Perspectives of Infrared and Ultraviolet Spectroscopy in the Exploration of the Venusian Atmosphere and Surface against the Background of Future Missions - An Overview and Outlook

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ABSTRACT

A new era in the study of Earth-like planets in exosolar systems has provided a fundamental and new impetus for understanding the evolution of planetary systems, placing traditional comparative planetology focused on our own system in a much broader context and a wide range of possible variability. Against this background, the study of our sister planet Venus in comparison to Earth is becoming increasingly important. Venus provides a laboratory for comparative planetology, with important insights into the sensitive effects of stellar environmental conditions on the evolution of habitable planets. A number of space missions to Venus, planned and under development, reflect this approach to comparative planetology in the Solar System and its application to understanding global stellar planetary systems. This article evaluates and classifies the planned Venus investigations using infrared and ultraviolet spectroscopy in terms of their ability to answer these questions. The article is based on known data from missions such as Venera 15/PMV (RU), VIRTIS, SPICAV and SPICAV-SOIR/VEX (ESA), and MERTIS (ESA), as well as many others in which the authors have been involved. We report on the key questions concerning the evolution of Venus, and the contribution of infrared and ultraviolet spectroscopy, and reflect on them in the light of planned space missions.

Keywords: Planetary remote sensing; Venus surface and atmosphere; UV, VIS, IR spectroscopy; comparative planetology

1. INTRODUCTION

Space-based spectral investigations from the UV to the IR have yielded groundbreaking results on the composition, state, dynamics, and evolution of the atmosphere of our sister planet Venus.[1-13] The discovery and exploitation of the nightside atmospheric windows in the NIR has also opened the possibility of globally observing large-scale compositional surface variations, which can be directly related to the results of topological and geological investigations.[4-7; 14, 15] There are two main reasons for the current upsurge in Venus exploration. First, new approaches to the climatological evolution of Earth in comparison to Venus in our Solar System encourage comparative studies.[6, 17] On the other hand, observations of exosolar planets point to global mechanisms of the formation of Earth-like planets, whose development is also determined by their stellar environments.[16] This paper focuses on the discussion of future planned space-based UV to IR projects/instruments that can shed new light on Venus and its evolution.

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2. VENUS IN THE LIGHT OF PREVIOUS SPACE-BASED INVESTIGATIONS FROM THE UV TO THE IR RANGE

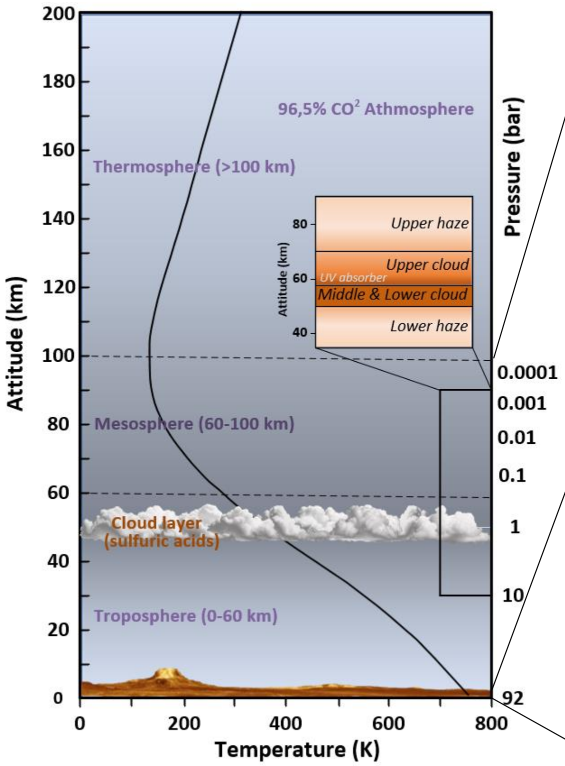
Atmospheric sounding

Earth and Venus followed different evolutionary paths that led to the dry, hot greenhouse driven Venusian climate and dense, super-rotating, CO_2-dominated atmosphere we find today. Space-based spectral measurements of the planet from orbit have provided key information about the composition of Venus' atmosphere, its dynamics, energy balance and the temperature and pressure profiles in different atmospheric layers. Such studies have been conducted in both nadir and occultation geometry.

