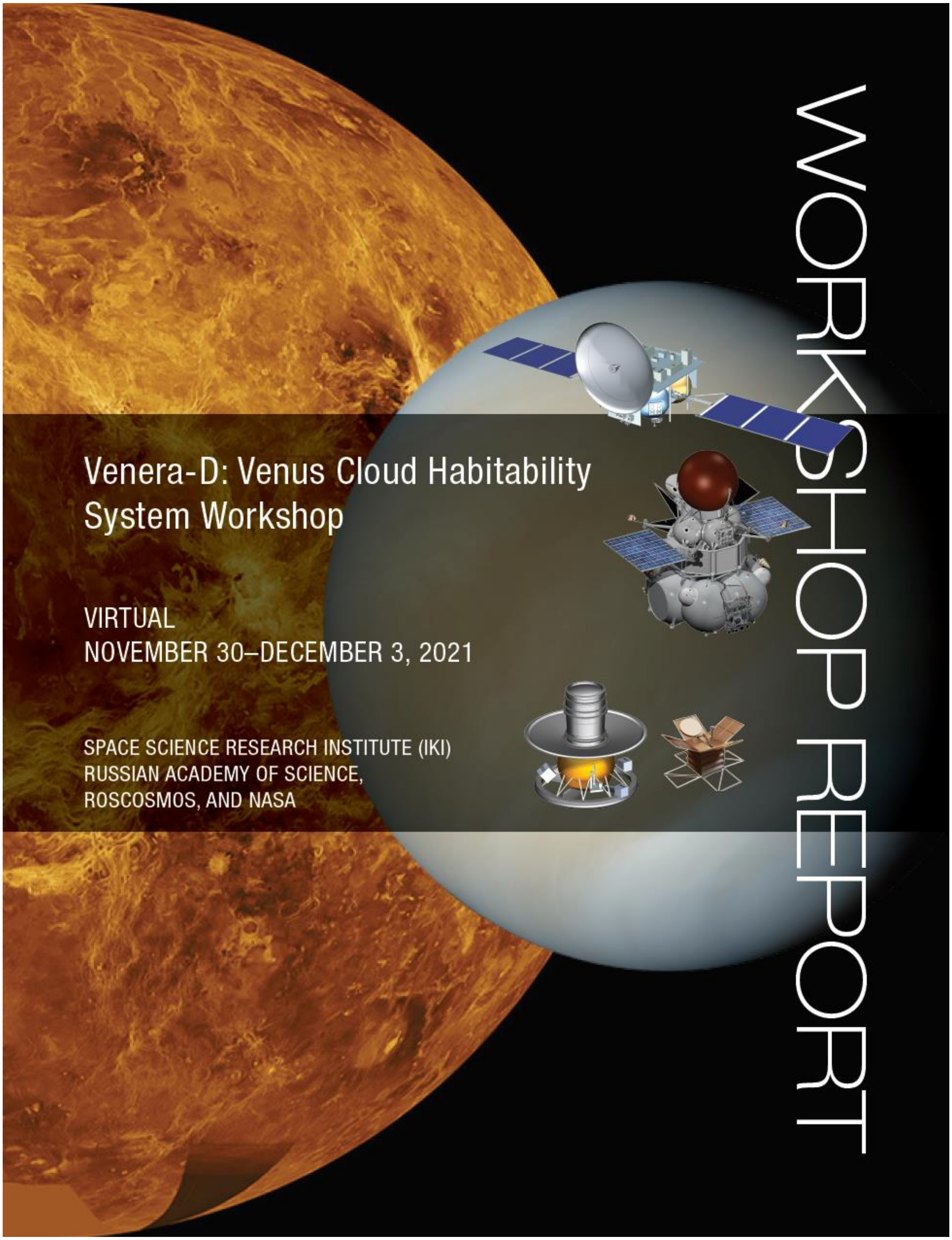

WORKSHOP REPORT

Venera-D: Venus Cloud Habitability System Workshop

VIRTUAL
NOVEMBER 30–DECEMBER 3, 2021

SPACE SCIENCE RESEARCH INSTITUTE (IKI)
RUSSIAN ACADEMY OF SCIENCE,
ROSCOSMOS, AND NASA

Archive Report Outline

1.0 Overview

1.1 Introduction

The Venera-D: Venus Cloud Habitability System Workshop (2021) was a continuation to the Venera-D Landing Sites and Cloud Habitability Workshop held in 2019. The 2019 workshop was held at the recommendation of the Roscosmos/IKI-NASA Joint Science Definition Team for the Venera-D mission. The recommendation came due to conversations and reemerging interest in the habitability of the Venusian clouds. A more general goal of the habitability interest, however, is to inform future missions and make the case that the Venusian atmosphere requires further exploration. A list of areas for future focus was the biggest outcome of the workshop, including recommendations from astrobiologists with biological perspectives, but not necessarily life detection. This area needs to be better integrated into mission design and further characterization of the atmosphere would likely be more helpful than *in situ* life detection.

The 2021 Workshop focused on the Cloud habitability discussed in the previous workshop by gathering and facilitating dialogue between scientists and engineers who have been researching habitability and developing instruments and methods to detect evidence of habitability on Venus. The four main objectives were: 1) to discuss the formation and stability of Venus clouds over time, 2) past and present habitability, 3) the best measurements and methods needed to address these questions, and 4) how future missions will contribute to understanding the cloud habitability system.

The Venera-D: Venus Cloud Habitability System Workshop was held virtually from November 29th to December 3rd, 2021. It featured 54 presentations and 3 panels and was viewed by 264 participants from 36 different countries. The presenters were asked to submit abstracts under one of the four different categories: 1) cloud layer habitability, 2) inputs (interior, surface, exogenous) to and outputs from the cloud layer over time, 3) measurements and instruments necessary to investigate the Venus cloud region, and 4) open questions or any additional investigations pertaining to the habitability of Venus clouds. On the second day of the workshop there was the Multi-agency Venus Exploration Science Directors panel where a joint announcement was made by NASA-ESA on the formation of the Venus Science Coordination (VeSCoor) group, and other Agencies were invited to participate.

The organizing committee created six different sessions for the workshop that encompassed a variety of topics relevant to Venus habitability. The “Present Habitability of Venus” session showcased talks on the difficulties life as we know it would have to overcome in order to evolve and survive on Venus and emphasized the need to take lessons learned from biology labs and Earth’s stratosphere and apply it to Venus. The “Missions to Venus” session featured presentations on the recently selected VERITAS, DAVINCI and EnVision missions, and a summary of scientifically interesting landing sites. The “Measurements, Instruments, and Mission Concepts to Venus” session featured talks on instruments, techniques, mission concepts, and methods to investigate the Venus cloud region and potentially identify microbes. A representative from the engineering firm NPO Lavochkin gave an update on the prospective Venera-D mission, including its objectives, intended instrumentation, and the next steps toward its realization. The “Putative Origins of Life and Past Habitability of Venus” session discussed the effects of chemical, geological, and astrophysical processes on the development and evolution of life, and how these processes can influence the search for life at Venus. The “Biosignatures at Venus” session discussed potential agnostic biosignatures at Venus, such as ammonia, phosphine, and the source of SO_2 depletion in the clouds, and the dangers of using Earth metrics in the search for Venusian life. The “Evolution of the Venusian Atmosphere” session had presentations on the possibility of a Venus ancient global ocean and discussed the geological and physical processes that helped shape the surface and atmosphere of Venus today. The Workshop also hosted e-lightning talks for sixteen poster presenters, as well as three different panels on upcoming international Venus missions and discussions on important topics that strongly influence our knowledge of Venus.

The first panel was “Phosphine at Venus” and featured six panelists with expertise in the Venus atmosphere and phosphine research. The panel discussed the phosphorus cycle, abiotic sources of phosphine, phosphine as a biosignature, and methods to detect phosphine in the atmosphere. DAVINCI will have the capability to detect several phosphorus-bearing gases and the mission team would like community feedback about making some modifications in order to detect PH_3.

The second panel was “Water on Venus” and it had five panelists. The panel discussed the different modeling methods and assumptions used to investigate Venus’ potential to host surficial liquid water in the ancient past. The panel deliberated if water is necessary for the emergence and survivability of life, and if we should look for life as we do not know it. More measurements on water abundance and the D/H ratio are crucial to compare to the Pioneer Venus original detection.

The third panel was “A Decade of Venus Exploration —*A Multi-Agency Perspective*”. The panel consisted of Agency Science Directors or their representatives from five different international space agencies, who are currently pursuing missions or are at Venus now. These agencies included IKI (Dr. Lev Zelenyi), NASA (Dr. Lori Glaze), ESA (Dr. Fabio Favata), JAXA (Dr. Yoshifumi Saito), and ISRO (Dr. Tirtha Das). The panel was moderated by Dr. Roger Bonnet from ISSI. The panel discussed their respective agency’s Venus missions and the possible ways in which science synergism between these missions could maximize science return. Panel members were supportive of the idea of the organization of an international Venus exploration group that could contribute to observational strategies, synergies, and help to define open questions. At this panel ESA-NASA jointly announced the formation of a Venus Science Coordinating (VeSCoor) group and invited the other Agencies to join.

Currently, the only planet known to harbor life in the universe is Earth, thus it is our best resource for defining conditions from which life emerged, and the conditions under which life has/can persistently reproduce. On Venus, the surface is inhospitable to life as we know it and as observed on Earth, even with the wide variety of conditions under which life has been detected on the Earth. However, the Venus clouds layer has similar ambient conditions to Earth with a less acidic environment and could be another sanctuary for life. This has been proposed previously by several scientists including Carl Sagan. Investigating this region, and the potential habitability of Venus’ past and present, will provide clues on the conditions necessary for life as we know it, to develop and to survive. This information will have important implications for the search for life on planets around other stars including exoVenuses and exo-Earths. In the recently released document on “Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032 (2022)” it underscores the importance of exploring Venus from an astrobiological perspective in the next decade. The document lists crucial questions and future investigations necessary to determine if Venus was, and still is, a habitable world. The document states that “Venus holds critical clues for understanding the role of climate change for a world becoming uninhabitable”. The decadal includes important questions such as “Determine if life-supporting chemical species, including reduced carbon- and phosphorus bearing molecules, are present in the atmosphere of Venus, via in situ atmospheric measurements.”, “Determine whether there are modern habitable environments in atmospheres by characterizing chemistry, including organic molecules, in the atmospheres of Venus and Titan.“, “Determine the availability though time of liquid water on Venus using measurements of present-day escape rates, isotopes and mineral phases in the crust, as well as atmospheric models integrating loss to space with interior and surface evolution.“, and “Determine whether Venus ever hosted liquid water on its surface by geomorphic mapping to search for water-formed landforms as well as mineralogy, chemistry, and isotopic measurements in situ or with samples that may record crust interaction with water and volatile evolution overtime.” The findings in the decadal highlight the need to continue to advance our knowledge on the potential for life on Venus, and the importance of Workshops such as this one to gather researchers to discuss Venus habitability.

1.2 Final Report Reading Guide

This section (*Section 1*) provides background information on the organization and motivation for the Venera-D: Venus Cloud Habitability System Workshop, including lists of the organizing committee and the scribes (1.3), and a summary of the preceding 2019 Venera-D Workshop (1.4). *Sections 2-5* correspond to the different sessions that were scheduled during the workshop. In each of those sections a brief summary of the discussion points is presented. This is followed by a list of open questions and recommended future actions, as articulated by each presenter. *Section 6-8* corresponds to the different discussion panels that were hosted during the workshop. These sections are written in bullet style format and documents the panel highlights, the future needs/recommendations that were given during the panel, and ways in which a future mission may address open questions. *Section 9* gives a brief overview of the missions, instruments, and mission concepts that were presented during the workshop. *Section 10* summarizes the upcoming selected and in-development missions, as well as lists their payloads and science goals. *Section 11-13* discusses the findings of this workshop, and how the themes of the workshop impact future Venus exploration modeling, technology and lab measurement needs and goals, as well as the next steps and community resources needed to meet these goals. *Section 14* provides the meeting program as reference for the report, with clickable links to the individual abstracts and on-line materials. And finally, *Section 15 is an Appendix,* it provides the notes taken by the scribes for each of the talks given during the workshop, as collated by the lead scribe for each session. The format of these notes follows the template given to each scribe, and thus the following bulleted inputs are provided: (a) the session highlights, (b) the recommended future actions, and (c) important comments made during the Question and Answer (Q&A) segment of each talk and panel.

1.3 Organizers and Scribes

Institutional Support

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Universities Space Research Association
Space Research Institute (IKI), Russian Academy of Sciences
National Aeronautics and Space Administration

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Natalie Punt; Fidum Veterinary Services, USA

1.4 Venera-D Landing Sites and Cloud Habitability Workshop (2019)

Below is a brief overview of the 2019 Workshop report, as well as the list of publications on Venus habitability of the cloud layer that came out as a result of the Workshop. At the workshop, three habitability focused working groups were developed during the Workshop and worked to identify focus areas:

1. Instrument development to increase understanding of the atmosphere (e.g., particle counter, nephelometer, water abundance and activity measurement, organics analyzer, etc.)
2. Instrument development for detection of biosignatures
3. Expanded measurements at putative habitable altitudes across multiple latitudes and Venusian daytime points.
    a. Measurements such as aerosol density, bulk composition, cloud particle composition
    b. Characterizing nutrient availability including CHNOPS elemental abundances and organics
4. Characterization of potential biosignatures, including isotopic abundances, and molecular complexity of putative organic compounds.
5. Detailing desired measurements specific to Venus conditions.
6. Develop simulations of the Venus cloud layer to test the viability of terrestrial microorganisms, using terrestrial analogs that live under similar conditions.
7. Model metabolic activities in Venus conditions, including sulfur/iron biochemistry
8. Understand the stability and absorbance of biomolecules under simulated conditions

The largest outcome of the 2019 workshop, was the Special Collection on Venus Cloud Layer Habitability published in the journal *Astrobiology* in October 2021. This special collection was made up of ten papers on topics ranging from an overview of why Venus is of interest to a portion of the astrobiology community, to possible life cycles of putative life, to possible explanations for the reported phosphine detection in the clouds. Questions raised during the first workshop, papers published in this special collection and elsewhere, including but not limited to those relating to water (ancient and present) and phosphine at Venus, motivated this second workshop to gather the ever-growing Venus astrobiology community in an effort to discuss new findings and new questions. Papers published in the *Astrobiology* special issue and other papers that motivated the workshop are listed below.

