may be a source of angular momentum, to address processes associated with super-rotation;
- Simultaneous monitoring of air mass flow and variations of composition to give insight into the role that atmospheric transport plays in the maintenance of a chemical balance in the lower Venus troposphere.

The JSDT has found that the science goals can be enhanced through inclusion of additional mission elements (Fig. 10) such as a

- Mobile aerial platform, e.g., the Venus Atmospheric Maneuverable Platform (VAMP) (Polidan et al. 2015; Lee et al. 2016)
- Super-pressure (Hall et al. 2008) or variable altitude Balloon
- Sub-satellite

In 2016, the JSDT completed pre-Phase A formulation of science goals and priorities along with its assessment of key areas for technology maturation (Senske et al. 2017b). The next phase of development will focus on a deeper examination of the science and instruments along with the definition of spacecraft requirements.

3.2.4 Indian Space Research Organization (ISRO)

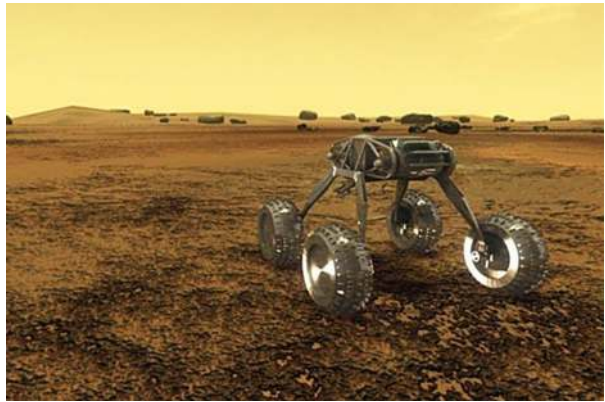
Following the success of the Chandrayaan-1 mission to the moon which included payloads from six countries and the present Mangalyaan Orbiter Mission to Mars, MOM, ISRO is also considering Venus as an exploration target for a mission that could launch as early as 2023. Three workshops have been conducted during 2012–2014 through individual scientists' efforts and a bilateral program between Belgium and ISRO that has raised the awareness of key science questions amongst the scientists from various ISRO centers. The conditions are opportune for ISRO to take a step towards exploring Venus, having had considerable success with Synthetic Aperture Radar, Moon Impact Probe and scientific payloads on Chandrayaan, Mangalyaan and numerous Earth orbiters.

4 Long-Term Goals for Venus Exploration

While there are many new advances that can be made in our current understanding of Venus using existing approaches and technologies, there are several high priority science goals that require development of new capabilities (Fig. 4). The biggest challenges to future Venus exploration are related to *in situ* observations on the surface or near the surface and within the clouds. Major advances in scientific knowledge can be achieved through long duration *in situ* operations as well as through improved maneuverability on the surface and within the atmosphere. The ability to implement such missions will require investments in many different areas, including the miniaturization of instruments that require less power and heat dissipation, development of efficient systems that can provide power and thermal control, and development of sensors, electronics and other subsystems that can operate at higher temperatures. The probability of achieving a mission with long-term survival capabilities is enhanced greatly by approaching this goal from several angles. Many studies have focused exclusively on long-term technology needs for Venus exploration (e.g., Balint et al. 2008; VEXAG 2014b; Kremic et al. 2015) and several examples are provided here.

One high priority, fundamental observation that needs to be made at Venus to understand the internal structure of the crust and core is a measurement of seismic activity. For example, a long-lived surface station that measures seismicity and heat flow (analogous to the InSight mission planned for Mars, Banerdt et al. 2013) would address several key objectives related to the structure of Venus' interior as well as improve understanding of the current level of volcanic and tectonic activity (Sotin et al. 2017, this issue). While recent efforts have indicated that some measurements can be made from orbit (Stevenson et al. 2015), detailed information on the interior structure of Venus will require a seismic station (or better yet, a network). Surface survival of many months is necessary to establish sufficient characterization of background levels of seismicity as well as to understand the frequency and magnitude of variations from the background. Such a long-lived surface station could also accommodate a meteorology station to characterize variability in temperature, pressure and winds in the near-surface atmosphere over a Venus day. Progress has been made on seismic sensors that can survive for very long durations on the Venus surface (Ponchak et al. 2012),

Fig. 11 Futuristic ideas for long-term surface mobility include wheeled rovers (Landis and Mellott 2007)



however many other technologies must be developed before such sensors can be implemented in a viable mission. Advances in three key areas are required to achieve long-term surface survival, (1) development of sensors, electronics and mechanisms that operate at high temperatures, (2) development of active thermal control systems that can effectively and efficiently dissipate heat in the high temperature ambient environment, and (3) development of radioisotope, or alternative (as yet undefined), power systems that can efficiently supply long-term power in the Venus surface environment. NASA's Hot Operating Temperature Technology (HOT Tech) program is investing in several areas including electronics, sensors, actuators, electronics packaging, oscillators and clocks for wireless communication, electric motors, and power generation.

It is important to note that significant advances in understanding do not necessarily require months of operation in the Venus surface environment. Even moderate lifetimes of a few weeks would increase the ability to include human-in-the-loop decision-making processes. Such capabilities would enable selection of sampling sites for detailed imaging, drilling, and/or sample analysis (as is done routinely by the Curiosity rover on Mars, Grotzinger et al. 2015).