The **VIRTIS** (Visible and InfraRed Thermal Imaging Spectrometer) aboard ESA's Venus Express (VEX) mission covered the investigation of temperature fields in the altitude range 60 to 95 km (nightside), studies of cloud structure, composition, and scattering properties (day- and nightside), studies of the polar vortex, determination of lower atmospheric composition below the clouds (nightside), determination of mesospheric composition (dayside), investigation of nightglows and other non-local thermodynamic equilibrium emissions (NLTE), surface temperature and emissivity studies. The VIRTIS mapping channel VIRTIS-M-IR was the first to provide continuous nightside measurements of Venus from orbit in the atmospheric NIR windows over a long period of time.[4-7, 14] In 1983, the **PMV** (Profile Measuring instrument for Venus) Fourier spectrometer aboard the Soviet Venera-15 mission, obtained radiation spectra of Venus in the range 6-36 µm covering the 55-90 km altitude range. In addition to CO_2, H_2O and SO_2 were detected and the H_2SO_4 aerosols of the cloud layers were investigated. The mid-infrared spectral data enabled the derivation of temperature profiles of the middle atmosphere with the help of radiative transfer simulations and retrieval algorithms.[1-3, 7, 14] The **MERTIS** (MErcury Radiometer and Thermal Infrared Spectrometer) instrument aboard ESA's BepiColombo mission was investigating the mesosphere of Venus in the 7-14 µm spectral range during two flybys at Venus in 2020 and 2021, respectively. From these measurement results atmospheric temperature profiles and cloud parameters of the upper troposphere and mesosphere (60-75 km) could be derived.[10-12] The SOIR (Solar Occultation in the Infra-Red) and SPICAV (SPectroscopy for Investigation of Characteristics of the Atmosphere of Venus)[8] instruments aboard VEx enabled the retrieval of vertical profiles of minor species, temperature, sulfuric acid upper haze, and discovered a sporadic ozone layer.[49] SPICAV was also used in nadir mode, where it measured water vapor in the lowermost atmosphere in the near IR[50, 51] and SO_2 variations at cloud top level in the UV range[52, 53]. Finally, the **VeRa** (Venus Express Radio Science) experiment completes the overall picture of vertical profiles of temperature, pressure and total neutral number density between 40 km and 100 km altitude.[9, 21] These more recent data, like those of their predecessor missions and ground-based data, are continuously incorporated into the Venus International Reference Atmosphere (**VIRA**) model, which contains tabulated values of temperature and number densities obtained during various investigations.[18, 19] The work by Limaye et al. provides an insight into the state of knowledge about the thermal structure of the Venusian atmosphere in the post-VEX period.[20] Finally, JAXA's Akatsuki spacecraft was able to record valuable data of Venus' atmosphere with a camera complex from a highly elliptical orbit around Venus from December 2015 to May 2024.[13] The four cameras on **Akatsuki** studied the dynamic evolution of cloud structures and the top level of the cloud layer on the day side as well as at lower altitudes on the night side.[26] The UV imager took UV images at 283 nm being sensitive to SO_2, and at 365 nm to study the unknown UV absorber.[27] Thus, the Akatsuki data comprehensively complement the recent space-based UV to IR observations of Venus.

Outstanding questions

Despite the remarkable success of the recent missions discussed above in understanding the atmosphere of Venus, it still left a number of questions unanswered (see Fig. 1). The thermal neutral escape in the thermosphere cannot yet be quantified. Better profiling and mapping of minor gases in the mesosphere such as H_2O, SO_2 and others, including their temporal dynamics, are needed to better understand the processes around their sources and sinks. A still unanswered question remains the origin and distribution of the unknown UV absorber, responsible for the absorption band detected at the near-UV and blue range of spectra in Venus' upper clouds.[23] The fine structure of the cloud layering and the formation of sulfuric acid above the cloud tops, where there is a supply of atomic oxygen resulting from dissociation of water and CO_2 by UV radiation and its combination with SO_2 is not finally understood.[22] Regarding Venus' atmospheric composition and chemistry apart from CO_2 (96.5%) and nitrogen (3%) noble gases, CO, small amount of water vapor, SO_2 and traces of hydrogen halides were detected. Halogens such as HCl and HF are obviously associated with volcanic eruptions but then buffered by reactions with the surface minerals. Noble gases, which are most likely also of volcanic origin may provide a record of these activities. [22] Of particular importance are the gaseous species in the Venusian atmosphere below the clouds (troposphere). VIRTIS/VEX was able to measure some of them. They include H_2O, HDO, HCl, CO, COS and SO_2, whereby so far only vertical profiles of the H_2O could be determined.[6, 7, 14] A more detailed study of these tropospheric gases and their spatial and temporal dynamics is crucial for gaining an understanding of the detailed processes of their formation. Finally, the processes of the general atmospheric circulation, consisting of the zonal superrotation, the Hadley circulation, and the polar vortices, are driven not only by the energy input from the Sun, but also by the physicochemical processes in the entire atmosphere that determine its energy balance. These questions are inseparable from those on the geological sources of volatiles in the Venusian atmosphere and the geochemical processes on its surface.