Lead Author(s)	Title (paper linked)
Sanjay Limaye	**Venus, an Astrobiology Target**
Oleg R. Kotsyurbenko and Jaime A. Cordova	**Exobiology of the Venusian Clouds: New Insights into Habitability through Terrestrial Models and Methods of Detection**
Sara Seager	**The Venusian Lower Atmosphere Haze as a Depot for Desiccated Microbial Life: A Proposed Life Cycle for Persistence of the Venusian Aerial Biosphere**
Charles Cockell	**Biologically Available Chemical Energy in the Temperate but Uninhabitable Venusian Cloud Layer: What Do We Want to Know?**
Rakesh Mogul	**Potential for Phototrophy in Venus' Clouds**

Tetyana Milojevic	**Phosphorus in the Clouds of Venus: Potential for Bioavailability**
Arthur Omran	**Phosphine Generation Pathways on Rocky Planets**
Wiliam Bains	**Phosphine on Venus Cannot Be Explained by Conventional Processes**
Noam R. Izenberg	**The Venus Life Equation**
Kevin H. Baines	**Investigation of Venus Cloud Aerosol and Gas Composition Including Potential Biogenic Materials via an Aerosol-Sampling Instrument Package**
Martin Turbet	**Day–night cloud asymmetry prevents early oceans on Venus but not on Earth**
John Hallsworth	**Water activity in Venus's uninhabitable clouds and other planetary atmospheres**
Paul Rimmer	**Hydroxide Salts in the Clouds of Venus: Their Effect on the Sulfur Cycle and Cloud Droplet pH**
Michael J. Way and Anthony Del Genio	**Venusian Habitable Climate Scenarios: Modeling Venus Through Time and Applications to Slowly Rotating Venus-Like Exoplanets**
Clara Sousa-Silva	**Phosphine as a Biosignature Gas in Exoplanet Atmospheres**
Jane Greaves	**Phosphine gas in the cloud decks of Venus**
Rakesh Mogul	**Venus' Mass Spectra Show Signs of Disequilibria in the Middle Clouds**
Geronimo Villanueva	**No evidence of phosphine in the atmosphere of Venus from independent analyses**
Pierre Amato	**Active microorganisms thrive among extremely diverse communities in cloud water**

2.0 Present Habitability of Venus

2.1 Summary

This session featured ten talks which are listed in the table below. The researchers provided presentations that focused on the challenges, based on life as we know it, and conditions that putative life would face in the clouds of Venus, such as (but not limited to) low pHs or acidic conditions and decreased water availability. Presenters discussed the effect of radiation and solar energy at Venus on putative life, with it likely not challenging to life, but enough photonic energy potentially being present allowing for round-the-clock photosynthesis. In addition, it was described that chemosynthesis may also be possible as a source of energy. Overall, presenters stressed the need for further laboratory studies including studies of microbial life in Earth's clouds, model development to understand Venus' rotation and potentially habitable past, and various measurements/sample collections for future in-situ missions, including development of life-detection instruments.

First Author	Affiliation	Talk Title
Amato P.	Université Clermont Auvergne, CNRS, France	*Terrestrial Hints for Prospecting Microbial Life in Venus Clouds*
Kotsyurbenko O. R.	Yugra State University, Russia	*Astrobiology of Venus: Basic Insights and Prospects (Application to Venera-D Mission)*
Schulze-Makuch D.	Technical University Berlin, Germany; School of the Environment, Washington State University, USA	*Habitability Challenges in the Venusian Clouds*
Grinspoon D. H.	Planetary Science Institute, USA	*Gaia on Venus: Planetary-Scale Considerations of Habitability*
Gentry D. M.	NASA Ames Research Center, USA	*Aerobiospheres and Planetary Habitability: Considerations from Earth to Venus and Beyond*
Dartnell L. R.	School of Life Sciences, University of Westminster, UK	*Constraints on a Potential Aerial Biosphere on Venus: Cosmic Rays and Solar Ultraviolet Radiation*
Mogul R.	California State Polytechnic University, USA	*Potential for Habitability and Round-the-Clock Phototrophy in Venus' Clouds*
Spacek J.	Firebird Biomolecular Sciences, LLC, USA	*The Organic Carbon Cycle in the Atmosphere of Venus and Evolving Red Oil*
Yang J.	Department of Atmospheric and Oceanic Sciences, School of Physics, China	*Climate and Habitability of Venus-Like Slowly Rotating Planets*
Limaye S. S.	University of Wisconsin, USA	*Speculations on Adaptations of any Life on Venus, Past and Present*

2.2 Summary of presented open questions, recommended next steps

Amato:

- Choose in situ or Venus analog experiments created in the lab for sample-based investigation of Venus' clouds
- Select a search object (cells / molecular biomarkers / imprints attesting to processes)
- Understand if it is possible to collect/accumulate/incubate samples from Venus' clouds and if biological assays are feasible and conceivable in given conditions
- Try to attempt direct bulk culturing of microbes in cloud simulations
- Calculate the minimal necessary population and growth rate for persistence vs physical turnover of the atmosphere
- Search for specific biological traits that would lengthen cloud droplet residence time and/or favor rapid spread among droplets
- Think of any known chemical characteristic unexplained by pure abiotic processes and that could attest to biological processes.
- We can understand more about potential microbial life in Venus' clouds if future missions will answer the following questions:
    - How fast can elements and matter cycle through Venus' atmosphere? What is the time scale of physical cycles?
    - Is there sufficient turbulence/dynamics to spread biomass among droplet microenvironments?
    - Is there any expectable spatial structuration of physio-chemical conditions? (hotspots of habitability?)

Kotsyurbenko:

- Need to reassess a modern concept of the environment
    - Include new types of ecosystems such as the aerogeochemical cycle
    - Include extreme survival capacities of hypothetical microorganisms unknown for terrestrial organisms on Earth
- Methods of detection of life
    - In situ detection of biomacromolecules
    - In situ microscopy
    - In situ detection of key functional molecules (pigments, enzymes, fatty acids, amino acids, etc)
    - Indirect: detection of biomarkers and biosignatures
        - Phosphine (organic)
    - Indirect: assessment of the possibility for the existence of trophic microbial interactions and biogeochemical cycles

Schulze-Makuch:

- The claimed presence of (organic) phosphine is extremely important for the possible detection of life
- Detecting phosphine in the IR range as well as diphosphine as an intermediate product in the photolysis reaction of phosphine to phosphorus and hydrogen may help resolve the debate over the presence of phosphine

- Test selected acidophilic microbes on how far they can adapt from one generation to the next in higher and higher sulfuric acid concentrations
- Investigate microbial adaptation mechanisms to hyperacidity, low water activity, and the lack of trace metals
- A mission solely dedicated to study mode 3 particles to reveal their interior composition would be of great importance
    - Mode 3 particle retrieval mission to Venus has been proposed before

Grinspoon:
- Crucial to understand sources of disequilibrium in Venus atmosphere
- Answer the following questions:
    - History of resurfacing: Has Venus been continuously active over geologic time?
    - What are the fluxes of gases between interior/surface/atmosphere and cloud reservoirs?
    - Are the clouds maintained by an active sulfur cycle involving outgassing and surface reaction/diffusion of gases? What is the equilibrium state of surface minerals?
    - Have the clouds existed continuously?
    - What were the conditions of the clouds at the time they coexisted with the last oceans, and what has been the trajectory of cloud conditions over time?
    - Was Venus ever an oceanic world and for how long?
- Future missions will help to know more about continents, volcanic history, subduction and heat flow:
    - Does Venus have Earth-like continents that formed in the presence of water?
    - Is volcanism steady, like Earth's, or catastrophic, implying episodic, past tectonics?
    - Is there active subduction? Did plate tectonics on Earth start the same way?
    - What is the derived global heat flow and does it prohibit the formation of plate tectonics?

Gentry:
- In situ targets
    - Differentiate size specific aerosol composition and residence dynamics
    - Understand water history – is there continuity?
    - Characterize mixing and lofting dynamics
- Stratospheric sampling lessons
    - Habitable microenvironments sparse and variable: need lots of sample
    - Vast majority of bioaerosols are dead/dormant: test instruments using more representative biosignature
    - Without sample return, need fast analysis cadence
        - Mass spec can be slow
        - Optical measurements require good baselines
- Earth lacks a perfect analogue to Venus's cloud and haze aerosols, but it has several environments that can together span important science and operational properties, so consider field analog testing.

Dartnell:
Endolithic habitable zone (HZ) in the terrestrial rocks and euphotic zone in the water column can be analogues for Venus clouds HZ in terms of influence of solar UV.

Mogul:
More accurate in-situ analysis of chemical composition of Venus clouds that will be made by future missions will support or refute the hypothesis proposed in their talk including if acidity and water activity may not be at levels restrictive to putative life.

Spacek:
Collect experimental data at simulated Venus conditions. Future in-situ data will also be needed to compare with their experimental results. The speaker discussed a mission concept that could launch in 2023-2024 that could have an autofluorescence nephelometer. This data can be compared with data obtained in the lab.

Yang:
Their experiments assume the initial state of Venus is cold or warm. More models are needed to investigate a variety of initial states. Furthermore, Venus' ancient rotation rate has important implications for an ancient ocean and needs to be constrained.

Limaye:

- We need to answer the following questions:
    - What was the initial rotation state of Venus (tilt and period)?
    - How did it change over time?
    - When did superrotation develop relative to loss of water?
    - When did the cloud cover change forcing UV, acidity, photosynthesis and other adaptations?
    - If any life ever evolved, when possibly did the migration to the clouds begin and end?
    - Does a slower clock play a role in adaptations to external stressors?
    - Without a moon, only atmospheric solar thermal and solar internal tides and impacts can change the rotation period of Venus?
    - Did Venus have a moon?
    - Did the shorter circadian clock in Venus clouds help or hinder survival of any life migrating from the surface?
- Recommendations:
    - Backward modeling of atmospheric evolution from the present state.
    - Forward modeling of evolution of atmosphere and climate of Venus from as early a state as possible.
    - Continued monitoring of the rotation rate of Venus for detecting any secular trends.
    - Noble gas isotopic measurements.
    - Inventory of trace species in the atmosphere.
    - Better assessment atmospheric escape (Lagrange point orbiters)
    - Surface rocks characterization.
    - Measurements of seismic activity.
    - Atmospheric escape estimates.
- The real amounts of the ionizing radiation on Venus can be lethal for microorganisms (based on current models).
- The VERITAS, DAVINCI, Venera-D, EnVision, ISRO Venus Orbiter missions will characterize the surface composition and may detect the presence of felsic rocks, which would indicate a potentially wet past.

3.0 Putative Origins of Life and Past Habitability of Venus

3.1 Summary

This session featured four talks (listed below) discussing parameters that are fundamental for the development of life and characteristics that could be biosignatures. Life on Venus may be composed of a biochemistry that is not found on Earth yet shares a universal agnostic biosignature of biopolymers composed of informational units that have the same size and structure within a supporting backbone with a repeating charge. It was also discussed that cosmic rays from supernovae may be an evolutionary pressure for homochirality, and thus homochirality may be a biosignature. The current understanding of life is that it may need liquid water to develop. Modeling of early Venus shows that it may have hosted liquid water for 0.9 Gyr after which metamorphic crustal decarbonation led to the release of CO_2 resulting in a runaway greenhouse effect. This period in time may have been conducive for the formation of life, perhaps even the development of stromatolite-like structures. Stromatolites are created by photosynthetic organisms and are considered the oldest fossils, still living, on Earth. They have distinct morphology and understanding their stability in simulated Venus conditions may inform the physical and chemical features that need to be considered for investigation on Venus.

First Author	Affiliation	Talk Title
Benner S. A.	Foundation for Applied Molecular Evolution, USA	*The Limits to Organic Life in the Solar System: From Cold Titan to Hot Venus*
Globus N.	University of California, Santa Cruz, USA	*Homochirality, Cosmic Rays, and Venus*
Höning D.	Potsdam-Institute for Climate Impact Research, Germany	*Habitability of an Early Stagnant-Lid Venus*
Kohler E.	NASA Goddard Space Flight Center, Greenbelt, USA	*Stromatolites on Venus — An Experimental Look into Their Stability and Where to Investigate*

3.2 Summary of presented open questions, recommended next steps

Benner:
There are two main challenges in understanding Venus: 1) Terran style life emerged finding a way to continuously evolve to survive for solvent replacement. 2) Overcoming Earth based chemistry bias to understand how organic chemistry is or has occurred on Venus. Agnostic Life Finder (ALF) is a suggested method to extract and identify polymers with a repeating charge in a solvent. Laboratory characterization of these polymers may explain life on Venus and on other planets. Studying non-Earth based chemistry yields insight into alternative ways to support life

including informational biopolymers with the necessary structural requirements for non-Earth like environments.

Globus:
Develop and identify instrumentation capable of detecting homochiral molecules in Venusian clouds. Study chirality in sample return missions from planetary bodies. Irradiate biological samples with polarized beams.

Höning:
The model used to calculate CO_2 partial pressures used global mean surface temperature. If varying surface temperatures (i.e.: differences in surface temperature due to lake precipitation, carbonate deposits at poles) were used then the distribution of carbonates may be different.

Kohler:
Future missions can look for evidence of fossils by observing areas on Venus that could have harbored life.

4.0 Biosignatures at Venus

4.1 Summary

This session featured four presenters (listed below) who discussed various biosignatures that are indicative of life. Major potential biosignatures include detecting concentrated geochemically distinct scarce elements in discrete metastable entities, the favoring of lighter isotopes in chemical structures, and homochirality. Another possible biosignature, ammonia, was discussed, and it was hypothesized to be synthesized by microbial life in Venusian clouds in order to overcome acidic environments. Three distinct metabolic pathways were also investigated to explain SO_2 depletion in the clouds, but it was found that none matched measured abundances of SO_2, CO, and H_2S. There was an update on the detected phosphine signal on Venus where the presenter defended the reliability of phosphine detection by explaining the robust techniques used to authenticate its identity, as well as refuted common misconceptions that challenged the legitimacy of its detection.