As with Mars, a major goal of Venus exploration is to achieve mobility (tens to hundreds of kilometers) on the surface in order to visit multiple locations and to ultimately return a sample from the surface to anchor the chronology of the observed surface stratigraphy. Near surface floating platforms that incorporate expandable metallic bellows, have been examined (e.g., Venus Mobile Explorer, Glaze et al. 2009). Such concepts are capable of remote observations of terrains over distances of ~ 10 km, but are limited in the number of surface sites that can be sampled directly for chemical composition and mineralogy. Surface mobile platforms with wheels or legs have also been envisioned (Fig. 11). In addition to the challenges of long-term power and surface survival (Landis and Mellott 2007), mobility poses additional challenges, including increased complexity with numerous mechanisms, as well as challenges with guidance, navigation and control. Specific technologies that require advancement include balloon, linear actuators, rotational motors, hinge and ball joints, electronics, wheels and chassis, and power generation (Kremic et al. 2015).

Key science objectives in the upper cloud layer, including characterization of atmospheric species such as the unknown UV absorber (Limaye et al. 2017; Marcq et al. 2018; Titov et al. 2018, this issue), and characterization of atmospheric composition at a range of altitudes and latitudes could be achieved by an advanced powered aerial platform. Examples include both fixed wing (Landis 2006) or semi-buoyant (Griffin et al. 2015; Lee et al. 2015; Polidan et al. 2015) concepts (Fig. 12) that incorporate solar panels on the upper surfaces

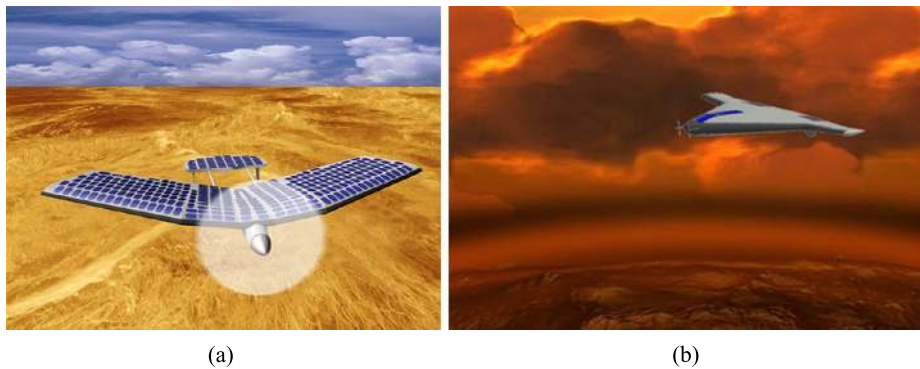


Fig. 12 (A) Fixed wing concept (Landis 2006) and (B) Venus Atmospheric Maneuverable Platform (VAMP) concept (Polidan et al. 2015)

that allow the vehicle to use solar power to charge on-board batteries when flying in the clouds for use when flying below the clouds or on the night side of Venus. The basic technologies needed for advanced aerial platforms are more or less available, but significant work is needed to demonstrate viability in the Venus environment (Kremic et al. 2015). The key challenges are atmospheric entry with complex deployment and demonstration that sufficient power can be generated. Other technologies being developed for Venus aerial platforms include variable altitude balloon concepts or cyclocopters (Husseyin 2016) that allow a VAMP-like (Fig. 12b) platform to fly at all atmospheric levels.

5 Summary

Despite tremendous scientific progress over the last decade, numerous compelling questions remain about Venus and its comparative relationship with the other terrestrial planets in our solar system. New missions capable of making *in situ* measurements in the atmosphere and at the surface, as well as those focused on understanding the surface and interior from orbit are natural follow-ons to the successful VEx and Akatsuki missions. However, despite interest and support from the scientific community demonstrated through multiple mission concept ideas, no international space agency has committed to a future Venus mission. Without a new flight mission, progress can be pursued through ground based observations, experimental studies, and numerical modeling. These studies not only advance the state of knowledge, but also continue to provide new information that can help guide requirements for future missions. While investments in technologies will enable new types of missions, including long-lived landers and platforms with surface or near-surface mobility, there are many high priority questions that can be addressed with existing technology. Venus is a more compelling exploration target than ever before, providing a critical endmember example of terrestrial planet formation and evolution within our own solar system nursery. Continued efforts to understand Venus' complex history will significantly enhance understanding of comparative planetology as well as provide a basis for exoplanet characterization.

Acknowledgements The authors would like to acknowledge helpful comments from the Venus III editors and an anonymous reviewer. L.S. Glaze was funded in part by the National Aeronautics and Space Administration WBS#811073.02.01.05.80.

Open Access This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.