Key open questions	
Altitude depending (detailed)	***General***
Atmosphere (mesosphere, troposphere): Mesosphere: profiling, mapping and dynamics of minor gases (CO, SO_2, H_2O and others) Identifying unknown UV absorber Clouds: H_2SO_4 formation, aerosol fine structure and dynamics SO_2-SO relation and corresponding reactions Troposphere: Monitoring and dynamics of H_2O, HDO, HCl, CO, COS and SO_2 Study of vertical H_2O profiles	***Atmosphere*:** • Hydrogen escape (thermosphere) • Noble gases • Halogens and hydrogen halides • Trace gases: abundance and variability (troposphere and mesosphere) • Thermo-photo-chemical processes (troposphere, mesosphere) • Temperature and pressure profile fine tuning • Energy balance
Surface: • Relate global geology, geomorphology to surface composition (at moderate spatial scales due to the atmospheric scattering) • Surface-atmosphere exchange processes • Search for sinks and sources of atmospheric gases • Surface buffers ($CaCO_3$ to $CaSO_4$ or FeS_2 to Fe_3O_4 reactions)? (temperature dependence) • Global weathering processes depending on altitude, pressure, temperature and their mineralogical sighs • Finding felsic composition areas to insight into the Fortunian and pre-Fortunian (studding the "early Venus")	***Surface:*** • Global surface mineralogy and temperature variation: context with geologic and morphologic structures • Episodical vs. continuous volcanic resurfacing (?) • Composition of Fortunian (tesserae) and information about pre-Fortunian (?) surface areas

Figure 1. Key questions investigating Venusian atmosphere and surface Left: Diagram of the temperature, altitude, pressure and structure of the Venus atmosphere with simplified day side temperature profile (copyright: gabriele.arnold@dlr.de). Right: Table of outstanding questions.

Surface studies

The dense atmosphere of Venus prevents direct observations of the surface on the day side of the planet in the visual region of the electromagnetic spectrum. Our knowledge of the **topology, geomorphology, and geology** of Venus is based primarily on radar data from the Magellan mission and the few descent or lander probes in the past. NASA's Magellan orbiter, launched in 1989, obtained global radar maps with a spatial resolution of 120–280 m, and altimetry information.[22] Using the planetary stratigraphic classification approach to geological mapping, Ivanov and Head identified distinctive units and a series of structures and related features, compared local and regional stratigraphic columns, and compiled a global stratigraphic column, defining rock-stratigraphic units, time-stratigraphic units, and geological time units.[25] The surface of Venus is characterized by shield volcanoes. The presence of hundreds of flow channels, some thousands of kilometers long and tens of kilometers wide, and large, viscous, pancake-like domes indicate a complex magma composition. Coronae were found to be globally distributed. Wide linear rift zones over thousands of kilometers connect broad topographic elevations, capped by corresponding volcanoes.[25] Only 10% of the surface is dominated by highlands, 20% by lowlands, and about 70% by depositional plains and rolling hills. Unlike Earth, the Magellan data show little evidence of plate tectonics. Venus appears to be a single lithospheric plate that loses heat by conduction and advection.

Only a few young impact craters have been discovered, indicating that most of the current surface of Venus was formed within the last several hundred million years. Tesserae are the oldest formations discovered. Ivanov and Head[25] place these structures in the Fortunian epoch, which means that they are probably no older than 1 billion years. Competing theories attempt to explain the relatively recent resurfacing of the Venusian surface. These include vertical crustal accretion with catastrophic mantle uplift and episodic plate tectonics versus mantle convection and a transition from a mobile lid to a stagnant lid regime. Alternatively, continuous resurfacing is discussed.[25]

In contrast to the topology, geomorphology and geology of the surface of Venus, little is known about the **composition** of the surface structures. This is mainly due to the fact that the radar signal is not very sensitive for mineralogical characterization. Most of our knowledge comes from a few regional *in-situ* investigations with the Venera and Vega landers[28] and from analyses of the emissivity of the Venusian surface in the night-side atmospheric window of Venus at 1.02 µm recorded by VIRTIS on VEX.[7, 14, 15] The *in-situ* data suggest a basaltic-tholeiitic composition. The Venus Express investigations provided evidence for recent volcanism based on local high emissivity values.[15]