First Author	Affiliation	Talk Title
Graham H.	NASA Goddard Space Flight Center, Greenbelt, USA	*The Limits of Parsimony: Agnostic Pathways for Understanding Life Detection*
Petkowski J. J.	Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, USA	*Towards an Explanation for Venusian Cloud Anomalies and Implications for the Habitability of the Clouds*

Jordan S.	Institute of Astronomy, University of Cambridge, UK	*Metabolic Signatures of an Aerial Biosphere in the Clouds of Venus: A Self-Consistent Photo-Bio-Chemical Model*
Greaves J. S.	School of Physics and Astronomy, Cardiff Univeristy, UK	*Update on Phosphine in Venus' Atmosphere*

4.2 Summary of presented open questions, recommended next steps

Graham:
There is a need to reformulate the understanding of habitability and biosignatures based on our current knowledge of life on Earth, but also potential life on other planetary bodies. Relying entirely on Earth based habitability metrics can hamper in the search for life on other bodies (including Venus).

Pętkowski:
It is important to send a future mission to Venus to determine which previous atmospheric measurements were true, which were errors, and to search for sources of life. It is also crucial to complete in situ measurements to understand cloud aerosols, PH_3, and the unknown UV absorber.

Jordan:
Future in-situ measurements of the lower atmosphere and remote sensing-based variations in SO_2 will test the chemical pathways and potential reactions as metabolic pathways of life on Venus.

Greaves:
Attaining data regarding infrared, millimeter spectra and chemical profiles can help understand the concentration and stability of PH_3 in Venus. DAVINCI's mass spectrometer will provide a chemical profile of Venus' clouds to confirm the presence of PH_3 or related P-bearing compounds on Venus. In the future they will 1) Observe Venus with Sofia 2) Acquire new spectra (proposed for JCMT Large Program in 2022/2023) 3) Model phosphine with various drift patterns, lifetimes, etc 4) Reconcile all data (infrared + millimeter spectra + in-situ mass-spec) with chemically plausible altitude profile.

5.0 Evolution of the Venusian Atmosphere

5.1 Summary

This session was composed of six presentations (table below) that addressed geologic events which could have influenced the evolution of the Venusian atmosphere and characterized the limits of habitability within the atmosphere. Clouds and rotation rate may have played a key role in Venus' climate by contributing to the formation/loss of surface liquid water in Venus' geological history. Venus is considered to be an "episodic lid" planet that lacks plate tectonics and may be in transition between tectonic and stagnant states. Venus has undergone extensive resurfacing events that have generated a thick outgassed atmosphere with high pressures suppressing outgassing and influencing internal temperatures which affects surface mobility. Large Igneous Provinces (LIPs) volcanism in the past may have led to a dramatic release of CO_2 resulting in global runaway greenhouse warming. The current high atmospheric pressure may control the rate of degassing of SO_2, H_2O and CO_2 from erupting magma. Thus, the current Venus atmosphere may be a "fossil atmosphere", largely inherited from a previous ancient epoch in Venus history. Venus' clouds are considered to be inhabitable when considering the limits of known Earth life. Direct observations and models imply that Venus' atmosphere is dry, with various levels of acidity and with clouds' water activity between 0.01-0.0001 at 80-100% sulfuric acid concentration.

First Author	Affiliation	Talk Title
Way M. J.	NASA Goddard Institute for Space Studies, USA	*Did an Ancient Habitable Venus Provide the Seeds for Life Today?*
Weller M. B.	Dept. of Earth, Env., and Planetary Sciences, Brown University, USA; Lunar and Planetary Institute, USA	*From Whiffs to Pulses: Links Between Tectonic Evolution, Outgassing, and Atmospheric Development*
Head J. W.	Brown University, USA	*Formation and Stability of the Venus Atmosphere: Insights from the Geological Record and Implications for Evidence of Life on Venus*
Ernst R. E.	Department of Earth Sciences, Carleton University, Canada; Faculty of Geology and Geography, Tomsk State University, Russia	*The Implications of Applying a Large Igneous Province (LIP) Context for Volcanism, Tectonics, and Atmospheric Evolution on Venus*
Turbet M.	Observatoire astronomique de l'Université de Genève, Switzerland	*Day-Night Cloud Asymmetry Inhibits Early Ocean Formation on Venus*
Hallsworth J.	Institute for Global Food Security, School of Biological Sciences, Queen's University Belfast, UK	*Venus's Clouds Are an Order of Magnitude Beyond the Acidity Limit, and Two Orders of Magnitude Below the Water-Activity Limit, for Active Life*

5.2 Summary of presented open questions, recommended next steps

Way:

- Comprehensive study to quantify the day-night cloud asymmetry impact on early ocean formation on Venus, compared to Earth. How does the cloud and atmospheric circulation feedbacks vary nonlinearly and non-monotonically with rotation period?
- DAVINCI may provide insights into Venus' history with D/H and noble gas isotopes measurements
- DAVINCI imaging with VERITAS, EnVision and Venera-D can provide a higher level of visualization and data collection to provide information for site selection.
- Identify a large impactor- careful isotopic measurements could identify a large impactor
- DAVINCI IR imagers on VERITAS/EnVision can be used to find remains of large igneous provinces or ancient aqueous features that may provide an explanation for the heat-death of Venus-like worlds.

Weller:

Future missions will more accurately constrain the current geology and the atmosphere of Venus which will facilitate the development of more precise models of Venus' past.

Head:

- What was the atmospheric pressure/water content/solar insulation tipping point that led to the general stabilization of this fossil atmosphere?
- Use inverse modeling instead of forward modeling: i.e. using current atmosphere as a baseline and work backwards in time
    - Benefits include the ability to assess:
        - Nature and magnitude of the major phases of volcanism
        - Style and magnitude of volatile output
        - Candidate effects of their volatile release on the observed atmosphere

Ernst:

- How to best distinguish grabens overlying dykes from purely extensional graben in venusian rift system?
- Detailed flow and graben (dyke) mapping of both planitia and younger volcanic centres and determination of relative ages from cross-cutting relationships can constrain the volume vs time release of CO_2 and SO_2. This will provide parameters for improved modelling of the evolution of the atmosphere and to test if Venus could have been Earth-like before it underwent a cataclysmic shift in its environment
- Understanding if LIPs can cause a runaway greenhouse effect that changed Venus from Earth-like conditions to current conditions

Turbet:

DAVINCI, VERITAS, and EnVision will collect data on the surface and atmosphere of Venus which will allow for more accurate models of Venus' past.

Hallsworth:

The data obtained from DAVINCI will constrain the abundance of water in the atmosphere.

6.0 Panel: Phosphine at Venus

Panelists: Giada Arney, Matt Pasek, Clara Sousa-Silva, Melissa Trainer, Colin Wilson, Kevin Zahnle

Moderator: Kandis-Lea Jessup

6.1 Summary

The members of the panel discussed the detection of PH_3 in Venus clouds and the hypothesis of cloud habitability. The opportunities to perform in-situ analysis to detect PH_3, P-bearing species are highlighted in light of future missions and instrument capabilities. The gaps in knowledge of atmospheric chemistry and measurement of cloud aerosols are a cause of potential false positive detection and biotic generation of PH_3 in Venus.

6.2 Summary of presented open questions, recommended next steps

Panel Highlights:

- Currently, very little is known about phosphine spectroscopically. More lab work is needed.
- PH_3 needs high hydrogen pressures to exist, such as in the clouds of Jupiter and Saturn
- PH_3 interacts unfavorably with oxygen environments/metabolisms
- PH_3 is found in anaerobic systems.
- Biosignatures: Is PH_3 a good biosignature?
    - Has a distinct spectrum that distinguishes it from other biomolecules
    - Is quantifiable yet can appear in other molecules
    - PH_3 has its own “false positive” signals that need to be accounted for through further research
- If phosphine is in the clouds, what state would it be in?

High altitudes >>	CO_2+ uv —> CO + O	> photochemistry
	$4PH_3 + 12O$ —> $P_4O_6 + 6H_2O$	> photochemistry
Cloud deck>>	$P_4O_6 + 6H_2O$ —> $4H_3PO_3$	> hydrolysis within cloud
Below clouds>>	H_3PO_3	> evaporation
	PH_3+ $4H_3PO_3$ —> $3H_3PO_4 + PH_3$	> thermal disproportionation
	$4H_3PO_4 + 4CO$ —> $P_4O_6 + 4CO_2 + 6H_2O$	> thermochemistry

Deep atmosphere>> P_4O_6

Surface >> calcium phosphate (apatite)

- Does PH_3 react with H_2SO_4?
    - Does PH_3 dissolve or react? Potential evidence of Solid sulfur trioxides phosphine turning into red phosphorus. At higher temperature, elimination of H_2O also creates more refractory polyphosphates $H_xP_yO_x$ that could protonate.
    - PH_3 may be able to dissolve into H_2SO_4 (must be confirmed experimentally)
    - PH_3 is very insoluble in H_2O but can be protonated in a strong acid
    - Phosphine is extremely poisonous
    - Unlikely to be a gas in the presence of H_2SO_4
- Source of phosphorus in the atmosphere?
    - Winds
        - LMD group in Paris is investigating diurnal variations which are enough to create mesoscale circulation, updrafts over mountains, etc. They have a Venus Climate Database that can be accessed by the community.
    - Volcanism
- If we did confirm PH_3 in Venus, would it be considered a biosignature?
    - Confidence of life detection (CoLD) scale (Green et al. 2021)
        - Level 1: Detection of a signal known to result from a biological activity
        - Level 2: Contamination ruled out
        - Level 3: Demonstration or prediction of biological production of signal in the environment of detection
        - Level 4: All know non-biological sources of the signal shown to be implausible in that environment
        - Level 5: Additional independent signal from biology detected
        - Level 6: Future observations that rule out alternative hypotheses proposed after the original announcement
        - Level 7: Independent, follow-up observations or predicted biological behavior in the environment.
    - More data on Venus' atmosphere and knowledge of PH_3 cycles is required to confidently address if it is produced biotically or abiotically
- If PH3 on Venus were shown to be biotic, what might that mean for life?
    - On Earth it currently isn't certain that PH_3 is generated by life. Life could be making anaerobic environments that are conducive for PH_3 formation.
    - Phosphine on Earth is globally found at $1 ng/m^3$ which is 1000-10000x less than the possible observation on Venus.
    - Redfield ratio states 106:16:1 of C:N:P in marine microorganisms. The biosphere of Venus could be $>10^{14}$ kg C if disproportionation is used to generate biophosphate
    - Speculation: if life is the source of PH_3, it may be extracting energy from disproportionation and conserving the phosphate for biomolecules
- What is the best way to detect PH_3 in the clouds?

- Mass Spectrometry is useful to detect phosphine (g) and other phosphorus species
    - However, PH_3 is found in a crowded part of the spectrum
    - Mass Spectroscopy can also be used to detect ammonia (another suggested potential biosignature)
- DAVINCI's TLS could be used to detect PH_3 and would be more sensitive
    - Looking for community input on its implementation on DAVINCI
- JUICE will fly by Venus and look at bands higher than used by Greaves et al. 2020, but the bands have several PH_3 lines. Ppb to ppt sensitivities depending on look angle
- In the future, a long duration aerial-platform on Venus would be able to take multiple measurements at multiple locations on Venus for longer periods of time.

Future needs/recommendations given within this discussion:

- Redefining habitability and the assessment of biosignatures using CoLD scale
- More lab work on the formation, stability, kinetics of PH_3 are needed.

Key take-aways of this panel:

- Current data does not give a complete picture of the existence of life in Venus
- PH_3 needs anaerobic environments to exist and under high temperatures it has been suggested to dissolve in H_2SO_4 and at low pH can be protonated.
- Confidence of life detection is an example of a progressive scale for communicating and assessing the possibility of life beyond Earth.
- There is still skepticism on the detection of phosphine and phosphine as a biosignature
- More lab work on the formation, stability, kinetics of PH_3 are needed. Furthermore, a better understanding of Venus' environment on spectroscopy is required e.g. how does the temperature, pressure, atmospheric density affect line broadening, shifting, etc.

Relevance to future missions:

- Future missions will provide more data to constrain the potential existence of PH_3 and P-bearing compounds as well as a better understanding of chemical interactions in the atmosphere.

7.0 Panel: Water on Venus

Panelists: John Hallsworth, Chris McKay, Paul Rimmer, Martin Turbet, Michael Way

Moderator: Mark Bullock

7.1 Summary

Water on Venus poses a major challenge to life as we know it, and it is highly unlikely that Earth-like life could persist in the cloud layers given the current conditions. Instead, astrobiologists must target “life as we don’t know it”. Venus may have had liquid water at some point in its geologic history, but the timing and duration of an early ocean on Venus remains a major outstanding question in Venusian planetary science. Future missions, especially DAVINCI, are expected to provide key insights into Venus’s atmospheric evolution and may offer clues to the water loss mystery. Additionally, there exists potential for synergy with exoplanet science as enabled by the space telescope JWST.

7.2 Summary of presented open questions, recommended next steps

Panel Highlights:

- Water activity limitations for life
    - Water activity, osmotic stress, and pH are major challenges for life on Earth. Water activity is the major limiter of life on Venus. Given Venus’ water conditions, non-conventional biochemistry (i.e. life as we don’t know it) is probably necessary for any life to persist.
    - Life on Earth has been presented with issues surrounding low water activity and has not evolved a mechanism to circumvent it.
    - Possible life forms may have evolved alternative mechanisms, such as the use of compartments to move protons through membranes, making them alien to us.
    - Different models by the panelists involving water used different temperature and pressure regimes
- Modeling ancient Venus to determine if it once hosted an ocean
    - Cold start model with slow rotation resulting in surface water.
        - 3 different models have observed this
        - Models use radiative transfer and cloud microphysics to describe atmospheric conditions.
    - Clouds on the dayside would cool Venus by reflecting solar flux while nightside clouds would result in warming.
    - However, there is a high albedo of dense atmospheres due to Rayleigh scattering that is not concordant with predicted calculations.
        - Albedo is determined by cloud presence and water vapor. If models do not start with clouds on day side, then albedos will be different.
    - Clouds evolved from sulphuric acid clouds. It is unclear when in Venus’ history that this happened.

Knowledge gaps, areas of study that would be useful for Venusian astrobiology, and synergy with other topics in planetary science:

- Why can’t life function below 0.585 water activity?

- How can we detect life as we don't know it, i.e., life different from Earth-based models?
- If we can search for hydrocarbon-based life on Titan, we can search for non-water-based life on Venus.
- When did Venus lose its water? At what rate?
- What was ancient Venus' rotation rate?
- How can exoplanet work help inform us about Venus's early history?
- We should still use knowledge of terrestrial life as a partial analog but only to a certain extent.
- Revisit the existing Venus datasets from past fly-bys and missions with new eyes (taking into account that results haven't been calibrated in a Venus-representative chemical environment, simply because the Venus chemical environment was not known when measurement techniques were designed).