References

- M. Allen, G. Chin (the VESPER Science Team), The VESPER mission to Venus, in *30th Div. of Plan. Sci., Abstract #48P.08* (1998)
- D.A. Allen, J.W. Crawford, Cloud structure on the dark side of Venus. *Nature* (1984). <https://doi.org/10.1038/307222a0>
- K.H. Baines, S.K. Atreya, D. Crisp, J.L. Hall, V.V. Kerzhanovich, S.S. Limaye, K. Zahnle, In-situ exploration of Venus by balloon—science objectives and mission architecture, in *40th Lunar and Plan. Sci. Conf., Abstract #1238* (2009)
- K.H. Baines, S.K. Atreya, M.A. Bullock, D.H. Grinspoon, P. Mahaffy, C.T. Russell, G. Schubert, K. Zahnle, The atmospheres of the terrestrial planets: clues to the origin and early evolution of Venus, Earth, and Mars, in *Comparative Climatology of Terrestrial Planets*, ed. by S.J. Mackwell et al. (University of Arizona Press, Tucson, 2013), pp. 137–160. https://doi.org/10.2458/azu_uapress_9780816530595-ch006
- T.S. Balint, K.H. Baines, Nuclear polar VALOR: an ASRG-enabled Venus balloon mission concept, in *American Geophysical Union Fall Meeting* (2008)
- T.S. Balint, E.A. Kolawa, J.A. Cutts, C.E. Peterson, Extreme environment technologies for NASA's robotic planetary exploration. *Acta Astronaut.* **63**(1–4), 285–298 (2008). <https://doi.org/10.1016/j.actaastro.2007.12.009>
- B. Banerdt et al., InSight: a discovery mission to explore the interior of Mars, in *44th Lunar and Planetary Science Conference* (2013), p. 1915
- G. Barentsen, D. Koschny, The Venus ground-based image Active Archive: a database of amateur observations of Venus in ultraviolet and infrared light. *Planet. Space Sci.* **56**(10), 1444–1449 (2008). <https://doi.org/10.1016/j.pss.2008.03.005>
- R. Beebe et al., *Opening New Frontiers in Space: Choices for the Next New Frontiers Announcement of Opportunity* (2008)
- M.J.S. Belton et al., *New Frontiers in the Solar System: An Integrated Exploration Strategy* (2003)
- B. Bézard, C. de Bergh, D. Crisp, J. Maillard, The deep atmosphere of Venus revealed by high-resolution nightside spectra. *Nature* **345**, 508–511 (1990)
- G. Bignami, P. Cargill, B. Schutz, C. Turon, *Cosmic Vision: Space Science for Europe 2015–2025* (2005)
- M. Bullock, J.L. Hall, D.A. Senske, J.A. Cutts, R. Grammier, *Venus Flagship Study Report* (2009)
- B.A. Campbell, D.B. Campbell, G.A. Morgan, L.M. Carter, M.C. Nolan, J.F. Chandler, Evidence for crater ejecta on Venus tessera terrain from Earth-based radar images. *Icarus* **250**, 123–130 (2015). <https://doi.org/10.1016/j.icarus.2014.11.025>
- B.A. Campbell, L.M. Carter, L.S. Glaze, D.B. Campbell, Pyroclastic flow deposits on Venus as indicators of renewed magmatic activity. *J. Geophys. Res.* (2017). <https://doi.org/10.1002/2017JE005299>
- C.L. Carilli, S. Rawlings, Science with the Square Kilometer Array. *New Astron. Rev.* **48**(11–12), 979–1601 (2004)
- E. Chassefière et al., The Lavoisier mission: a system of descent probe and balloon flotilla for geochemical investigation of the deep atmosphere and surface of Venus. *Adv. Space Res.* **29**(2), 255–264 (2002). [https://doi.org/10.1016/S0273-1177\(01\)00576-2](https://doi.org/10.1016/S0273-1177(01)00576-2)
- E. Chassefière et al., European Venus Explorer (EVE): an in-situ mission to Venus. *Exp. Astron.* **23**(3), 741–760 (2009). <https://doi.org/10.1007/s10686-008-9093-x>
- G. Chin, Vesper—Venus chemistry and dynamics orbiter—a NASA Discovery mission proposal: submillimeter investigation of atmospheric chemistry and dynamics, AOGS201 (2011)
- J. Clavel, ESA's cosmic vision 2015–2025 program, in *Astronomical Data Analysis Software and Systems XVIII*, ed. by D. Bohlender, D. Durand, P. Dowler. ASP Conference Series, vol. 411 (2009), pp. 89–98
- M. Coradini, S. Limaye et al., *Venus Gravity Assist Science Opportunity: Report of the VeGASO Panel* (2015). <http://www.lpi.usra.edu/vexag/reports/VEGASO-04-24-15.pdf>
- L. Cottareau, N. Rambaux, S. Lebonnois, J. Souchay, The various contributions in Venus rotation rate and LOD. *Astron. Astrophys.* (2011). <https://doi.org/10.1051/0004-6361/201116606>
- V. Cottini, S. Aslam, E. D'Aversa, L. Glaze, N. Goriuss, T. Hewagama, N. Ignatiev, G. Piccioni, CUVE—Cubesat UV Experiment: unveil Venus' UV absorber with cubesat UV mapping spectrometer, in *European Planetary Science Congress 2017, Abstract #EPSC2017-771* (2017)