Outstanding questions

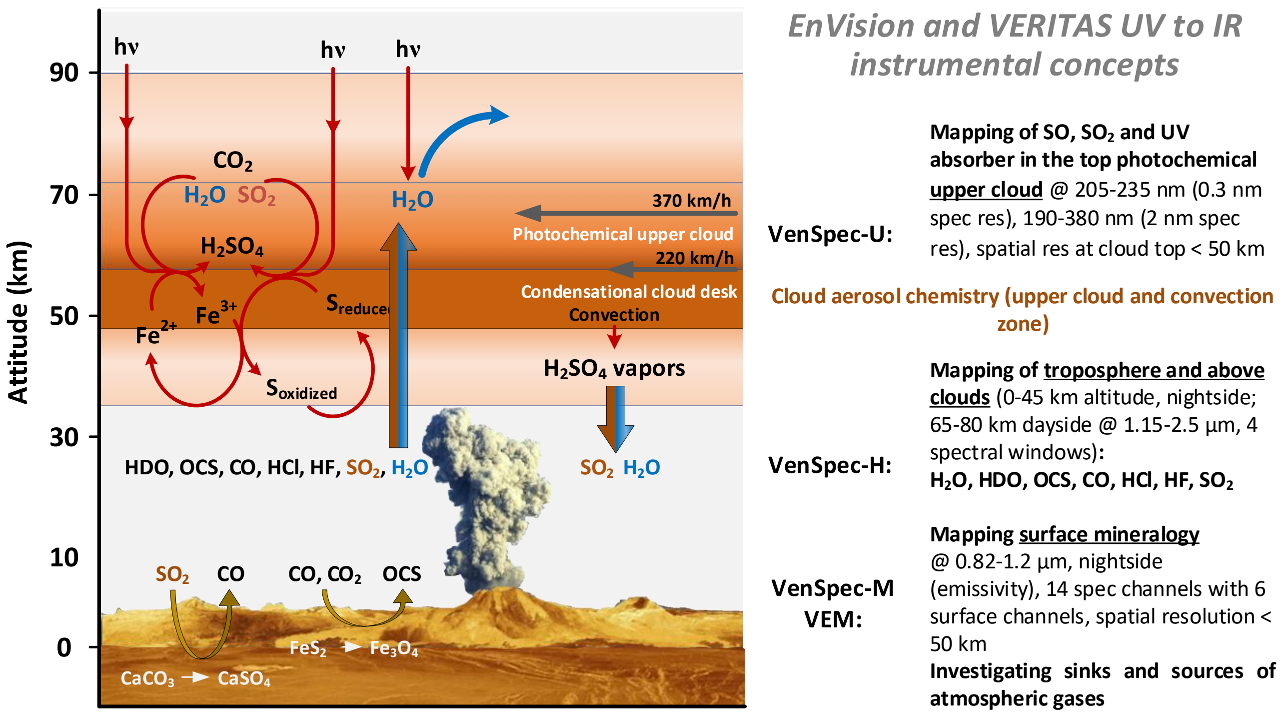
The study of the global surface mineralogy is one of the central open questions in the exploration of Venus (see Fig. 1). On the one hand, the global comparison of geological structures and their mineralogical composition provides important insights into the formation of individual structures and the surface as a whole. Possible evidence for felsic deposits in the older areas can provide a deeper insight into the history of ancient Venus and extend the time horizon of our knowledge into pre-Fortunian times. On the other hand, the surface mineralogy of Venus is an important feature for identifying sources and sinks of atmospheric gases, studying outgassing and possible volcanism, and better understanding cloud chemistry. In particular, the sulfur cycle and water vapor release are not independent of buffer reactions on the Venusian surface. The high pressure and temperature at the surface of Venus and the presence of a number of reactive species in the atmosphere (e.g. sulfur dioxide) and in the rocks lead to some possibilities for gas-solid phase reactions. The sulfur in the lower atmosphere of Venus reacts with the presumably common minerals on the surface, especially calcite. This would require the gas to be emitted by volcanoes at a rate slightly above the estimated average sulfur dioxide emission rate of volcanoes on Earth to provide enough SO_2. However, if the surface is low in calcite and instead has a high proportion of pyrite (FeS_2), for example, the observed amounts of SO_2 could actually be in equilibrium with the surface without any volcanism. Knowledge of the global distribution of rocks and minerals on the surface of Venus is therefore fundamental to understanding the history of the planet and the structure and chemistry of its atmosphere. It is also a link to processes in the interior of the planet, which are not discussed in this paper.

3. UPCOMING SPACE-BASED UV-TO-IR EXPERIMENTS TO STUDY VENUS' ATMOSPHERE AND SURFACE

The importance of understanding the evolution of Venus compared to the terrestrial planets of our solar system and possible exoplanets has led to the selection and preparation of important space missions to our neighbouring planet. A fleet of spacecraft will study Venus in the coming decades and help to answer some of the unanswered questions. The EnVision (ESA, launch 2031)[29], VERITAS (Venus Emissivity, Radio science, InSAR, Topography, and Spectroscopy, NASA, launch 2031)[30], and DAVINCI (Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging, NASA, launch 2031/32)[31] missions are expected to significantly advance our understanding of Venus. The following considerations will be limited to the remote sensing spectral investigation of Venus from UV to IR with the help of the missions mentioned and will not focus on aspects of the analyses of other payload instruments of these missions.

EnVision, is an orbital mission and was selected as the fifth medium mission (M5) of ESA's Cosmic Vision program. It will house a suite of three spectrometers (VenSpec)[32] including VenSpec-H, a spectral high spectral resolution IR spectrometer for the 1.0 to 2.5 µm range, VenSpec-U, a dual UV spectral imager, and VenSpec-M, an NIR surface emissivity mapper covering the main nightside atmospheric windows of Venus. The core element of VenSpec-M is the Venus Emissivity Mapper (VEM), which will be part of the VERITAS orbital mission in the same design.