Relevance to future missions:

- Future missions (especially DAVINCI) may give better insights into the evolution of Venus' early atmosphere, particularly its water, as the history of water on Venus is currently scientifically contested.
    - If water loss happened later than expected, this has repercussions for cooling of magma oceans.
- JWST should also provide useful constraints for exoplanet science and Venus science.

8.0 Panel: "A Decade of Venus Exploration — A Multi-Agency Perspective" in Dedication to Tommy Thompson

Panelists*:* Lori Glaze (NASA), Lev Zelenyi (IKI), Fabio Favata (ESA), Yoshifumi Saito (JAXA), Tirtha Das (ISRO)

Moderator: Roger Bonnet (ISSI)

Main Points: All groups welcome international collaboration and organization of an interagency Venus exploration group. NASA points to decades of previous international Mars collaborations as possible models for how such interagency cooperation may be successfully implemented. In addition, the panelists recognize the need to increase the capabilities of Earth-Venus communications.

Panel Highlights:

- Dr. Roger Bonnet (ISSI) presented the following questions to jump-start discussion:

1. Can we agree to create a Venus exploration interagency group before the selected missions launch?
2. Is the successful interagency group that was created for the investigation of Halley's comet a good working model for a Venus interagency group?
3. Has COSPAR been approached about providing a venue or an organizational structure for this interagency group?
4. Has ISSI been approached about providing a venue or an organizational structure for an international Venus exploration group?

- All panel members supported future collaboration in Venus exploration and COSPAR 2022 could be a good opportunity to further this discussion. All supported the organization of an international Venus Exploration Group that would contribute to observational strategies, synergies, and to help define open questions. ESA and NASA have already been discussing how to organize collaboration within the selected Venus missions.
- Roscosmos welcomes instrumental contributions from other agencies and is ready to move beyond individual collaborations into the realm of interagency cooperation.
- ESA and NASA are developing coordination that they hope will lay the groundwork for further participation between other space agencies that have selected future Venus missions.
- NASA and ESA announced a joint Venus Science Coordination (VeSCoor) Group and invited other Agencies to join.
- IKI and ISRO expressed interest in joining VeSCoor.
- JAXA currently has no selected Venus missions, but a Venus Exploration Study Group will be created under ISAS to discuss Venus science and to create a Venus roadmap. The international collaborations established with Akatsuki have been fruitful and are encouraged to continue.
- ISRO welcomes international cooperation in the form of payload contributions, scientific collaborations, and mission collaborations in the future. Shukrayaan-1 is in the final stages of approval, and has received contributions from Russia, NASA, and Germany. They are on-track for a 2025 launch.

9.0 Measurements, Instruments, and Mission Concepts to Venus

9.1 Summary

The session consisted of nine presentations (table below) on different topics ranging from mission concepts of in-situ exploration to applications of instruments for detecting atmospheric constituents and updates in the HITRAN database. Venera-D mission updates were discussed as well as the science objectives of the different modules i.e., orbiter, landing module, and atmospheric module. Mission concepts of aerial platforms (e.g., balloons and probes) are put forward to measure the composition of noble gases, trace gases, and perform descent imaging. Methods of detecting life using biocidal destruction of cell walls and optofluidic instruments are proposed for real-time detection of chemical species.

First Author	Affiliation	Talk Title

Vodopyanov K. L.	CREOL, The College of Optics & Photonics, University of Central Florida, USA	*Trace Molecular Sensor Based on Mid-Infrared/THz Frequency Combs*
Simon K.	Impossible Sensing, USA	*Real Time Cloud Composition Profiles with an Optofluidic Instrument*
Sedykh O.	Lavochkin	*Update on Venera-D*
Sasaki S.	Tokyo University of Technology, Japan	*Fluorescence Microscopic Observation of Model Microorganisms Suspended in Sulfuric Acid*
Baines K. H.	Jet Propulsion Laboratory, USA	*Venus Cloud Explorer — Understanding Venus's Habitable Zone (VHZ) via a Long-Lived In-Situ Aerial Observatory*
Bullock M. A.	Science and Technology Corp, USA	*Sustained In Situ Exploration of the Habitability of Venus' Clouds*
Esposito L. W.	LASP, University of Colorado Boulder, USA	*Investigating the Venus Clouds from Balloon and Orbit*
Sorokin V. V.	Research Center of Biotechnology of the Russian Academy of Sciences, Winogradsky Institute of Microbiology, Russia	*Conversion of Living Matter to Inanimate Material as the Method of Detection of Life Signs: Application to Venera-D Mission*
Gordon I. E.	Center for Astrophysics | Harvard & Smithsonian, USA	*HITRAN2020: Deciphering Spectra from the Cytherean Atmosphere*

10.0 Missions to Venus

The talks in this session featured presentations on two upcoming missions to Venus (DAVINCI and EnVision), and information that is relevant to a future Venera-D lander. The three selected upcoming missions, DAVINCI, EnVision, and VERITAS, will address several key questions about the atmosphere of Venus, including information that will be pertinent to the potential habitability of Venus. The last talk discussed potential landing sites on Venus, the types of data that should be obtained at the landing site, and the criteria for a successful lander mission. Below is a summary of the three talks as well as a short summary on VERITAS, Venera-D, and Shukrayaan-1.

10.1 Constraints on Site Selection

The next lander to the surface of Venus, such as Venera-D, should land in a location with broad applicability to the whole of Venus and not somewhere that is unique. A lander should descend somewhere safe, but also in a location that will address key science questions on the surface of Venus. Potential locations of interest include: regional volcanic plains (+canali), volcanic shield plains, shield clusters, lobate plates, smooth volcanic plains, ridge and groove belts. The lander should obtain data on the chemistry of the surface (major/trace elements, stable isotope ratios), as well as investigate surface-atmosphere interactions and the local geologic landforms, such as tesserae. A lander should aim to address the age of the Venusian surface, the composition of the tesserae, and if the Venusian regional plains are comparable to Earths' Large Igneous Provinces.

10.2 Recent NASA/ESA Selections

10.2.1 DAVINCI

10.2.1.1 Launch dates and orbit plan

Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging (DAVINCI) is slated to launch in the summer/fall of 2029 before the decent sphere, DS, will descend into the atmosphere of Venus in 2031. The Carrier Imaging Relay Spacecraft (CRIS) will be collecting data during both flybys as well as relaying data to Earth after the descent of the DS (Garvin et al., 2022).

10.2.1.2 Overview of Science goals & payload

Science Goals:
The science goals of DAVINCI as given in (Garvin et al., 2022) are:
"1. Atmospheric origin and planetary evolution: What is the origin of Venus's atmosphere, and how has it evolved? Was there an early ocean on Venus, and, if so, when and where did it go? How and why is Venus different than (or similar to) Earth, Mars, and exo-Venuses?
2. Atmospheric composition and surface interaction: Is there any currently active volcanism and what is the rate of volcanic activity? How does the atmosphere interact with the surface? What are the chemical and physical processes in the clouds and subcloud atmosphere?
3. Surface properties: Are there any signs of past processes in surface morphology and reflectance? How do tesserae compare with other major highlands and lowlands?"

Payload:
DAVINCI is composed of the DS and CRIS. The instruments on the DS are:
- Venus Mass Spectrometer (VMS)
- Venus Tunable Laser Spectrometer (VTLS)
- Venus Atmospheric Structure Investigation (VASI)
- Venus Descent Imager (VenDI)
- Venus Oxygen Fugacity Student Collaboration Experiment (VfOx)

The CRIS will have:
- Venus Imaging System for Observational Reconnaissance (VISOR)
- Compact Ultraviolet to Visible Imaging Spectrometer (CUVIS)

10.2.2 EnVision

10.2.2.1 Launch dates and orbit plan

EnVision's current launch date is late 2031-2032. EnVision will be in a low-eccentricity, near-polar and low altitude (220-400 km) orbit.

10.2.2.2 Overview of Science goals & payload

Science Goals:

The Science Goals of Envision are given in (https://sites.lesia.obspm.fr/envision/science/):

"1. To characterise the sequence of events that generated the regional and global surface features of Venus, and characterise the geodynamics framework that controls the release of internal heat over Venus history;
2. To search for ongoing geological processes and determine whether the planet is active in the present era;
3. To characterise regional and local geological units, to better assess whether Venus once had condensed liquid water on its surface and was thus perhaps hospitable for life in its early history."

Payload:

- Venus Synthetic Aperture Radar with polarimetry(VenSAR)
- Venus High Resolution Spectrometer (VenSpec-H)
- Venus Ultraviolet Spectrometer VenSpec-U
- Venus Pushbroom Multispectral Imager (VenSpec-M)
- Subsurface Radar Sounder (SRS)
- Radio Science Experiment (RSE)

10.2.3 VERITAS

10.2.3.1 Launch dates and orbit plan

Venus Emissivity, Radio science, InSAR, Topography, And Spectroscopy (VERITAS) is currently expecting to launch in late 2027 (Smrekar et al., 2021a) and will enter a low circular orbit (< 250 km) (Smrekar et al., 2021b).

10.2.3.2 Overview of Science goals & payload

Science Goals:
According to the VERITAS website (https://www.jpl.nasa.gov/missions/veritas) the science goals are:

"1. What are the composition and origin of the major geologic terrains on Venus?
2. Is volcanism there steady or catastrophic in nature?
3. What are the major tectonic processes that shape Venus? Is subduction currently active?
4. What are the size and state of the core? How viscous is the mantle?
5. Does Venus' surface have active deformation and volcanism? Are there signatures of recent volcanism?
6. Are Venus' plateaus like Earth's continents?

7. Is there water deep in the interior of Venus, and does it reach the atmosphere via volcanism?"

Payload:
VERITAS will have two instruments and will also be completing a gravity science investigation:

- Venus Interferometric Synthetic Aperture Radar (VISAR)
- Venus Emissivity Mapper (VEM)
- Gravity Science

10.3 Missions in Development

10.3.1 Venera-D

The Phase A Completion Date is currently slated for February 2023. Venera-D is expected to have an orbiter module (16 instruments), landing module (11 instruments), TAM (3 instruments), aerostatic module, autonomous seismic stations, and autonomous scientific stations. The mission has a variety of science objectives and will investigate numerous aspects of Venus from the atmosphere down into the interior of the planet. For more in-depth details on the mission please see Section 15.3.1 Presenter: Oleg Sedykh (Lavochkin Representative).

10.3.2 Shukrayaan-1

The current launch date according to ISRO is 2025 or 2027. The payload and science goals have not yet been finalized. It is known that it will have a radar as part of its payload.

11.0 Role of Modeling in Venus Exploration

The information presented in the sections below summarize the presentations and various discussions that occurred throughout the workshop.

11.1 Current Knowledge and On-going Work

Numerical modeling has been a critical tool in the exploration of Venus. It has provided potential solutions to unknown questions about Venus using the few data points that have been collected from ground-based observation and *in situ* analysis thus far. These models run the gamut of thermodynamic models, GCMs, geodynamic models, radiative transfer models, etc. Computer simulations have been used to investigate chemical and physical reactions within the atmosphere as well as its interaction with the surface. This informs on the steady state of the atmosphere but is also vital in determining the source of the reactions, whether they are abiological or potentially biological. For example, models investigating sources of enrichment or depletion of compounds in the atmosphere to determine if they signify agnostic biosignatures. There has been geodynamic and geophysical modeling done to assess the evolution of Venus' atmosphere over time. Such models suggest that perhaps Venus is currently between tectonic and stagnant states, and perhaps Venus' atmosphere has been static for some time due to the high surface pressure suppressing volatile degassing from magmatic sources. This has important implications on Venus' past environmental conditions and thus its habitability. Astrophysical processes on Venus, such as bombardment by cosmic rays and solar UV radiation, have also been modeled, and it has been determined that these radiation sources may not be detrimental for putative life in the lower/middle clouds. Finally, several researchers have modeled early Venus to determine if it was once temperate enough to host an ancient ocean. The models imply that Venus' rotation rate would affect the development of clouds, and the presence of clouds play a major role in the formation and stability of an ocean. If Venus was once clement, some models suggest that a cataclysmic event, such as large igneous province volcanism, an impactor, or the triggering of global metamorphic crustal decarbonation, could have initiated a runaway greenhouse effect that transformed Venus into the arid planet it is today.

11.2 Future Goals

Numerical modeling has provided clues for the physical processes that dictated the formation and evolution of Venus, however, additional models are still needed to address the numerous mysteries that remain. For example, there is still much work that needs to be completed on modeling if proposed metabolic pathways could even exist in the atmosphere of Venus. This includes the availability and movement of potential nutrients into and out of the cloud regions, what processes would affect their movement, and the sources of these nutrients, such as (but not limited to) volcanism. Most importantly, further studies need to be completed to understand the maximum possible biomass that could be present, and energy fluxes needed to sustain life in the clouds, if it is even life as we know it. It would be beneficial to recruit modelers from the biology and ecology fields to model potential ecological architectures in the atmosphere of Venus. Additional simulations on lifecycles, reaction rates, and sources and sinks of gases are also crucial to determine if they could exist and furthermore be considered agnostic biosignatures. Many aspects of the hazes of Venus remain a mystery and more models and lab work are needed to understand their physics, and interactions with other gases in the atmosphere. Some of the information required to do some of the listed simulations may not be readily available, and modelers are recommended to collaborate with experimentalists to obtain chemical/physical data.

There have been numerous attempts at using models to determine the possibility of an ancient surficial ocean on Venus. This is a complex issue, and additional modeling using a range of different starting parameters for early Venus are crucial. This includes modeling the formation mechanisms of Venus, its starting water abundance, any potential late delivery of water, early surface temperature, past planetary rotation, addition of any outgassing and resurfacing events, etc. It was discussed several times during this workshop that Venus' past rotation rate has a significant influence on cloud formation and thus the formation and stability of an ancient ocean, and this needs to be examined in more detail.

While models continue to be instrumental in investigating Venus, new data is required to fill in the gaps in knowledge necessary to more accurately simulate Venus. For example, detection and measurements of all the gases in the atmosphere, including various noble gases that can inform on Venus's past, confirming the D/H ratio, collecting and analyzing cloud particles, observing any changes (increases or decreases) of gas over time which could be indicative of a number of atmospheric/geologic processes including potentially active volcanism and ultimately, directly searching for signs of life. New data of the surface will also provide critical information to add to models, such as observing evidence of large igneous province volcanism, aqueous alteration of rocks, and the geochemistry of the surface. This knowledge would help to constrain the different elements that may be exchanged between the surface and atmosphere, as well as provide clues on if Venus may have hosted an ocean. The upcoming missions will be able to elucidate on many of these questions, but some analysis using ground-based telescopes can be completed now.