- D. Crisp, M.A. Allen, V.G. Anicich, R.E. Arvidson, S.K. Atreya, K.H. Baines, W.B. Banerdt, G.L. Bjoraker, S.W. Bougher, B.A. Campbell, R.W. Carlson, G. Chin, A. Chutjian, R.T. Clancy, B.C. Clark, T.E. Cravens, A.D. Del Genio, L.W. Esposito, B. Fegley, M. Flasar, J.L. Fox, P.J. Gierasch, R.M. Goody, D.H. Grinspoon, S. Gulikis, V.L. Hansen, R.R. Herrick, D.L. Huestis, D.M. Hunten, M.A. Janssen, J. Jenkins, C.L. Johnson, G.M. Keating, A.J. Kliore, S.S. Limaye, J.G. Luhmann, J.I. Lunine, P. Mahaffy, P.J. McGovern, V.S. Meadows, F.P. Mills, H.B. Niemann, T.C. Owen, K.I. Oyama, R.O. Pepin, J.J. Plaut, D.C. Reuter, M.I. Rixhardson, C.T. Russell, R.S. Saunders, J.T. Schofield, G. Schubert, D.A. Senske, M.K. Shepard, T.G. Slinger, S.E. Smrekar, D.J. Stevenson, D.V. Titov, E.A. Ustinov, R.E. Young, Y.L. Yung, Divergent evolution among Earth-like planets: the case for Venus exploration, in *The Future of Solar System Exploration, 2003–2013*. ASP Conference Series, vol. 272 (2002)
- D. Daou, Small Innovative Missions for Planetary Exploration (SIMPLEx), in *European Planetary Science Congress 2017, Abstract #EPSC2017-146* (2017)
- A. Davaille, S.E. Smrekar, S. Tomlinson, Experimental and observational evidence for plume-induced subduction on Venus. *Nat. Geosci.* **10**, 349–355 (2017). <https://doi.org/10.1038/ngeo2928>
- D.F. Doody, Aerobraking the Magellan spacecraft in Venus orbit. *Acta Astronaut.* **35**(94), 475–480 (1995). [https://doi.org/10.1016/0094-5765\(94\)00214-7](https://doi.org/10.1016/0094-5765(94)00214-7)
- T. Encrenaz, T.K. Greathouse, H. Roe, M. Richter, J. Lacy, B. Bézard, T. Fouchet, T. Widemann, HDO and SO₂ thermal mapping on Venus: evidence for strong SO₂ variability. *Astron. Astrophys.* **543**, A153 (2012). <https://doi.org/10.1051/0004-6361/201219419>
- T. Encrenaz, T.K. Greathouse, M.J. Richter, C. DeWitt, T. Widemann, B. Bézard, T. Fouchet, S.K. Atreya, H. Sagawa, HDO and SO₂ thermal mapping on Venus. III. Short-term and long-term variations between 2012 and 2016. *Astron. Astrophys.* (2016). <https://doi.org/10.1051/0004-6361/201628999>
- L.W. Esposito, Sulfur dioxide: episodic injection shows evidence for active Venus volcanism. *Science* **223**(4640), 1072–1074 (1984)
- L.W. Esposito, SAGE New Frontiers mission to Venus, in *42nd Lunar and Plan. Sci. Conf., Abstract #1519* (2011)
- L.W. Esposito, J.-L. Bertaux, V. Krasnopolsky, V.I. Moroz, L.V. Zasova, Chemistry of lower atmosphere and clouds, in *Venus II: Geology, Geophysics, Atmosphere, and Solar Wind Environment*, ed. by S.W. Bougher, D.M. Hunten, R.J. Phillips (1997), pp. 415–458