The VenSpec[34, 35, 36] suite on EnVision will synchronously and continuously study and monitor the troposphere, parts of the mesosphere, and the surface of Venus from orbit, providing better access to the complex processes of surface-atmosphere interaction, surface composition, and atmospheric chemistry. VEM on VERITAS and VenSpec-M on EnVision, in conjunction with the advanced radar systems on both missions, will be able to provide global references for higher spatial resolution surface mapping and material-mineralogical mapping. Fig. 2 shows the comprehensive approach of the VenSpec studies for this purpose.



Fig, 2. Left: Scheme of Venusian atmosphere, atmospheric and surface processes (copyright: gabriele.arnold@dlr.de). Right: VenSpec/VEM science approach (after Helbert et al.[33])

VenSpec-U will search for atmospheric effects of geological activity, investigate the amount of outgassing, and study the feedback of atmospheric chemistry on surface geochemistry at Venusian day side. The relationship between mesospheric gas fluctuations and volcanism is of central interest. It provides causes for the fluctuations of the mesospheric sulfur-containing gases (SO, SO_2) and allows the investigation of the link between cloud and particle fluctuations and volcanism. A possible detection of ash or sulfate clouds caused by volcanism and a connection between the sulfuric acid clouds on Venus and volcanism could be investigated. VenSpec-U is a dual nadir pointing channel UV spectral imager. The lower spectral resolution channel encompasses the190-380 nm spectral range at a spectral resolution of 2 nm, whereas the high spectral resolution channel covers a spectral range of 205-235 nm at a spectral resolution of 0.3 nm and typical SNR values better than 100. With a FOV of 20° the spatial resolution at top cloud level will range from 6 to 48 km. The instrument takes heritage from SPICAM/Mex, SPICAV/Vex and PHEBUS/BepiColombo (see Fig. 3 left).[37, 54]

VenSpec-H will detect variations of the SO_2, OCS, CO, HCl, HF, H_2O and HDO abundances in the lower atmosphere to characterize volcanic plumes and other sources of gas exchange with the Venusian surface. VenSpec-H will also observe these species above the clouds to understand the high variability of the Venusian atmosphere and its chemistry. Observations will be made in the atmospheric windows of 1.16 - 1.18 µm, 1.7 - 1.74 µm and 2.3 - 2.5 µm during the night, probing the lower atmosphere and in the spectral windows 1.36 - 1.4 µm and 2.3 - 2.5 µm during the day measuring above the clouds. VenSpec-H (see Fig. 3 middle) is a high spectral resolution nadir pointing Echelle spectrometer with spatial resolution of 100 km (heritage from SPICAV-SOIR/VEX, NOMAD/EMTGO). It will operate an MCT (Mercury Cadmium Telluride) detector with a modified integrated dewar cooler assembly (T=150 K).[38]

VenSpec-M/VEM will provide a global map of rock types on the surface, monitor for active volcanism by its heat signature and by the enhancement of water vapor in a volcanic plume, and study change within the mission and in comparison, to other ongoing and previous missions using measurements at Venusian night side. It is a nadir pointing pushbroom multispectral imaging system (heritage from MERTIS, BepiColombo) using an InGaAs detector. The telecentric optics images the scene onto a filter array, and the image is relayed by a three-lens objective onto the detector. VEM's optical sub-system sits on top of the electronics compartment and the power supply. Of VEM's total of 14 narrow spectral bands, six would see the surface through all Venus atmospheric windows; three compensate for stray light; three measure cloud transparency; and two measure water abundance. A 45° FOV yields a swath width of 207 km at an altitude of 250 km providing a thorough sampling of surface emissivity and orbit-orbit repeat coverage. The spatial resolution at surface level is limited mainly due to the radiance scattering at the cloud aerosols to 50-100 km. (see Fig. 3, right).[39, 40]

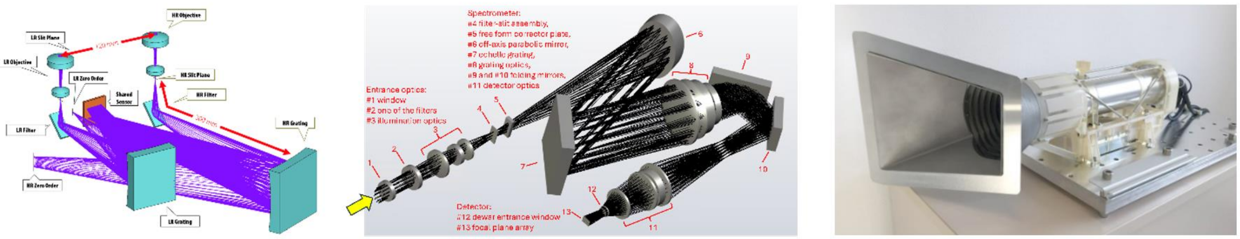


Fig. 3 The VenSpec spectrometers: From left to right: VenSpec-U (credit: Lesia, https://sites.lesia.obspm.fr/envision-venspec-u) , VenSpec-H, optical path (credit: Lesia, http://dites.lesia.obspm.fr/envision/envision-venspec-h); VenSpec-M/VEM, development model (credit: DLR(CC BY-NC-ND 3.0).