12.0 Role of Experiments and Fieldwork in Venus Exploration

The information presented in the sections below summarize the presentations and various discussions that occurred throughout the workshop.

12.1 Current Knowledge and On-going Work

Obtaining new data on the atmosphere of Venus can be challenging, and *in situ* data of the clouds has not been collected in over 40 years. As the community waits for new data that will be collected by the upcoming missions, researchers have been contemplating ways to address questions on Venus's habitability through experiments and fieldwork. Several researchers throughout the workshop addressed the desire to study the development and evolution of extremophilic microbes in simulated Venus conditions, however, as of yet very little has been done in this regard. This includes experiments with microbes that have different potential metabolic pathways and in limiting conditions present in Venus' environment such as low water activity and highly acidic pH. In recent years there has been an increase in the availability of Venus simulation chambers, but most have not, if any, been used for astrobiological studies. It was importantly noted, however, that regardless of if terrestrial life survives in the simulated Venus conditions, these experiments cannot act as a confirmation that life does/could exist on Venus. If there is life on Venus, it may not be similar life as we know it here on Earth and thus is important to differentiate what experimentalists are looking for. For example, some studies, unrelated to Venus, have investigated different types of genetic code, but it is not known what type could have developed at Venus.

The stratosphere of Earth has been discussed as a possible analog to the Venusian clouds, at least with respect to life in the clouds. Several researchers discussed the possibility of investigating Earth's stratosphere to better understand potential life cycles of putative life on Venus. However, there are several challenges to such an investigation. While microbial life is found throughout the atmosphere, collecting non-dormant samples has proven challenging, in addition to developing cultures for future study. Additionally, completing *in situ* analysis is a challenge because it requires sensitive instruments and quick analysis, and the samples may require prior preparation. Finally, as mentioned before, the microbes collected and studied are likely not representative of those that may be found in Venus' clouds, and thus results must be viewed critically/cautiously. On Venus, putative life may move between different environmental states, such as between the different layers of the clouds, which may affect their current state (dormancy, reproduction, etc) in their life cycle.

12.2 Future Goals

There is plenty of experimental work that needs to be completed to develop an understanding of the habitability of Venus. Experiments on the development and survivability of microorganisms under simulated Venus conditions are greatly underexplored. Further work studying if life can survive on the chemicals available in the atmosphere on Venus, and the different potential metabolic pathways it may utilize are required. Investigations on the limiting factors for life, such as water and pH, are also crucial. Experiments investigating the habitability and adaptability of terrestrial life in the simulated environments of other planetary bodies have already been conducted. Similar studies should be completed for the Venus environments with appropriate biological samples for that environment. While extremely challenging, researchers should also investigate other potential avenues of biochemistry since putative life at Venus may be dissimilar to life on Earth. This direction of research may even affect the definition of life as we know it. Experiments are also recommended to understand how microorganisms utilize phosphorus in the context of synthesizing phosphine. Lastly, but most importantly, it is critical to investigate abiotic chemical reaction pathways to further understand reactions in the atmosphere. This will improve the understanding of Venus' atmosphere and, furthermore, will help differentiate between biotic and abiotic signals. Crucially, experiments testing the durability and accuracy of equipment/instruments that may be sent to Venus in simulated Venus conditions are required to confirm that they can operate suitably in its hostile environment. Experiments should be completed in Venus simulation apparatuses which have become more widespread and available in recent years. Simulating the Venus cloud layer can be less challenging than the surface since the temperature and pressure are similar to conditions on Earth.

Future experiments studying microbial life in Earth's aerobiosphere may inform on putative life in the clouds of Venus. Currently, most of their life cycle remains a mystery, including if they are active or dormant at high altitudes. It is not even known if they can reproduce in these conditions since this process has yet to be observed *in situ*. There needs to be an effort to promote fieldwork opportunities and provide funding sources to collect and study microbial life on Earth, as well as to develop methods and instruments that can be useful in the field and perhaps even sent to Venus in the future.

Finally, many details of the atmosphere of Venus still remain elusive hindering the ability to experimentally investigate terrestrial life in Venus cloud-like conditions The only way to remedy this issue is to complete more ground-based observations and to collect *in situ* data on Venus.

13.0 Summary of Workshop Outcomes

13.1 Summary

The Workshop provided an opportunity to discuss the habitability of Venus from a biological, chemical, astrophysical, and geologic perspective. Venus' past, and its evolution to its current state, was a frequent discussion point throughout the workshop. This topic is crucial in ascertaining if Venus had conditions that were conducive, not just for the formation of life, but for it to thrive on Venus. These questions included if Venus had an ancient ocean, if the temperature on Venus was once clement, what was the composition of the atmosphere in the past, and did Venus have global plate tectonics. The workshop participants also deliberated on if Venus has the right conditions today to provide for life. Such discussion points included if there is enough water in the atmosphere today to support microbial life, if radiation could be a problem for their survival, and what nutrients and energy pathways are they utilizing to sustain themselves. Our lack of knowledge about microbes in Earth's stratosphere was also addressed, and the need to further investigate this environment through labs and fieldwork to inform on microbial life cycles on Venus. However, several people noted that we should also not allow Earth life to dictate how we investigate Venus life since they are vastly different environments which would have promoted vastly different biological adaptations. A key focus during the workshop was the methods and instruments necessary to detect life. It was agreed upon that *in situ* analysis of the atmosphere is fundamental to further understand Venus as a potentially habitable planet. There were *in situ* instruments proposed that could directly look for organic components in the clouds, and instruments that could search the atmosphere for agnostic biosignatures. In the meantime, there were calls for more experiments studying microbial life, to further enhance numerical models on Venus' past and current state, and to continue to utilize Earth-based telescopes to investigate Venus' atmosphere. Similarly to the Venera-D Workshop in 2019, a second Special Collection on Venus Habitability is currently planned to be published in the journal Astrobiology in the near future.

Session	Summary
Present Habitability of Venus	The researchers provided presentations that focused on the challenges, based on life as we know it, and conditions that putative life would face in the clouds of Venus, such as (but not limited to) low pHs or acidic conditions and decreased water availability. Presenters discussed the effect of radiation and solar energy at Venus on putative life, with it likely not challenging to life, but enough photonic energy potentially being present allowing for round-the-clock photosynthesis. In addition, it was described that chemosynthesis may also be possible as a source of energy. Overall, presenters stressed the need for further laboratory studies including studies of microbial life in Earth's clouds, model development to understand Venus' rotation and potentially habitable past, and various measurements/sample collections for future in-situ missions, including development of life-detection instruments.

Putative Origins of Life and Past Habitability of Venus	This session discussed parameters that are fundamental for the development of life and characteristics that could be biosignatures. Life on Venus may be composed of a biochemistry that is not found on Earth yet shares a universal agnostic biosignature of biopolymers composed of informational units that have the same size and structure within a supporting backbone with a repeating charge. It was also discussed that cosmic rays from supernovae may be an evolutionary pressure for homochirality, and thus homochirality may be a biosignature. The current understanding of life is that it may need liquid water to develop. Modeling of early Venus shows that it may have hosted liquid water for 0.9 Gyr after which metamorphic crustal decarbonation led to the release of CO2 resulting in a runaway greenhouse effect. This period in time may have been conducive for the formation of life, perhaps even the development of stromatolite-like structures. Stromatolites are created by photosynthetic organisms and are considered the oldest fossils, still living, on Earth. They have distinct morphology and understanding their stability in simulated Venus conditions may inform the physical and chemical features that need to be considered for investigation on Venus.
Biosignatures at Venus	This session discussed various biosignatures that are indicative of life. Major potential biosignatures include detecting concentrated geochemically distinct scarce elements in discrete metastable entities, the favoring of lighter isotopes in chemical structures, and homochirality. Another possible biosignature, ammonia, was discussed, and it was hypothesized to be synthesized by microbial life in Venusian clouds in order to overcome acidic environments. Three distinct metabolic pathways were also investigated to explain SO2 depletion in the clouds, but it was found that none matched measured abundances of SO2, CO, and H2S. There was an update on the detected phosphine signal on Venus where the presenter defended the reliability of phosphine detection by explaining the robust techniques used to authenticate its identity, as well as refuted common misconceptions that challenged the legitimacy of its detection.
Evolution of the Venusian Atmosphere	This session addressed geologic events which could have influenced the evolution of the Venusian atmosphere and characterized the limits of habitability within the atmosphere. Clouds and rotation rate may have played a key role in Venus' climate by contributing to the formation/loss of surface liquid water in Venus' geological history. Venus is considered to be an "episodic lid" planet that lacks plate tectonics and may be in transition between tectonic and stagnant states. Venus has undergone extensive resurfacing events that have generated a thick outgassed atmosphere with high pressures suppressing outgassing and influencing internal temperatures which affects surface mobility. Large Igneous Provinces (LIPs) volcanism in the past may have led to a dramatic release of CO2 resulting in global runaway greenhouse warming. The current high atmospheric pressure may control the rate of degassing of SO2, H2O and CO2 from erupting magma. Thus, the current Venus atmosphere may be a "fossil atmosphere", largely inherited from a previous ancient epoch in Venus history. Venus' clouds are considered to be inhabitable when considering the limits of known Earth life. Direct observations and models imply that

	Venus' atmosphere is dry, with various levels of acidity and with clouds' water activity between 0.01-0.0001 at 80-100% sulfuric acid concentration.
Panel: Phosphine at Venus	The members of the panel discussed the detection of PH3 in Venus clouds and the hypothesis of cloud habitability. The opportunities to perform in-situ analysis to detect PH3, P-bearing species are highlighted in light of future missions and instrument capabilities. The gaps in knowledge of atmospheric chemistry and measurement of cloud aerosols are a cause of potential false positive detection and biotic generation of PH3 in Venus.
Panel: Water on Venus	Water on Venus poses a major challenge to life as we know it, and it is highly unlikely that Earth-like life could persist in the cloud layers given the current conditions. Instead, astrobiologists must target "life as we don't know it". Venus may have had liquid water at some point in its geologic history, but the timing and duration of an early ocean on Venus remains a major outstanding question in Venusian planetary science. Future missions, especially DAVINCI, are expected to provide key insights into Venus's atmospheric evolution and may offer clues to the water loss mystery. Additionally, there exists potential for synergy with exoplanet science as enabled by the space telescope JWST.
Panel: A Decade of Venus Exploration — A Multi-Agency Perspective	All groups welcome international collaboration and organization of an interagency Venus exploration group. NASA points to decades of previous international Mars collaborations as possible models for how such interagency cooperation may be successfully implemented. In addition, the panelists recognize the need to increase the capabilities of Earth-Venus communications.
Measurements, Instruments, and Mission Concepts to Venus	The session consisted of different topics ranging from mission concepts of in-situ exploration to applications of instruments for detecting atmospheric constituents and updates in the HITRAN database. Venera-D mission updates were discussed as well as the science objectives of the different modules i.e., orbiter, landing module, and atmospheric module. Mission concepts of aerial platforms (e.g., balloons and probes) are put forward to measure the composition of noble gases, trace gases, and perform descent imaging. Methods of detecting life using biocidal destruction of cell walls and optofluidic instruments are proposed for real-time detection of chemical species.
Missions to Venus	The talks in this session featured presentations on two upcoming missions to Venus (DAVINCI and EnVision), and information that is relevant to a future Venera-D lander. The three upcoming selected missions, VERITAS, DAVINCI and EnVision will address several key questions about the atmosphere of Venus, including information that will be pertinent to the potential habitability of Venus. The last talk discussed potential landing sites on Venus, the types of data that should be obtained at the landing site, and the criteria for a successful lander mission. In this section there is also a summary of the three talks as well as a short summary on VERITAS, Venera-D, and Shukrayaan-1.

13.2 Actions and Next Steps

13.2.1 In-situ instrumentation

- Community input on mass spectrometer (VTLS) for DAVINCI
  - On VTLS for 4th laser channel
  - VTLS is a tunable laser spectrometer on DAVINCI being developed at JPL by Chris Webster et al.
- Community action: let's fly an aerial platform in the cloud-level of Venus to characterize its chemistry and habitability!
- Development and testing of instrumentation for life detection under Venus conditions should be taking place.
  - Look into the type of instrumentation needed to be developed and lab tests (using facilities such as NASA Glenn Chamber GEER, which simulate Venus atmospheric and surface conditions) required to detect life (atmosphere and surface) under Venus conditions.
  - Suggestion to detect living form as a biosystem. A cell system closed from surrounding environments. Talk from Dmitry Skladnev is useful for this idea.
- Although challenging (based on orbit dynamics/engineering aspects), has any consideration been given as to whether we could design an Venus atmospheric return sample mission to return a sample of atmosphere from Venus to Earth for study in laboratories?
  - Atmosphere sample return to most usefully settle the life question
- What are the measurements needed to get at the question about the composition of aerosols?
  - D/H ratio, water measurements, oxy-acids, phosphate, sulfate (what form is it)
  - A document needs to be developed to send to NASA
  - Mogul et al., in Astrobiology 2021: " Looking ahead, mass spectrometers amenable to sampling vapors of sulfuric and phosphoric acids (Wurz et al., 2012; Ren et al., 2020), ionized chemical species (Baines et al., 2021), and/or sublimated salts (Hänni et al., 2019) could help in detailing the acid, conjugate base, and water abundances in the aerosols, and thereby directly address the potential for habitability in Venus' clouds."
- To understand the water loss, we need a good interface of convection between the neutral atmosphere and the ionosphere (ionosphere is normally the start of thermosphere due to absorption of solar energy)
- Regarding aerial platforms, inclusion of UAS platforms as discussed by Mark Bullock and others.
  - Also stress the utilization of NASA SBIR program to develop new technologies for Venus exploration by small businesses
- For phosphine we need terrestrial studies to understand how it can be biologically produced and by which microorganisms

13.2.2 Community and Agencies

- Community letter on why we should search for life at Venus vs Mars and why it's not a futile effort
  - Could create a roadmap on Venus astrobiology
    - A group needs to be formed to develop this roadmap which can then be shared with the agencies and the community.