- L. Esposito, D. Atkinson, K. Baines, A. Allwood, F. Altieri, S. Atreya, M. Bullock, A. Colaprete, M. Darrach, J. Day, M. Dyar, B. Ehlmann, K. Farley, J. Filiberto, D. Grinspoon, J. Head, J. Helbert, S. Madzunkov, G. Piccioni, W. Pospel, M. Ravine, A. Treiman, Y. Yung, K. Zahnle, The New Frontiers Venus In Situ Atmospheric and Geochemical Explorer (VISAGE) mission proposal, in *European Planetary Science Congress 2017, Abstract #EPSC2017-275* (2017)
- B. Fegley, G. Klingelhofer, K. Lodders, T. Widemann, Geochemistry of surface-atmosphere interactions on Venus, in *Venus II*, ed. by S.W. Bougher, D.M. Hunten, R.J. Phillips (University of Arizona Press, Tucson, 1997)
- T. Fukuhara, M. Futaguchi, G.L. Hashimoto, T. Horinouchi, T. Imamura, N. Iwagaimi, T. Kouyama, S. Murakami, M. Nakamura, K. Ogohara, M. Sato, T. Sato, M. Suzuki, M. Taguchi, S. Takagi, M. Ueno, S. Watanabe, M. Yamada, A. Yamazaki, Large stationary gravity wave in the atmosphere of Venus. *Nat. Geosci.* (2017). <https://doi.org/10.1038/ngeo2873>
- Y. Futaana, G.S. Wieser, S. Barabash, J.G. Luhmann, Solar wind interaction and impact on the Venus atmosphere. *Space Sci. Rev.* **212**(3–4), 1453–1509 (2017, this issue). <https://doi.org/10.1007/s11214-017-0362-8>
- J.-C. Gerard, S.W. Bougher, M.A. Lopez-Valverde, M. Pätzold, P. Drossart, G. Piccioni, Aeronomy of the Venus upper atmosphere. *Space Sci. Rev.* **212**(3–4), 1617–1683 (2017, this issue). <https://doi.org/10.1007/s11214-017-0422-0>
- R.C. Ghail, C. Wilson, M. Galand, D. Hall, C. Cochrane, P. Mason, J. Helbert, F. MontMessin, S. Limaye, M. Patel, N. Bowles, D. Stam, J.-E. Wahlund, F. Rocca, D. Waltham, T. Mather, J. Biggs, M. Genge, P. Paillou, K. Mitchell, L. Wilson, U. Singh, EnVision: taking the pulse of our twin planet. ESA M5 proposal document. *Exp. Astron.* **33**(2), 337–363 (2012)
- R.C. Ghail et al., VenSAR on EnVision: taking Earth observation radar to Venus. *International Journal of Applied Earth Observation and Geoinformation* (2017). <https://doi.org/10.1016/j.jag.2017.02.008>
- M.S. Gilmore, L.S. Glaze, C.L. Baker, G.J. Tahu, M. Adams, G. Karpati, M.J. Amato, *Venus Intrepid Tesseria Lander: Mission Concept Study Report to the NRC Decadal Survey Inner Planets Panel* (2010). http://www.lpi.usra.edu/vexag/reports/VITaL_FINAL_040809.pdf
- M.S. Gilmore, A. Treiman, J. Helbert, S. Smrekar, Venus surface composition constrained by observation and experiment. *Space Sci. Rev.* **212**(3–4), 1511–1540 (2017, this issue). <https://doi.org/10.1007/s11214-017-0370-8>
- L.S. Glaze et al. (DAVINCI the DAVINCI Science Team), Deep atmosphere investigation of noble gases, chemistry, and imaging, in *47th Lunar and Plan. Sci. Conf., Abstract #1560* (2016)