Detailed descriptions of the VenSpec suite and its organization[41], the scientific objectives and instrumental requirements of VenSpec-H[42], the design of the VenSpec-H instrument[43], the development of the filter wheel for VenSpec-H[44], the instrument design of the VEM[45], the laboratory support for the interpretation of the VEM spectra[46], the design and operation of VenSpec-U[47,48] can be found in other proceedings publications of this conference.

4. CONCLUSION

The results show that we are facing a new chapter in the exploration of Venus in the immediate planetological context and in comparison, with exoplanets, which also touches on fundamental aspects of planetary habitability. The planned spectral-optical analyses of the VEM on VERITAS and the VenSpec complex on EnVision will focus on the surface-troposphere-mesosphere system of Venus, including the H_2SO_4-dominated cloud system. Some of the key questions, such as the global surface composition, its relation to geology, the sources and sinks of atmospheric gases, the role of current volcanic activity, insight into older pre-Fortunian processes, and questions about the climatic evolution of Venus will receive new impetus. Cloud chemistry and outgassing, variability of SO_2, precise monitoring of tropospheric and mesospheric gases and their variability on spatial and temporal scales can be studied in detail. The combination of these investigations with data from the Subsurface Radar System (SRS), Radio Science and VenSAR (S-band operating radar as microwave radiometer and altimeter) measurements on EnVision and the Venus Interferometric Synthetic Aperture Radar (VISAR) on VERITAS will provide the basis for a comprehensive treatment of many of the open questions about the Venusian surface, troposphere and mesosphere system. Finally, the results expected from the DAVINCI decent probe will complete this comprehensive approach.

REFERENCES

[1] Oertel,, D. et al., "Infrared spectrometry of Venus from Venera 15 and Venera 16", *Adv. Space Res.* 5(9), 25-36 (1985), https://doi.org/10.1016/0273-1177(85)90267-4.

[2] Moroz, V. I. et al., "Venus spacecraft infrared spectra" *Applied Optics* 25, 1710-1719 (1986), https://doi.org/10.1364/AO.25.001710.

[3] Zasova, L.V. et al., "Infrared spectrometry of Venus: 769 IR Fourier spectrometer on Venera 15 as a precursor of PFS for Venus express", *Adv. Space Res.* 34,1655–1667, (2004), https://doi.org/10.1016/j.asr.2003.09.067.

[4] Drossart, P. et al., "Scientific goals for the observation of Venus by VIRTIS on ESA/Venus Express mission", *Planet. Space Sci.* 55, 1653–1672 (2007), https://doi.org/10.1016/j.pss.2007.01.003.

[5] Piccioni,, G. et al., "VIRTIS (Visible and Infrared Thermal Imaging Spectrometer) for Venus Express", *609 ESA-SP 1295* (2007).

[6] Arnold, G.E. et al., "VIRTIS/VEX observations of Venus: overview of selected scientific results", *J. Appl. Remote Sensing* 6(1), 063580 (2012), https://doi.org/10.1117/1.JRS.6.063580.

[7] Arnold, G.E. et al., "Scientific and instrumental requirements for VIS/IR studies of Venusian atmosphere from the upper cloud level down to the surface in light of future space missions", *Proc. SPIE 12, Infrared Remote Sensing and Instrumentation XXIX, 1183009* (2021), https://doi.org/10.1117/12.2594012.

[8] Bertaux, J.-L., et al., "SPICAV on Venus Express: Three spectrometers to study the global structure and 340 composition of the Venus atmosphere", *Planet. Space Sci.* 55, 1673–1700 (2007), https://doi.org/10.1016/j.pss.2007.01.016.