- ESA and NASA have proposed developing a Venus Science coordination group
    - Would give a good opportunity to coordinate amongst the community
        - Once the coordinating group is formed it would be good to share this document with them
    - Continuing dialogue should occur with Venera-D
        - A reiteration of the JSDT may be useful
    - A lot of these questions/ideas can be addressed/shared in the new interagency collaborations
    - Action taking place already to do interagency dialogue
- A second interagency roundtable could take place at the COSPAR meeting

13.2.3 Information needed about Venus

- Oleg shared three points related to the roadmap of Venus astrobiology
    - To finalize the roadmap it is important to be in contact with all representatives of the missions to Venus and make conclusions from the actual situation, proposing some kind of unifying research scheme.
    - If we are planning astrobiological experiments in missions to Venus, then we should consider such experiments that will give us reliable data on the presence of life in the clouds. The detection of various simple molecules that may be associated with the activity of living organisms are indirect signs of life. They are very important, since we can get detailed data on chemistry, and therefore, calculate the thermodynamics of the corresponding biological processes and suggest which processes can take place and which cannot. I think that we need to also have experiments related to the detection of the presence of living organisms themselves as we know them on Earth, as closed biosystems, cells, with a certain organization.
    - At the first workshop on Venera-D mission, we created different working groups dealing with different aspects of Venus exploration like geology, physics of atmosphere, landing sites, habitability. Since now we have so many excellent data, ideas, concepts within astrobiology of Venus, could it be reasonable to create a similar working group structure within the direction of astrobiology (or habitability) of Venus? That could make cooperation within specific areas closer with periodic contacts between members of the working groups, initiate joint topic papers?
- Many support a reanalysis of the old datasets from Pioneer, Magellan, Veneras, Vega
    - An archive would be good idea
    - IKI has received this request and they are looking for it
        - Important to science and to science history
    - Re-examination of the Venera/Vega lander datasets beyond imaging to include the spectrophotometry, XRFS, gamma-ray data, and the electrical properties and mechanical properties
    - A formal request should be made to revisit these old Venus results will help IKI to help them get funding for doing this.
- Spectroscopy community would like a wish list from Venus scientists including what needs to be provided to properly interpret spectra at different wavelengths.
    - Setting up a modeling workshop to get these wish lists itemized for the next level of lab work for the next missions
    - It was mentioned that the VEXAG technology SAW has been discussing another modeling workshop possibly in 2023

- Modeling of what's biologically possible and impossible is needed if we're going to invoke life for a lot of the observations we are trying to explain.
  - Examples: What amount of biomass and fluxes would you need for life?
  - Understanding minimum limits on population sizes and functional ecological architecture for a sustainable Venus biosphere would be very interesting.
- It was suggested that there could be continued broad reporting of advancements in instruments and technologies and coordinated advocacy for maturation of selected or future missions.

13.2.4 Terrestrial based models

- Important to get GEER and other kinds of similar chambers "certified for biology"
  - It can currently replicate the physicochemical conditions of the atmosphere
  - Adjustments being made to prepare it for other Venus characteristics including chemistry
  - This won't be just GEER but rather develop further instrumentation.
  - JPL is developing a Venus Cloud Simulator specifically designed to simulate the conditions in the cloud layer
- Important to get information on optical constants and a database on a wide range of environments of what we might see out there. Looking for what may be due to life and what's not due to life.
  - Making sure we have experimental, model, instrumental work done to be able to account for things like intersecting droplets, etc. How can we adjust our credence about the old data in light of the new data by connecting them?
- Discussions need to take place on whether we need to focus on life as we know it or not.
  - How we're defining habitability is also dependent on what we know about the habitability of Earth life

14.0 References

Venera-D: Venus Cloud Habitability System Workshop

November 29-December 3, 2021

Program

Times listed are Universal Time (UTC). Time Zone Converter

2:00 p.m. UTC

6:00 a.m. PST
8:00 a.m. CST

9:00 a.m. EST
3:00 p.m. CET
11:00 p.m. JST

Monday, November 29, 2021

2:00 p.m.	Present Habitability of Venus

Tuesday, November 30, 2021

1:30 p.m.	Panel: A Decade of Venus Exploration — A Multi-Agency Perspective
3:10 p.m.	Missions to Venus
4:10 p.m.	Measurements, Instruments, and Mission Concepts to Venus (Part 1)

Wednesday, December 1, 2021

2:00 p.m.	Measurements, Instruments, and Mission Concepts to Venus (Part 2)
4:20 p.m.	Poster Lightning Talks

Thursday, December 2, 2021

2:00 p.m.	Putative Origins of Life and Past Habitability of Venus
3:30 p.m.	Biosignatures at Venus
4:45 p.m.	Panel: Phosphine at Venus

Friday, December 3, 2021

2:00 p.m.	Evolution of the Venusian Atmosphere
3:55 p.m.	Panel: Water on Venus
4:55 p.m.	Conclusion

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15.0 Summaries of Presentations

15.1 Day 1

15.1.1 Present Habitability of Venus

Presenter: Pierre Amato

Talk name: Terrestrial Hints for Prospecting Microbial Life in Venus Clouds

Summary: Amato discussed studies of Earth aerobiology and how these investigations may be applied to investigate communities of putative life in the clouds of Venus. Amato specifically mentioned various requirements for studying life in the clouds, such as the need for sensitive measurements and detailed analyses.

Talk Highlights:

- We can apply knowledge from Earth aerobiology to investigate potential microbial life in Venus' clouds.
  - On Earth there have been experiments to capture microbes in the clouds and aerosols
  - Earth clouds can be sparse, 1 cell every 10,000 droplets
- Requirements for investigating microbes in the clouds
  - Need for sensitive and specific methods
    - Signal amplification
      - Cultures, q(PCR), MDA
    - Analysis after treatment
      - Flow cytometry/fluorimetry, luminescence
    - Direct analysis
      - Flow cytometry/fluorimetry, mass spec
  - Offline analysis
    - Allow analysis of large sample volumes, preconcentration
    - Need for accumulating samples
  - Online analysis
    - Need for high throughput analysis (thousands of particles)
    - Highly sensitive direct method required

        - Problems with specificity (false positives)
        - Possibility of derivation signals (add stain, reagent, etc)
    - Certain bacteria get enriched/depleted in precipitation versus their source cloud
        - Contribution of local v. distant sources
        - Partitioning possibly related with biological traits
    - Functioning of cloud communities
        - Metabolic functioning in bacteria is largely oriented toward the fight against oxidants, cold, osmotic shock, etc
        - Probably utilization of C1 compounds (formaldehyde, methanol, etc)
        - Elevated binding and transmembrane transport
        - Transcription/translation activities: maintenance of metabolic activity
        - Lipid modification in membranes
- Potential microbes in Venus' clouds likely has a lower diversity than in Earth's clouds
    - Due to acidic and extreme terrain and restriction of life to only the clouds
- There's likely a higher biomass due to a permanent fight against gravity that results in shorter generation times relative to residence time
- Specific trophic modes (acidophiles, autotrophs)
- The microbial activity likely has an influence on the environmental chemistry; which traits contribute to this may be more obvious on Venus

The talk relates to the session goals in the following ways:

Amato made some considerations about potential microbial life in Venus' clouds according to accumulated knowledge from Earth aerobiology and comparing Earth and Venus' atmosphere. This in addition to the influence that living microbes may have on atmospheric processes.

Future needs/recommendations given within the talk:

- Choose online or offline analyses for investigation of Venus' clouds
- Select a search object (cells / molecular biomarkers / imprints attesting of biotic processes)
- Understand if it is possible to collect/accumulate/incubate samples from Venus' clouds and if biological assays are feasible and conceivable in given conditions
- Try to simply attempt direct bulk culturing of Venus' microbes in cloud samples if Venus' clouds indeed harbor life that persists
- Calculate the minimal necessary population and growth rate for persistence vs physical turnover
- Search for specific biological traits that would lengthen cloud droplet residence time and/or favor rapid spread among droplets conceivable
- Think of any known chemical characteristic unexplained by pure abiotic processes and that could attest of biological processes

Key take-aways of the talk:

- On Earth the atmosphere is a vector between terrestrial and atmospheric ecosystems, not a reservoir like on Venus.
- Life is present in the clouds/aerosols of Earth. Though sparse, there are methods to capture and study them
- Earth has higher microbial diversity with low cloudborne biomass while Venus most likely has lower microbial diversity (if life is present) due to ecological selection and higher biomass due to physical constraints such as gravity

Ways in which future missions may impact the conclusions of the talk, as defined by the speaker:

- We can understand more about potential microbial life in Venus' clouds if future missions will answer the following questions:
  - How fast can elements and matter cycle through Venus' atmosphere? What is the time scale of physical cycles?
  - Is there sufficient turbulence/dynamics to spread biomass among droplet microenvironments?
  - Is there any expectable spatial structuration of physico-chemical conditions? (hotspots of habitability?)

Presenter: Oleg R. Kotsyurbenko

Talk name: Astrobiology of Venus: Basic Insights and Prospects (Application to Venera-D Mission)

Summary: Kotsyurbenko described the challenges to putative Venus life, specifically the lack of water, in addition to how putative life and the environment may be part of a geochemical cycle. The presenter also acknowledged various studies needed to be made to understand the possibility of life on Venus, some studies which may be done on Earth.

Talk Highlights:

- Current challenges for astrobiology at Venus
    - Extreme conditions in Venusian clouds
        - Low water activity (lower than limit for terrestrial organisms)
        - Low pH
    - Possible detection of phosphine and its sources on Venus
    - Absence of water on ancient Venus
    - Feasibility of biogeochemical cycles
        - Aerogeochemical lithoautotrophic life in Venusian clouds
            - Sulfur and iron centered metabolic pathways?
        - How to maintain biomass?
- Universal principle of systems approach needs to be applied in order to understand sustainable development of biological life
- Did life originate at the surface, the atmosphere, or from space (panspermia)?
- Possible methods for life detection
    - In situ detection of biomacromolecules
    - In situ microscopy
    - In situ detection of key functional molecules (pigments, enzymes, fatty acids, amino acids, etc)
    - Indirect detection of biomarkers and biosignatures
    - Assessment of the possibility for the existence of trophic microbial interactions and biogeochemical cycles
- Incorporation in geochemical cycles is an important condition for the stable existence of life on a planet

The talk relates to the session goals in the following ways:

- In the latter half of the 20th century, hypothesis regarding biological molecules in the clouds of Venus began to emerge and grew increasingly more sophisticated to include hypothesis about photosynthetic pigments, acidophilic sulfate reducing chemotrophs, thermal acidic sulfur dependent phototrophic organisms, sulfur allotropes, and UV radiation dependent biochemical cycles.
- The presentation discussed some challenges to possible life on Venus and what needs to be considered for it to survive (feasibility of biogeochemical cycles). In addition, the presenter listed a few methods of detection for life.

Future needs/recommendations given within the talk:

- Cumulate a modern concept of the environment
    - Include new types of ecosystems such as the aerogeochemical cycle

    - Include extreme survival capacities of hypothetical microorganisms unknown for terrestrial organisms on Earth
- Methods of detection of life
    - In situ detection of biomacromolecules
    - In situ microscopy
    - In situ detection of key functional molecules (pigments, enzymes, fatty acids, amino acids, etc)
    - Indirect: detection of biomarkers and biosignatures
        - Phosphine
    - Indirect: assessment of the possibility for the existence of trophic microbial interactions and biogeochemical cycles

Key take-aways of this talk:

There are many challenges for life to adapt and thrive in the atmosphere of Venus. However, there are ways for life to adapt to Venus conditions. Biomass maintenance can be provided by the turnover of bioelements and their cycling which in turn can be provided by biogeochemical activity. The principal difference between Earth and Venus is the possibility of transfer of surface microbiota to the clouds on Earth while a closed system is expected on Venus. Future observations (in situ and indirect) are very important to determine if Venus harbors life.

Ways in which future missions may impact the conclusions of the talk, as defined by the speaker:

- Methods of detection of life
    - In situ detection of biomacromolecules
    - In situ microscopy
    - In situ detection of key functional molecules (pigments, enzymes, fatty acids, amino acids, etc)
    - Indirect: detection of biomarkers and biosignatures
        - Phosphine
    - Indirect: assessment of the possibility for the existence of trophic microbial interactions and biogeochemical cycles

Presenter: Dirk Schulze-Makuch

Talk name: Habitability challenges in the Venusian clouds

Summary: Schulze-Makuch presented an overview of how the Venus environment has changed with respect to habitability. It was acknowledged that putative life is facing extreme challenges but it was also mentioned that some forms of life and metabolisms may be able to withstand these challenges and they should be investigated in laboratory experiments. Finally, Schulze-Makuch mentioned the usefulness of the upcoming missions but also stressed that other measurements are needed/desirable.