- L.S. Glaze, M.L. Adams, M.J. Amato, C.L. Baker, G. Karpati, *Venus Mobile Explorer: Mission Concept Study Report to the NRC Decadal Survey Inner Planets Panel* (2009). http://www.lpi.usra.edu/vexag/reports/VME_FINAL_ITAR_Compliant.pdf
- L.S. Glaze, J. Garvin, N. Johnson, G. Arney, D. Atkinson, S. Atreya, A. Beck, B. Bezaud, J. Blakesberg, B. Campbell, S. Clegg, D. Crisp, D. Dyar, F. Forget, M. Gilmore, D. Grinspoon, J. Gross, S. Guzewich, N. Izenberg, J. Johnson, W. Kiefer, D. Lawrence, S. Lebonnois, R. Lorenz, P. Mahaffy, S. Maurice, M. McCanta, A. Parsons, A. Pavlov, S. Sharma, M. Trainer, C. Webster, R. Wiens, K. Zahnle, M. Zolotov, in *VICI: Venus In Situ Composition Investigations, European Planetary Science Congress 2017, Abstract #EPSC2017-346* (2017)
- K.S. Griffin, J. Carpenter, G.L. Lee, R. Polidan, D. Sokol, B. Wainfan, W. James, D. Poulos, Lifting entry/atmospheric flight (leaf) unified platform for ultra-low ballistic coefficient atmospheric entry and maneuverable atmospheric flight at solar system bodies. US Patent Application #US 14/297,370 (2015)
- D. Grinspoon, A. Pavlov, M. Adams, Venus Climate Mission (VCM) (2010). http://www.lpi.usra.edu/vexag/reports/VCM_report_FINAL.pdf
- J.P. Grotzinger, J.A. Crisp, A.R. Vasavada, Curiosity's mission of exploration at Gale crater, Mars. *Elements* **11**(1), 19–26 (2015). <https://doi.org/10.2113/gselements.11.1.19>
- J.L. Hall, D. Fairbrother, T. Frederickson, V.V. Kerzhanovich, M. Said, C. Sandy, J. Ware, C. Willey, A.H. Yavrouian, Prototype design and testing of a Venus long duration, high altitude balloon. *Adv. Space Res.* **42**, 1648–1655 (2008)
- J. Helbert, D. Wendler, I. Walter, T. Widemann, E. Marcq, G. Guignau, S. Ferrari, A. Maturilli, N. Mueller, D. Kappel, J. Jaenchen, M. D'Amore, A. Boerner, D. Dyar, G.E. Arnold, S. Smrekar, The Venus Emissivity Mapper (VEM) concept, in *Proc. SPIE 9973, Infrared Remote Sensing and Instrumentation XXIV, 9973OR* (2017). <https://doi.org/10.1117/12.2237568>
- S. Husseyin, Design considerations for a stopped-rotor cyclocopter for Venus exploration. NASA Technical Report, 20160012563 (2016)
- M.A. Ivanov, J.W. Head, Tessera terrain on Venus: a survey of the global distribution, characteristics, and relation to surrounding units from Magellan data. *J. Geophys. Res.* **101**, 14861–14908 (1996)
- O. Karatekin, I. Holin, Venus rotation, observations & predictions, in *International Venus Science Conference*, Oxford (2016)
- A. Komjathy, A. Didion, B. Sutin, B. Nakazono, A. Karp, M. Wallace, G. Lantonie, S. Krishnamoorthy, M. Rud, J. Cutts, J. Makela, M. Grawe, P. Lognonne, B. Kenda, M. Drilleau, J. Helbert, Remote sensing of seismic activity on Venus using a small spacecraft: initial modeling, in *49th Lunar and Planetary Science Conference, Abstract #1731* (2018)
- V.A. Krasnopolsky, A photochemical model for the Venus atmosphere at 47–112 km. *Icarus* **218**(1), 230–246 (2012). <https://doi.org/10.1016/j.icarus.2011.11.012>
- T. Kremic et al., *Venus Science Priorities for Laboratory Measurements and Instrument Definition Workshop Report* (2015)
- T. Kremic, D. Senske, L. Zasova, A. Ocampo, T. Economou, N. Eismont, L. Esposito, M. Gerasimov, N. Ignatiev, M. Ivanov, K. Lea Jessup, I. Khatuntsev, O. Korablev, S. Limaye, A. Martynov, A. Burdanov, Venera-D: technology implication, in *The Seventh Moscow Solar System Symposium, Paper #7MS3-VN-10* (2016), pp. 93–95
- T. Kremic, R. Ghail, M. Gilmore, W. Kiefer, S. Limaye, G. Hunter, C. Tolbert, M. Pauken, C. Wilson, SAEVe: a concept study for a long duration small sat class Venus lander, in *49th Lunar and Planetary Science Conference, Abstract #2744* (2018)
- R. Kremnev et al., VEGA balloon system and instrumentation. *Science* **231**(4744), 1408–1411 (1986)
- G.A. Landis, Robotic exploration of the surface and atmosphere of Venus. *Acta Astronaut.* **59**(7), 570–579 (2006). <https://doi.org/10.1016/j.actaastro.2006.04.011>
- G.A. Landis, K.C. Mellott, Venus surface power and cooling systems. *Acta Astronaut.* **61**(11–12), 995–1001 (2007). <https://doi.org/10.1016/j.actaastro.2006.12.031>
- S. Lebonnois, V. Eymet, C. Lee, J. Vatant d'Ollone, Analysis of the radiative budget of the Venusian atmosphere based on infrared Net Exchange Rate formalism. *J. Geophys. Res.* **120**, 1186–1200 (2015). <https://doi.org/10.1002/2015JE004794>
- S. Lebonnois, N. Sugimoto, G. Gilli, Wave analysis in the atmosphere of Venus below 100-km altitude, simulated by the LMD Venus GCM. *Icarus* **278**, 38–51 (2016). <https://doi.org/10.1016/j.icarus.2016.06.004>
- C. Lee, M.I. Richardson, A discrete ordinate, multiple scattering, radiative transfer model of the Venus atmosphere from 0.1 to 260 μm . *J. Atmos. Sci.* **68**(6), 1323–1339 (2011). <https://doi.org/10.1175/2011JAS3703.1>
- G. Lee, R. Polidan, F. Ross, D. Sokol, S. Warwick, Lifting Entry & Atmospheric Flight (LEAF) system concept applications at solar system bodies with an atmosphere, in *47th DPS Meeting* (2015), p. 310.13
- G. Lee, S. Limay, R. Polidan, J. Arenberg, Venus Atmospheric Maneuverable Platform (VAMP)—air vehicle platform and entry CONOPS, in *The Seventh Moscow Solar System Symposium, Paper #7MS3-VN-11* (2016), p. 96