[9] Häusler, B. et al., "Radio Science investigations by VeRa onboard the Venus Express spacecraft", *Planet. Space Sci.* 54, 1315–1335 (2006), https://doi.org/10.1016/j.pss.2006.04.032.
[10] Arnold, G.E. et al., "First results of MIR spectroscopic investigations of the Venusian atmosphere by MERTIS during the two flybys of the BepiColombo spacecraft", *Proc. SPIE 12233, Infrared Remote Sensing and Instrumentation XXX, 1223303* (2022). https://doi.org/10.1117/12.2632548.
[11] Arnold, G.E. et al., "New results in exploration of Venusian mesosphere by MERTIS MIR measurements during the two Venus flybys of the BepiColombo spacecraft", *Proc. SPIE 12233, Infrared Remote Sensing and Instrumentation XXXI, 1268608* (2023), https://doi.org/10.1117/12.2675699.
[12] Helbert, J. et al., "MERTIS observations of the atmosphere of Venus during the second BepiColombo flyby", *Nature Communications*14-8225 (2023), https://doi.org/10.1038/s41467-023-43888-7.
[13] Nakamura, M. et al., "Overview of Venus orbiter, Akatsuki", *Earth Planets Space* 63, 443-457 (2011), https://doi.org/10.5047/eps.2011.02.009.
[14] Haus, R. and Arnold, G., "Radiative transfer in the atmosphere of Venus and application to surface emissivity retrieval from VIRTIS/VEX measurements*", Planet. Space Sci.* 58, 1578-1598, (2010). https://doi.org/10.1016/j.pss.2010.08.001.
[15] Smrekar, S.E. et al., „Recent hotspot volcanism on Venus from VIRTIS emissivity data", *Science* 328 (5978) 605-608 (2010), https://doi.org/10.1126/science.1186785.
[16] Kane, R.R. et al., „Venus as a laboratory for exoplanetary science", *arXiv:1908.02783v2* (2019), https://doi.org/10.1029/2019JE005939.
[17] Taylor, F. and D. Grinspoon, "Climate evolution of Venus", *J. Geophys. Res. 114*, E00B40 (2009), https://doi.org/10.1029/2008JE003316.
[18] Seiff, A. et al., "Models of the structure of the atmosphere of Venus from the surface to 100 kilometers altitude", *Adv. Space Res*. 5, 3–58 (1985).
[19] Zazova, L.V. et al., "Structure of the Venusian atmosphere from surface up to 100 km", *Cosmic Res.* 44(4), 364-383 (2006), https://org.doi/10.1134/S0010952506040095.
[20] Limaye, S.S. et al., "The structure of Venus atmosphere: Intercomparison of Venus Express and ground based observations of vertical temperature and density profiles", *Icarus* 294, 124-155 (2017), https://org.doi/10.1016/j.icarus2017.04.020.
[21] Ando, H. et al., "Thermal structure of Venusian atmosphere from the sub-cloud region to the mesosphere as observed by radio occultation", *Sci. Rep*. 10, 3448 (2020), https://org.doi/10.1038/s441598-8.
[22] Taylor, F.W., Svedham H., Head J.W., "Venus: The Atmosphere, Climate, Surface, Interior and Near-Space Environment of an Earth-Like Planet", *Space Science Rev*., 214, 35 (2018), https://doi.org/10.1007/s11214-018-0467-8.
[23] Pérez-Hoyos, S. et al., „Venus upper clouds and the UV absorber from MESSENGER/MASCS observations", *J. Geophys. Res. Planets*123, 145-162 (2018), https://org.doi/10.1002/2017JE005406.
[24] Pettengill, G.H. et al., „Magellan: Radar performance and data products", *Science* 252, (503), 260-265 (1991), https://org.doi/10.1126/science.252.5003.260.
[25] Ivanov, M.A. and Head, J.W., "M.A. Ivanov, J.W. Head, Global geological map of Venus", *Planet. Space Sci*. 59, 1559–1600 (2011).
[26] Limaye, S.S. et al., "Venus looks different from day to night across wavelengths: morphology from Akatsuki multispectral images", *Earth, Planets and Space* 70:24 (2018), https://org.doi/10.1186/s40623-018-0789-5.
[27] Yamazaki, A. et al., "Ultraviolet imager on Venus orbiter Akatsuki and its initial results", *Earth, Planets and Space* 70:23 (2018), https://org.doi/10.1186/s40623-018-0789-6.
[28] Abdrakhimov, A.M. and Basilevsky, A.T., "Geology of Venera and Vega Landing-site Regions", *Solar System Res*. 36 (2), 136-159 (2002).
[29] European Space Agency (ESA) (2021), EnVision assessment study report. Yellow book, ESA/SCI (2021)1, pages 1-111. https://sci.esa.int/documents/34375/36249/EnVision_YB_final.pdf.
[30] Smrekar, S.E. et al., "VERITAS (Venus emissivity, radio science, InSAR, topography, and spectroscopy): a discovery mission". In: 2022 institute for electrical and electronics engineers/*IEEE aerospace conference* (AERO) (2022) 1–20. https://doi.org/10.1109/AERO53065. 2022.9843269.
[31] Garvin, J.B. et al., "Revealing the mysteries of Venus: The DAVINCI mission", *Plant. Sci. J*. 3:117 (2022), https://doi.org/10.3847/PSJ/ac63c2.