Talk Highlights:

- Venus was likely habitable in the distant past and it could have had a thriving biosphere on its surface. Later on, as the surface became uninhabitable, life could have possibly retreated to the atmospheric habitat under directional selection
- Search for life is limited to an ecosystem not a single species or organism
- Energy cycling between phototrophs and chemotrophs is likely Challenge to life on Venus
- <u>Chemoautotrophic metabolism carried out by sulfate or metal reducers</u>
    - It obtains energy by reducing sulfur dioxide to either hydrogen sulfide or carbonyl sulfide
    - These reactions would explain the low concentration of carbon monoxide and the atmosphere and the trace amounts of hydrogen sulfide and carbonyl sulfide
- <u>Phototrophic metabolism</u>
    - This metabolism allows for the conversion of some of the hydrogen sulfide to sulfur which could then be used as protection against UV radiation and could also possibly produce water
- Adaptation to UV -radiation
    - S8 could work.
        - Thermally stable and nonreactive with sulfuric acid
        - Absorbs strongly in UV wavelengths and re-emits in visible
        - Microbes could deposit elemental sulfur on cells to convert UV radiation to EM frequencies usable for photosynthesis
- Investigate microbial adaptation mechanism to hyperacidity, low water activity, and lack of trace metals
    - Deliquescence
- Test selected acidophilic microbes how far they can adapt from one generation to the next to higher and higher sulfuric acid concentrations
- Mode 3 particle retrieval mission to Venus
    - Mode particle with largest diameter.
    - Present in lower cloud deck
    - Non-spherical, unique from other cloud particles, and composed of non-absorbing material coated with sulfur acid

The talk relates to the session goals in the following ways:

- Could life on Venus adapt to current conditions in the clouds
    - Explore the possibility that life that arose/transported to Venus adapted to the clouds from an earlier ocean

    - Assuming there was liquid water early in its history, the descendants of early life forms on Venus may have adapted to the increasingly warm dry in acidic conditions through selection
    - The organisms expected to find on a hot early ocean on Venus are likely to have the same metabolic processes of phototrophic thermophilic microbes present on early Earth

Future needs/recommendations given within the talk were:

- The claimed presence of phosphine is extremely important for the possible detection of life
    - Critics claim that the phosphine is misdetected sulfur dioxide
- Others re-examined mass spectral data and found phosphine among other chemical compounds
- Detecting phosphine in the IR range as well as diphosphine as an intermediate product in the photolysis reaction of phosphine to phosphorus and hydrogen may help resolve the debate over the presence of phosphine
- Test selected acidophilic microbes how far they can adapt from one generation to the next to higher and higher sulfuric acid concentrations
- Investigate microbial adaptation mechanisms to hyperacidity, low water activity, and the lack of trace metals

The key take-away of this talk was:

- Venus was most likely habitable in its past and could have had a thriving biosphere on its surface. as the surface became inhabitable life may have retreated to the atmosphere
- No known life on Earth has demonstrated survival in environmental conditions present in the lower cloud deck
- However, many examples of adaptability of life and Venusian life exists, thus the search for life should not be limited to Earth's parameters
- The detection of phosphine needs to be further examined before it can be confirmed
- More lab experiments need to be conducted to test life’s resistance to stress is present in the clouds of Venus such as low water activity and hyper acidity
- Newly planned mission will provide important insights and constraints present in the Natural History of Venus. However, a mission dedicated to examine mode 3 particles would be even more astrobiologically important

Ways in which future missions may impact the conclusions of the talk, as defined by the speaker:

- Davinci+, Veritas, Envision and Venera D will help explore the geological past and the Natural History of Venus
- A mission solely dedicated to study mode 3 particles to reveal their interior composition would be of great importance
- Mode 3 particle retrieval mission to Venus has been proposed before

Comment from Q&A:

1) Pigments (Bchl b, carotenoids) that are predicted for the phototrophs in Venus clouds and possibility of their remote detection

Presenter: David Grinspoon

Talk name: Gaia on Venus: Planetary-Scale Considerations of Habitability

Summary: Grinspoon discussed using alternative criteria for habitability, focusing on geological and chemical activity and how these planetary characteristics are contributing to a biosphere, noting that Venus has similar properties to Earth. Grinspoon also presented various questions that should be addressed with respect to Venus habitability, primarily focusing on Venus' past.

Talk Highlights:

- Life as a planetary property - the life on Earth functions as a single organism which maintains environmental conditions necessary for its survival. (Gaia hypothesis, 1960s by Lovelock and Margulis)
- Life is a planetary scale phenomenon with a cosmological lifespan ("Living Worlds Hypothesis")
- Sustained and vigorous geochemical cycling will support the evolution of a robust biosphere
- Disequilibrium atmospheric states have emerged as the primary biosignature for exoplanets
- Clouds and climate balance are likely being actively maintained by fluxes of volcanic gases and reaction/diffusion of atmospheric gases with surface minerals on Venus
- Earth and Venus possess the general properties of inhabited planets (an atmosphere with signs of flagrant chemical disequilibrium, solar driven chemical and dynamical cycles and active, internally driven cycling of volatile elements between the surface, atmosphere and interior)
- Key exploration questions:
    - History of resurfacing: Has Venus been continuously active?
    - What are the fluxes of gases between interior/surface/atmosphere and cloud?
    - Are clouds maintained by an active sulfur cycle involving outgassing and surface reaction/diffusion of gases?
    - Have clouds existed continuously?
    - What were the conditions of the clouds at the time they coexisted with the last oceans?
    - Was Venus ever oceanic and for how long?
- Life on Earth exists at the inner surface between two powerful and permanent convective heat engines
    - This is not just lucky but an essential condition for a biosphere
    - Life is driven by the internal convection as well as the external convective atmosphere
    - The only other planetary body in the solar system where this condition is met is on Titan and Venus
    - "if life needs an active planet with continuous sources of energy and nutrients and is less picky about its chemical choices than we have imagined then Venus may be the best hope for other life nearby"

The talk relates to the session goals in the following ways:

The alternative criteria for habitability (vigorous geological and chemical activity instead of presence of liquid water and physical conditions which overlap those found on Earth -T, P, pH, etc.) was reviewed in the talk. The talk also focused on what is life and if a planet could be considered to be alive because it is an interconnecting web of lifeforms.

Future needs/recommendations given within the talk were:

- Crucial to understand sources of disequilibrium in Venus atmosphere
- Answer the following questions:
    - History of resurfacing: Has Venus been continuously active over geologic time?
    - What are the fluxes of gases between interior/surface/atmosphere and cloud reservoirs?
    - Are the clouds maintained by an active sulfur cycle involving outgassing and surface reaction/diffusion of gases? What is the equilibrium state of surface minerals?
    - Have the clouds existed continuously?
    - What were the conditions of the clouds at the time they coexisted with the last oceans, and what has been the trajectory of cloud conditions over time?
    - Was Venus ever an oceanic world and for how long?

Key take-aways of this talk:

- Earth may be considered one whole lifeform due to the interconnectivity of the entire planet, from the interior to the surface to atmosphere to the organisms that inhabit it.
- If life needs an active planet, with continuous sources of energy and nutrients, then Venus may be the best hope for other life nearby.
- Alternative criteria for habitability
    - the living world hypothesis treats life as a planetary scale phenomenon with the cosmological lifespan
    - sustained and vigorous Geo chemical cycling will support the evolution of a robust biosphere, requires internally driven geological activity
    - uniquely vigorous geological and chemical activity is key for life

Ways in which future missions may impact the conclusions of the talk, as defined by the speaker:

- Future missions will help to know more about continents, volcanic history, subduction and heat flow:
    - Does Venus have Earth-like continents that formed in the presence of water?
    - Is volcanism steady, like Earth's, or catastrophic, implying episodic, past tectonics?
    - Is there active subduction? Did plate tectonics on Earth start the same way?
    - What is the derived global heat flow and does it prohibit the formation of plate tectonics?

Comments from Q&A:

During the after talk discussion it was proposed to detect dead microorganisms raining out from time to time by surface isotope fractionation (in case of existence of aerial biosphere and its coupling to the geochemical cycle); the residence time and multiplication of eventual microbes in droplets were debated.

Presenter: Diana Gentry

Talk name: Aerobiospheres and Planetary Habitability: Considerations from Earth to Venus and Beyond

Summary: Gentry presented on various studies on terrestrial aerobiology and how knowledge from these studies may be applied to studying putative Venusian aerial life, including the requirements for a stable aerial biosphere. It was mentioned that Earth's stratosphere may be a good Venus analogue to study, however it was also stressed that while the terrestrial atmosphere is full of life, it is mostly dormant.

Talk Highlights:

- Earth's atmosphere is full of life but most of it is dormant.
    - Dormancy not indefinite; damage accumulates
    - Entering and exiting dormant state has a high cost
    - Microorganisms on Earth that have adapted to desert lake environments by entering dormant states have demonstrated about 90% loss of their population
- The extremes of survival that's easy to measure in a lab it's not the same thing that's needed for our biosphere to be stable in the long term.
    - Survival v thrival
    - Sparse biospheres are vulnerable to rare catastrophes
- Biosphere stability: population growth must outpace population loss
    - Airborne duration is affected by gravity, air density, viscosity, turbulence, etc
    - Fast microbe reproduction is affected by low nutrients, low energy, periods of inactivity
- Short- & long-term variability of conditions matter, variability can itself be a stressor.
- Earth's atmosphere as a whole in terms of bulk measurement is below what's considered to be habitable from a perspective of solely just water activity
- Earth's stratosphere is better Venus analogue
    - Relatively isolated
    - Overall low water content (ψ=-1.5x10^9 Pa)
    - Sulfate aerosol layer not observed to be populated
    - Only a very few handful samples have been taken from the stratosphere under the conditions that allow for biological analysis.
    - Only viable cells found are dormant surface survivors of desiccation, irradiation, etc
    - Reproduction not yet observed in situ
    - Venus:
        - Sulfuric acid aerosols (~80% H_2SO_4, 20% H_2O), distinct size ranges
        - T, P, radiation are within microbial limits
        - CHNOPS, energy sources supported in theory
        - pH is -1.5 -0.5, but acidity (H_0 ~ -6 , -11) exceeds known habitats
        - water activity (a_w ~0.02, 0.004) appears insufficient for metabolism
    - Water
        - Water or equivalent solvent is required for habitation
        - Intermittent water availability leads to periods of inactivity in population growth
    - In situ targets
        - Differentiate size specific aerosol composition and residence dynamics
        - Understand water history

        - Characterize mixing and lofting dynamics
    - Stratospheric sampling lessons
        - Habitable microenvironments sparse and variable: need lots of sample
        - Vast majority of bioaerosols are dead/dormant: test instruments using more representative biosignatures
        - Without sample return, need fast analysis cadence
            - Mass spec can be slow
            - Optical measurements require good baselines
        - Earth has multiple Venus science and operational analogues

The talk relates to the session goals as defined in the meeting schedule in the following ways:

Assuming Earth-like lifeforms, the presenter discussed what may be needed for life to be present on Venus. Also discussed important but sometimes overlooked constraints, such as dormancy for long periods of time can cause strain and microbes' airborne time is affected by various atmospheric factors such as gravity, air density, viscosity, turbulence, etc.

Future needs/recommendations given within the talk were:

- In situ targets
    - Differentiate size specific aerosol composition and residence dynamics
    - Understand water history – is there continuity?
    - Characterize mixing and lofting dynamics
- Stratospheric sampling lessons
    - Habitable microenvironments sparse and variable: need lots of sample
    - Vast majority of bioaerosols are dead/dormant: test instruments using more representative biosignature
    - Without sample return, need fast analysis cadence
        - Mass spec can be slow
        - Optical measurements require good baselines
- Earth lacks a perfect analogue to Venus's cloud and haze aerosols, but it has several environments that can together span important science and operational properties, so consider field testing.

The key take-away of this talk was:

In terms of Earth biology, there are many unknowns on if life has the environment it needs to thrive on Venus. We need to consider many aspects of the atmosphere such as water activity, air density, turbulence, vertical nutrient movement, etc. Lastly it was discussed that the stratosphere of Earth can be an analogue and we should use the lessons from studying life in the terrestrial stratosphere and apply it to Venus.

Ways in which future missions may impact the conclusions of the talk, as defined by the speaker:

None provided

Comment from Q&A:

- Microenvironments can be created by microbes. They can form clusters and the ones on the outside die and become UV shields, help retain nutrients, etc.
- Currently simulating the Venusian atmosphere and incorporating microbes is challenging because long-term suspension of aerosols is difficult. Future capabilities to address this would be useful.
- As Earth's stratosphere is in many ways comparable to Martian surface atmosphere conditions, we could use information obtained from analysis of Martian lofted dust.
- Earth’s stratosphere is a better Venus analogue, but we don't find active life in the stratosphere.
- Venus clouds are more homogeneous than Earths', but microorganisms could themselves create microenvironments with microclimate by forming clusters.
- The duration for a mission with an atmospheric platform that is sufficient for enough sampling and in-situ analyses is complicated to count.
- Now it is challenging to conduct the long-term experiments modeling Venus atmospheric conditions with the introduction of microorganisms. So short-term or based on plates/liquid cultures experiments are more popular. However they have some significant drawbacks as analogues.

Presenter: Lewis Dartnell

Talk name: Constraints on a Potential Aerial Biosphere on Venus: Cosmic Rays and Solar Ultraviolet Radiation

Summary: Dartnell discussed how cosmic rays and solar ultraviolet radiation may be a challenge to putative life, primarily at higher altitudes. However, it was highlighted that such radiation does not challenge survival in the lower and middle clouds and that photosynthetically active radiation could be used by photosynthetic microbes.

Talk Highlights:

- Presenter investigated models on how the potential Venusian HZ challenged by
    - Cosmic Rays (GCR + extreme solar particle events)
    - Solar UV penetration
- Findings: Cosmic Rays/Ionizing radiation model
    - GCR ionizing radiation peaks at ~62.5 km, the top of the aerial HZ, but not at harmful dose rates
    - Peak energy deposition from extreme SEP events is up to 6 orders of magnitude greater than GCR, but at higher altitudes
- Findings: Solar UV model
    - UV radiation environment around 60-62 km altitude (top of HZ) is similar to it on Martian surface (severely challenged by UV penetration)
        - Top of thermally defined HZ, D. radiodurans endure ~80 sec of UVC irradiance
        - 59 km - biologically-weighted UV < surface of the Archean Earth
        - 54 km - "biologically-weighted UV < present-day Earth's surface
- Penetration of ionizing radiation or UV do not challenge survival in lower and middle cloud layers
- Penetration of Photosynthetically Active Radiation (PAR) would allow microbes to photosynthesizes whilst screened from UV

The talk relates to the session goals in the following ways:

They concluded that penetration of ionizing radiation or UV does not challenge survival in lower and middle cloud layers. Therefore, life could be present in the atmosphere of Venus.

Future needs/recommendations given within the talk were:

Endolithic HZ in the terrestrial rocks and euphotic zone in the water column can be analogues for Venus clouds HZ in terms of influence of solar UV.

Key take-aways of this talk:

Penetration of ionizing radiation or UV do not challenge survival in lower and middle cloud layers. Rather than the amount of UV present in the atmosphere, the balance between energetic expenses of repairing UV into cellular damage and potential energetic income from photosynthesis is of greater importance and interest

Ways in which future missions may impact the conclusions of the talk, as defined by the speaker:

Did not discuss

Comments from Q&A:

- The work does not take into account potential life using UV wavelengths for photosynthesis and photolytic-driven disequilibrium chemistry.
- In terms of many of the environmental parameters (temperature, pressure, radiation, etc.) the lower levels of Venus clouds are benign. However high acidity and low water availability are problematic.
- How calculus of visible photosynthetic flux to UV flux ratio would change, if potential microbes weren't doing photosynthesis themselves but rather making metabolic use of the disequilibrium chemistry created by the photolytic action of UV on the ambient atmosphere? Investigation of the photo-driven disequilibrium is a good area for further work.
- There is the possibility of exploiting UV wavelengths for photosynthesis.
- Another potential mechanism: microbes can secrete or excrete shells or surrounding droplets of substances which absorb UV and create useful chemicals, which the microbes then resorb. So they could make use of this very energetic radiation source without frying themselves.
- The "UV absorber" is still unidentified and does absorb more than half of the solar energy striking Venus ("a lot" of potentially metabolic energy).