- S.S. Limaye, D. Grassi, A. Mahieux, A. Migliorini, S. Tellmann, D. Titov, Venus atmospheric thermal structure and radiative balance. *Space Sci. Rev.* (2017, this issue). <https://doi.org/10.1007/s11214-018-0525-2>
- R.D. Lorenz, M. Panning, Empirical recurrence rates for seismic signals on planetary surface. *Icarus* **303**, 273–279 (2018). <https://doi.org/10.1016/j.icarus.2017.10.008>
- D.T. Lyons, R.S. Saunders, D.G. Griffith, The Magellan Venus mapping mission: aerobraking operations. *Acta Astronaut.* **35**(9–11), 669–676 (1995)
- D.G. Lyons, J.G. Beerer, P. Esposito, M.D. Johnston, W.H. Willcockson, Mars global surveyor: aerobraking mission overview. *J. Spacecr. Rockets* **36**(3), 307–313 (1999). <https://doi.org/10.2514/2.3472>
- E. Marcq, J.-L. Bertaux, F. Montmessin, D. Belyaev, Variations of sulphur dioxide at the cloud top of Venus's dynamic atmosphere. *Nat. Geosci.* **6**(1), 25–28 (2012). <https://doi.org/10.1038/ngeo1650>
- E. Marcq, F.P. Mills, C.D. Parkinson, A.C. Vandaele, Composition and chemistry of the neutral atmosphere of Venus. *Space Sci. Rev.* **214**(1), 1–55 (2018, this issue). <https://doi.org/10.1007/s11214-017-0438-5>
- K. McGouldrick, O.B. Toon, An investigation of possible causes of the holes in the condensational Venus cloud using a microphysical cloud model with a radiative-dynamical feedback. *Icarus* **191**, 1–24 (2007). <https://doi.org/10.1016/j.icarus.2007.04.007>
- O. Mousis, R. Hueso, J.-P. Beaulieu, S. Bouley, B. Carry, F. Colas, A. Klotz, C. Pellier, J.-M. Petit, P. Rousselot, M. Ali-Dib, W. Beisker, M. Birlan, C. Buil, A. Delsanti et al., Instrumental methods for professional and amateur collaborations in planetary astronomy. *Exp. Astron.* (2014). <https://doi.org/10.1007/s10686-014-9379-0>
- M. Nakamura et al., Planet-C: Venus climate orbiter mission of Japan. *Planet. Space Sci.* **55**(12), 1831–1842 (2007). <https://doi.org/10.1016/j.pss.2007.01.009>
- M. Nakamura et al., Return of the Japanese Venus climate orbiter AKATSUKI. *Acta Astronaut.* **93**, 384–389 (2014). <https://doi.org/10.1016/j.actaastro.2013.07.027>
- M. Nakamura et al., AKATSUKI returns to Venus. *Earth Planets Space* **68**(1), 75 (2016). <https://doi.org/10.1186/s40623-016-0457-6>
- T. Navarro, G. Schubert, S. Lebonnois, Atmospheric mountain wave generation on Venus and its influence on the solid planet's rotation rate. *Nat. Geosci.* (2018). <https://doi.org/10.1038/s41561-018-0157-x>
- V.I. Oyama, G.C. Carle, F. Woeller, J. Pollock, Venus lower atmospheric composition. *Science* **203**, 802–805 (1979)
- R. Polidan, G. Lee, F. Ross, D. Sokol, L. Bolisay, Venus atmospheric maneuverable platform science mission, in *47th DPS Meeting* (2015), p. 217.03
- G.E. Ponchak, M.C. Scardelletti, B. Taylor, S. Beard, R.D. Meredith, G.M. Beheim, G.W. Hunter, W.S. Kiefer, High temperature, wireless seismometer sensor for Venus, in *RWW 2012—Proc. 2012 IEEE Top. Conf. Wirel. Sensors Sens. Networks, WiSNet 2012* (2012), pp. 9–12. <https://doi.org/10.1109/WiSNet.2012.6172141>
- R.Z. Sagdeev et al., Overview of VEGA Venus balloon in situ meteorological measurements. *Science* **231**(4744), 1411–1414 (1986)
- A. Sanchez-Lavega, A. Wesley, G. Orton, R. Hueso, S. Perez-Hoyos, L.N. Fletcher, P. Yanamandra-Fisher, J. Legarreta, I. de Pater, H. Hammel, A. Simon-Miller, J.M. Gomez-Forrellad, J.L. Ortiz, E. Garcia-Melendo, R.C. Puetter, P. Chodas, The impact of a large object with Jupiter in July 2009. *Astrophys. J. Lett.* **715**, L155–L159 (2010). <https://doi.org/10.1088/2041-8205/715/2/L155>
- A. Sanchez-Lavega, S. Lebonnois, T. Imamura, P. Read, D. Luz, The atmospheric dynamics of Venus. *Space Sci. Rev.* **212**(3–4), 1541–1616 (2017, this issue). <https://doi.org/10.1007/s11214-017-0389-x>
- B. Sander, R.T. Clancy, First measurements of ClO in the Venus atmosphere—altitude dependence and temporal variation. *Icarus* (2018). <https://doi.org/10.1016/j.icarus.2018.04.022>
- D. Senske, T. Kremic, L. Zasova, A. Ocampo, T. Economou, N. Eismont, L. Esposito, M. Gerasimov, N. Ignatiev, M. Ivanov, K. Lea Jessup, I. Khatuntsev, O. Korablev, S. Limaye, A. Martynov, A. Burdanov, The Venera-D mission concept: evaluation by a joint science definition team of a means for the comprehensive scientific exploration of Venus, in *Fall Meeting of the American Geophysical Union, Paper #P41B-2069* (2016)
- D. Senske, T. Kremic, L. Zasova, A. Ocampo, T. Economou, N. Eismont, L. Esposito, M. Gerasimov, N. Ignatiev, M. Ivanov, K. Lea Jessup, I. Khatuntsev, O. Korablev, S. Limaye, A. Martynov, A. Burdanov, The Venera-D concept, scientific exploration of Venus in the post-2025 timeframe, in *Planetary Science Vision 2050 Workshop, Abstract #8027* (2017a)
- D. Senske, T. Kremic, L. Zasova, A. Ocampo, T. Economou, N. Eismont, L. Esposito, M. Gerasimov, N. Ignatiev, M. Ivanov, K. Lea Jessup, I. Khatuntsev, O. Korablev, S. Limaye, A. Martynov, A. Burdanov, Venera-D: expanding our horizon of terrestrial planet climate and geology through the comprehensive exploration of Venus. Report of the Venera-D Joint Science Definition Team (2017b). <http://www.lpi.usra.edu/vexag/meetings/meetings-of-interest/Venera-D-Report.pdf>