[32] Helbert, J. et al., "The VenSpec suite on ESA EnVision mission to Venus", *SPIE Optical Engineering + Applications*, 2019, San Diego, Proceedings Volume 11128, Infrared Remote Sensing and Instrumentation XXVII; 1112804 (2019), https://doi.org/10.1117/12.2529248.
[33] Helbert, J. et al., "The VenSpec suite on the ESA Envision mission – a holistic investigation of the coupled surface atmosphere system of Venus", 16th EPSC Congress 2022, 18-23 September 2022, Granada, Spain, EPSC2022-374 (2022), https://org.doi/10.5194/epsc2022-374.
[34] Citation ESA: VenSpec-U - EnVision - Cosmos (esa.int), sighted:18 July 2024.
[35] Citation ESA: VenSpec-H - EnVision - Cosmos (esa.int), sighted:18 July 2024.
[36] Marcq, E. et al., "Evidence for SO_2 latitudinal variations below the clouds of Venus", *A&A* 648 (2021), https://doi.org/10.1051/0004-6361/202140837.
[37] Marcq, E. et al., "Science case for the VenSpec-U instrument on board EnVision", *Lunar and Planet. Sci. Conference*, The Woodlands, TX, March 13-17, LPI 2891 (2023).
[38] Neefs, E. et al., "VenSpec-H spectrometer on ESA EnVision mission; Design, modeling, analysis", *Acta Astronautica*, accepted 2024.
[39] Helbert, J. et al., "The Venus emissivity mapper (VEM) concept". In: *Infrared remote sensing and instrumentation XXIV. Proceedings SPIE*, San Diego, Aug 2016, Paper 9973-26 (2016).
[40] Widemann, T. et al., "Venus evolution through time: key science questions, selected mission concepts and future investigations", *Space Sci. Rev*. 218-56 (2023), https://doi.org/10.1007/s11214-023-00992-w.
[41] Wolff, F. et al., "The VenSpec organization: collaborative development from instrument proposal to scientific analysis", *Proc. SPIE 13144, Infrared Remote Sensing and Instrumentation XXXII, 13144-12* (2024).
[42] Robert, S. et al., "Scientific and instrumental requirements of the IR spectrometer VenSpe-H onboard EnVision", *Proc. SPIE 13144, Infrared Remote Sensing and Instrumentation XXXII, 13144-35* (2024).
[43] De Cock, R. et al., "Design of the VenSpec-H instrument on Esa's EnVision mission", *Proc. SPIE 13144, Infrared Remote Sensing and Instrumentation XXXII, 13144-14* (2024).
[44] Székely, G. S. et al., "Development of a filter wheel for VenSpec-H", *Proc. SPIE 13144, Infrared Remote Sensing and Instrumentation XXXII, 13144-15* (2024).
[45] Hagelschur, T. et al., "The Venus Emissivity Mapper (VEM): instrument design and development for VERITAS and EnVision", *Proc. SPIE 13144, Infrared Remote Sensing and Instrumentation XXXII, 13144-16* (2024).
[46] Allemanno, G. et al., "Spectral mixing analysis of laboratory emissivity spectra for improved VEM/VenSpec-M data interpretation", *Proc. SPIE 13144, Infrared Remote Sensing and Instrumentation XXXII, 13144-19* (2024).
[47] Lustrement, B. et al., "Design of the VenSpec-U instrument on board EnVision", *Proc. SPIE 13144, Infrared Remote Sensing and Instrumentation XXXII, 13144-20* (2024).
[48] Conan, L. et al., "The VenSpec-U spectrometer onboard EnVision mission: a sensitivity study"; *Proc. SPIE 13144, Infrared Remote Sensing and Instrumentation XXXII, 13144-21* (2024).
[49] Montmessin, F. et al., "A layer of ozone detected in the nightside upper atmosphere of Venus", *Icarus* 216, 82-85 (2011), https://doi.org/10.1016/j.icarus.2011.08.010.
[50] Bézard, B. et al., "The 1.10-and 1.18-µm nightside windows of Venus observed by SPICAV-IR aboard Venus Express", *Icarus* 216, 173-183 (2011), https://doi.org/10.1016/j.icarus.2011.08.025.
[51] Fedorova, A. et al., "The CO_2 continuum absorption in the 1.10- and 1.18-µm windows on Venus from Maxwell Montes transits by SPICAV IR onboard Venus Express", *Planet, Space Sci.* 113-114, 66-77 (2015), https://doi.org/10.1016/j.pss.2014.08.010.
[52] Marcq, E. et al., "Variations of Sulphur dioxide at the cloud top of Venus's dynamic atmosphere", *Nature Geosci*. 6, 25-28 (2013), https://doi.org/10.1038/ngeo1650.
[53] Marcq, E. et al., "Climatology of SO2 and UV absorber at Venus' cloud top from SPICAV-UV nadir dataset", *Icarus* 335, 113368 (2020), https://doi.org/10.1016/j.icarus.2019.07.002.
[54] Marcq, E. et al., "Instrumental requirements for the study of Venus' cloud tog using the UV imaging spectrometer VeUV", *Adv. Space Res.* 68 (1), 275-291 (2021), https://doi.org/10.1016/j.asr.2021.03.012.