- J.C.J. Smith, J.L. Bell, 2001 Mars Odyssey aerobraking. *J. Spacecr. Rockets* **42**(3), 406–415 (2005). <https://doi.org/10.1007/978-0-306-48600-5>
- S.E. Smrekar, C. Sotin, Constraints on mantle plumes on Venus: implications for volatile history. *Icarus* **217**(2), 510–523 (2012). <https://doi.org/10.1016/j.icarus.2011.09.011>
- S.E. Smrekar, S. Hensley, M.D. Dyar, J. Helbert (the VERITAS Science Team), VERITAS (Venus Emissivity, Radio science, InSAR, Topography And Spectroscopy): a proposed Discovery mission, in *47th Lunar and Plan. Sci. Conf., Abstract #2439* (2016)
- S. Smrekar, S. Hensley, M. Wallace, M. Lisano, M. Darrach, C. Sotin, D. Lehman, M.D. Dyar, J. Helbert, Venus Origins Explorer (VOX) concept: a proposed New Frontiers mission, in *2018 IEEE Aero. Conf.* (2018). <https://doi.org/10.1109/AERO.2018.8396625>
- C. Sotin, A. Davaille, A. Lenardic, S. Smrekar, Venus interior structure and dynamics. *Space Sci. Rev.* (2017, this issue). <https://doi.org/10.1007/s11214-018-0518-1>
- C. Sotin, G. Avice, J. Baker, A. Freeman, S. Madzunkov, T. Stevenson, N. Arora, M. Darrach, G. Lightsey, B. Marty, Cupid's Arrow: a small satellite concept to measure noble gases in Venus' atmosphere, in *49th Lunar and Planetary Science Conference, Abstract #1763* (2018)
- D.A. Spencer, R. Tolson, Aerobraking cost and risk decisions. *J. Spacecr. Rockets* **44**(6), 1285–1293 (2007). <https://doi.org/10.2514/1.24303>
- S. Squyres, *Vision and Voyages for Planetary Science in the Decade 2013–2022* (National Academy of Sciences, Washington, DC, 2011). <https://www.nap.edu/catalog/13117/vision-and-voyages-for-planetary-science-in-the-decade-2013-2022>
- D. Stevenson, J.A. Cutts, D. Mimoun, Probing the interior structure of Venus. Keck Institute for Space Studies Report (2015). http://authors.library.caltech.edu/59019/1/2015_KISS_Venus_Final_Report.pdf
- H. Svedhem, First results from Venus Express aerobraking campaign, in *COSPAR Scientific Assembly* (2014)
- T. Tavenner, E.F. Young, M.A. Bullock, J. Murphy, S. Coyote, Global mean cloud coverage on Venus in the near-infrared. *Planet. Space Sci.* **56**(10), 1435–1443 (2008). <https://doi.org/10.1016/j.pss.2008.06.013>
- F.W. Taylor, H. Svedhem, J.W. Head III, Venus: the atmosphere, climate, surface, interior and near-space environment of an Earth-like planet. *Space Sci. Rev.* **214**(1), 1–36 (2017, this issue). <https://doi.org/10.1007/s11214-018-0467-8>
- D. Titov, N. Ignatiev, K. McGouldrick, V. Wilquet, C. Wilson, Clouds and hazes. *Space Sci. Rev.* (2018, this issue)
- VEXAG, Roadman for Venus exploration (2014a). <http://www.lpi.usra.edu/vexag/reports/Roadmap-140617.pdf>
- VEXAG, Venus technology plan (2014b). <http://www.lpi.usra.edu/vexag/reports/Venus-Technology-Plan-140617.pdf>
- VEXAG, Goals, objectives, and investigations for Venus exploration (2016). <http://www.lpi.usra.edu/vexag/reports/GOI-Space-Physics-Update-0816.pdf>
- C. Wilson, N. Wells, Balloon-deployed probes for Venus, in *5th Int. Plan. Probe. Wkshp.*, Bordeaux, 23–29 June (2007)
- C.F. Wilson, E. Chassefière, E. Hinglais, K.H. Baines, T.S. Balint, J.-J. Berthelier, J. Blamont, G. Durré, C.S. Ferencz, R.E. Grimm, T. Imamura, J.-L. Josset, F. Leblanc, S. Lebonnois, J.J. Leitner, S.S. Limaye, B. Marty, E. Palomba, S.V. Pogrebenko, S.C.R. Rafkin, D.L. Talboys, R. Wieler, L.V. Zasova, C. Szopa (the EVE team), The 2010 European Venus Explorer (EVE) mission proposal. *Exp. Astron.* **33**, 305–335 (2012). <https://doi.org/10.1007/s10686-011-9259-9>
- C. Wilson, K. Baines, E. Chassefière, R. Ghail, J. Helbert (the EVE and Envision Science Teams), Venus: key to understanding the evolution of terrestrial planets. White Paper in Response to ESA's Call for Definition of Science Themes for L2/L3 Missions (2013). <https://arxiv.org/ftp/arxiv/papers/1703/1703.10961.pdf>
- C. Wilson, C.-M. Zetterling, W.T. Pike, Venus long-life surface package. ESA White Paper (2016). [arXiv:1611.03365v1](https://arxiv.org/abs/1611.03365v1)
- E. Young et al., A balloon-borne stratospheric telescope for Venus observations. *Proc. SPIE* (2008). <https://doi.org/10.1117/12.790032>
- L. Zasova, V. Moroz, L. Esposito, C. Na, SO₂ in the middle atmosphere of Venus: IR measurements from Venera-15 and comparisons to UV data. *Icarus* (1993). <https://doi.org/10.1006/icar.1993.1113>
- L. Zasova, N.I. Ignatiev, M.V. Gerasimov, Future Venus exploration: mission Venera-D, in *45th Lunar and Planetary Science Conference, Abstract #6037* (2014)
- X. Zhang, M.C. Liang, F.P. Mills, D.A. Belyaev, Y.L. Yung, Sulfur chemistry in the middle atmosphere of Venus. *Icarus* **217**(2), 714–739 (2012). <https://doi.org/10.1016/j.icarus.2011.06.016>