Presenter: Rakesh Mogul

Talk name: Potential for Habitability and Round-the-Clock Phototrophy in Venus' Clouds

Summary: Mogul discussed analyses that show that putative life may have two possible sources of energy: solar and thermal, with round-the-clock photosynthesis potentially being possible. In addition, the talk also highlighted that some calculations show that acidity and water activity may not be at levels restrictive to putative life.

Talk Highlights:

- There are 2 viable sources of photonic energy on Venus: solar energy (high power, diurnal input) and thermal energy (lower power but permanent input)
- Used Radiative Transfer Model to study
- Photon Fluxes at Venus and Earth
  - Wavelength of peak photon fluxes at Venus clouds has more/equal energy to the maximum on Earth
  - UV in Venus clouds is less than flux on Earth
    - Light in Venus cloud is more energetic and less caustic
  - Three potential phototrophic windows on Venus (according to wavelengths of photon flux)
  - Earth Life in Venus' Light
    - Absorption features overlap with windows in Venus Clouds
    - Earth pigments overlap with Venus' solar and thermal light
  - Solar photon fluxes between Earth and the middle clouds of Venus are similar
    - Solar energy on Venus is a good source of energy
  - Thermal Flux from the surface at the middle clouds is greater than the black sea
    - Thermal energy's lower power and flux can be used as an energy source throughout the day and night
- At least one spectrum at Venus at 53.5 kilometers was obtained and several different absorption spectrum obtained from anoxygenic phototrophs were superimposed, chlorophyll a and b was used as control
  - features of many anoxygenic phototrophs overlap with the phototropic window in Venus clouds especially in WL
- Thermal emissions coming from Venus surface or hot atmosphere spectrum (~900-3500 nm) was also superimposed
  - The spectrum overlapped with the phototroph window WL which indicates the reliability of the radiative transfer model. this light can also come through the clouds and be detected by some orbiter or ground based telescope
- The omission from the surface and or hot atmosphere overlaps with the absorption of the bacteria chlorophyll b.
- This indicates that Earth pigments overlap with both Venus solar light and thermal light
- Acidity v Phototrophy
  - At higher concentrations of H_2SO_4, the Hammett Acidity function is a better measure of acidity than pH.
  - Based on Thermodynamic calculations and Refractive Index Values, H_0 is too low for life to exist
  - Based on Refractive Index Values, are there other candidates instead of H_2SO_4 such as NH_4HSO_4? Or others?
    - RI and Radio Occultation are supportive of NH_4HSO_4 on Venus
  - If add 0.5 mole ratio of NH_3 to model, H_0=-0.1 to -1.5 (less negative)

        - This addition also increases water activity
- Model with NH_3 indicates
    - Aerosols are potentially buffered
    - Acidity and water activity are potentially suitable for acidophilic microbial growth

The talk relates to the session goals in the following ways:

The presenter concludes that acidity and water activity are potentially suitable for acidophilic microbial growth in the Venusian clouds. They also state that the solar energy and the thermal energy in the clouds of Venus can be used by microbial life and that round-the-clock photosynthesis is possible

Future needs/recommendations given within the talk were:

The presenter did not address. However, more data on the composition of the aerosols on Venus would be beneficial. More accurate in-situ analysis of chemical composition of Venus clouds that will be made by future missions will support or refute the hypothesis proposed in this talk (acidity & water activity are potentially suitable for acidic cultivation).

Key take-aways of this talk:

- Acidity and water activity could be suitable for acidic cultivation
- Solar photon fluxes between Earth and the middle clouds of Venus are similar
    - Solar energy on Venus is a good source of energy
- Thermal Flux from the surface at the middle clouds is greater than the black sea
    - Thermal energy's lower power and flux can be used as an energy source throughout the day and night
- Model with NH_3 indicates
    - NH_4HSO_4 could be in the aerosols
    - Aerosols are potentially buffered
    - Acidity and water activity are potentially suitable for acidophilic microbial growth

Ways in which future missions may impact the conclusions of the talk, as defined by the speaker:

Presenter did not address. However, a mission that better constrains the aerosol composition would be beneficial

Comments from Q&A:

The possibility of presence of some biosolutes like extracellular polysaccharides secreted by microorganisms actively controlling their environment in the aerosols that effectively reduce vapor pressure or loss of the water was discussed after the talk.

Presenter: Jan Spacek

Talk name: The Organic Carbon Cycle in the Atmosphere of Venus and Evolving Red Oil

Summary: Spacek introduced the red-oil hypothesis where organic carbon becomes red-oil in the presence of concentrated sulfuric acid. Spacek described that this red oil may be self-replicating and contemplated whether it could be considered life. The group will be investigating experiments to understand red-oil in the future and an autofluorescence nephelometer will be flying to Venus in 2023 to search for signs of it.

Talk Highlights:

- Organic carbon in concentrated sulfuric acid is not oxidized and becomes a complex chemical compound mixture called red oil
    - Continued reaction results in what appears to be a black sludge
    - The term red oil comes from the side reaction of acid catalyzed alkylation during octane production. As the reaction proceeds the clear solution grows increasingly more red or even black
- Using NMR and MS spectra to determine the composition of the red oil
- New C-C bonds are formed even when starting from single-carbon species. Red oil conversion increases the complexity of material. The new products are large molecules
- By changing various parameters such as concentration of the chemical and sulfuric acids and the temperature the resulting chemical species is different with different fluorescence patterns
- Based on these results, the autofluorescence nephelometer flying to Venus in 2023 will be tuned to 350 nm.
- UV/vis absorbance of red oil is “tunable” depending on the initial reactants, their concentrations, and reaction conditions
- Organic Carbon gasses (formaldehyde) accumulate in the sulfur acid droplets. Any organic carbon in sulfuric acid above 60% concentration becomes red oil. Red oil is acid soluble, colored, UV-vis absorbent, and fluorescent.
- Will be completing experiments in a CO_2/CO atmosphere in the future
- Potential for life in concentrated sulfuric acid
    - No organic carbon is stable in sulfuric acid above ~60% w/w
        - Includes wax, membrane, etc
    - UV absorber is responsible for ~50% of the solar energy capture in the cloud.
    - Some red oil self-replicates. Regions of droplets converting organizer carbon to the red oil faster are elected by the solar heating/uplifting.
        - Are these evolving self-replicators life?
    - The red oil and reduced carbon cycle in the Venus atmosphere can explain the lower haze, the uv/vis absorber, the asymmetric mode 3 particles, the yellow coloration of the clouds, and the upper haze

The talk relates to the session goals in the following ways:

The presentation concluded that organic carbon is not stable in sulfuric acid above 60% w/w. It is also discussed if self-replication of red oil is a form of life, and the red oil life hypothesis was proposed in the talk.

Future needs/recommendations given within the talk were:

One future need is to collect experimental data at simulated Venus conditions which the speaker will be doing in the future. Future in-situ data is also needed to compare with their experimental results

Key take-aways of this talk:

- Potential for Life in Concentration Sulfuric Acid
    - No organic carbon is stable in sulfuric acid above ~60% w/w
        - Includes wax, membrane, etc
    - The red oil and reduced carbon cycle in the Venus atmosphere can explain the lower haze, the uv/vis absorber, the asymmetric mode 3 particles, the yellow coloration of the clouds, and the upper haze
- The red oil hypothesis suggests that some red oil gains self-replicating ability and regions of droplets converting organic carbon to the red oil faster or selected for by solar heating

Ways in which future missions may impact the conclusions of the talk, as defined by the speaker:

The speaker discussed a mission concept that could launch in 2023-2024 that could have an autofluorescence nephelometer. This data can be compared with data obtained in the lab to determine the composition

Comments in Q&A

- In the H_2-poor environment the photochemical production of formaldehyde might be difficult
    - Water should be reduced enough to combine with CO_2 to make formaldehyde based on photochemistry. Also, volcanic activity can inject reduced carbon into the clouds.
- Wax, sulfur, and other substances in > 60% sulfuric acid have all been tested experimentally and are all reactive. This includes sodium dodecyl sulfate and paraffin at room temperature over several days.

Presenter: Jun Yang

Talk name: Climate and Habitability of Venus-Like Slowly Rotating Planets

Summary: Yang described how the past and present habitability of Venus could be dependent on the rotation rate of Venus, primarily because of its contribution to the presence of clouds. Yang describes the necessity for more models to understand Venus' ancient rotation rate, as this could provide clues to understand just how habitable Venus was in the past.

Talk highlights:

- Venus has a slower rotation rate, longer solar day and higher stellar flux than Earth.
- Clouds are important to maintain a habitable world
- If we put Earth at Venus orbit, can it still be habitable?
- 3D GCM to simulate climate
  - Slow rotation rate
  - Longer solar day
  - Higher stellar flux
- As you slow down the rotation, the temperatures do not increase as rapidly due to its correspondence with albedo
- Rapidly rotating planets form cloud bands while slow rotating planets have cloud decks that shield the planet from incident radiation and keeps it cool due to an increase in Hadley cells
- More clouds form on slowly rotating planets and the cloud converges and cloud water amount increases with insolation
- If Venus went through a runaway greenhouse, it had a higher rotation rate at that time.
- Atmospheric circulation and clouds on slowly rotating or tidally locked planets
  - More clouds in subsolar region reflect radiation back to space. Acts to cool surface so slow rotating planet can be closer to host start
  - Stabilizing cloud feedback expands the habitable zone

The talk relates to the session goals in the following ways:

The habitability of Venus has been considered in terms of climate that is determined by the slow rotating speed of Venus. Understanding if Venus could have had an ocean and could have had conditions to harbor life increases the chance that life may be present today.

Future needs/recommendations given within the talk were:

These experiments assume the initial state is cold or warm. More models are needed for other initial states.

The key take-away of this talk was:

- More clouds form on slow rotating planets and the cloud converged and cloud water amount increases with insulation
  - Albedo of slow rotating planets is much higher
- Clouds have a strong cooling effect on slowly rotating planets and cloud feedback moves the inner edge of the habitable zone towards the host star

- A planet with modern Earth's atmosphere in Venus orbit and with modern Venus rotation rate would be habitable. This implies that if Venus went through a runaway greenhouse, it had a higher rotation rate at that time

Ways in which future missions may impact the conclusions of the talk, as defined by the speaker:

Did not discuss

Comments from Q&A:

- Now there are 3 models showing slow rotating cloud albedo effect on Venus.
- The inner edge of the HZ may be highly dependent upon rotational state.
- When condensation occurs, latent heat release increases, which should increase the speed of the superrotation. Latent heat release may be the key factor that controls the speed of the superrotation.
- Superrotation is included in the model. When condensation occurs, latent heat release increases, which should increase the speed of the superrotation. Latent heat release is a very important key factor that controlling the speed of the superrotation.

Presenter: Sanjay Limaye

Talk name: Adaptations of any Past and Present Life on Venus

Summary: Limaye described the possibility of putative life on Venus having a circadian clock, similar to microbes here on Earth, and how this may have affected their evolution from Venus' watery past to now. Limaye also introduced various questions that need to be addressed if this was the case both relating to Venus' characteristics and the putative life.

Talk highlights:

- Liquid water, if present, could have survived on the surface for 10s of million –3 billion years.
- Keeping the rhythm close to the circadian clock appears to have an evolutionary advantage.
- Seasonal changes on Earth and laboratory experiments show that the circadian
    - rhythm in primitive life can vary significantly from the clock.
- The durations of day and night define the clock, but other cyclic phenomenon
    - can also control it (lunar tides).
- Clouds present a shorter circadian clock.

The talk relates to the session goals in the following ways:

The significance of the circadian clock for potential microorganisms in Venus clouds and its influence on the adaptations are proposed in the talk.

Future needs/recommendations given within the talk were:

- We need to answer the following questions:
    - What was the initial rotation state of Venus (tilt and period)?
    - How did it change over time?
    - When did superrotation develop relative to loss of water?
    - When did the cloud cover change forcing UV, acidity, photosynthesis and other adaptations?
    - If any life ever evolved, when did the migration to the clouds begin and end?
    - Does a slower clock play a role in adaptations to external stressors?
    - Without a moon, only atmospheric solar thermal and solar internal tides and
        - impacts can change the rotation period of Venus?
    - Did Venus have a moon?
    - Did the shorter circadian clock in Venus clouds help or hinder survival of any life migrating from the surface?
- Recommendations:
    - Backward modeling of atmospheric evolution from the present state.
    - Forward modeling of evolution of atmosphere and climate of Venus from as early a state as possible.
    - Continued monitoring of the rotation rate of Venus for detecting any secular trends.
    - Noble gas isotopic measurements.
    - Inventory of trace species in the atmosphere.
    - Better assessment atmospheric escape (Lagrange point orbiters)
    - Surface rocks characterization.

    - Measurements of seismic activity.
    - Atmospheric escape estimates.

Key take-aways of this talk:

If life is extant today in the Venus cloud cover the question is does it contribute to solar radiation absorption and contrasts. If there is no life present, the question of the absorbers of solar radiation will still be with us until we learn their identity.

Ways in which future missions may impact the conclusions of the talk, as defined by the speaker:

- The real amounts of the ionizing radiation on Venus can be lethal for microorganisms (current data are received from modeling).
- During VERITAS, DAVINCI, Venera-D, EnVision, ISRO Venus Orbiter missions surface rocks will be characterized and felsic rocks (evidence of presence of water in the past) may be found.

Main points of after-talk discussion:

- Circadian clocks probably didn't evolve early in the history of life on Earth. Certainly didn't become prevalent until eukaryotes and multicellular organisms emerged.
- The history of rotation rate is clearly important for understanding the history of habitability, but circadian clocks are not likely essential for a biosphere.
- Circadian clocks are postulated as a way to maximize the energy acquisition.
- Macrofauna can adapt quickly to circadian cycles.
- The Earth's rotation slowed from 6 hours to 24 hours due to ocean tides which are not likely to be that important on Venus (with possibly no oceans and no moon).
- There are a large number of studies that show how solid body tidal dissipation can affect Venus' rotation rate.

15.2 Day 2

15.2.1 Missions to Venus

Presenter: Allan Treiman

Talk name: Venera-D Lander: Constraints on Site Selection

Summary: The presentation discussed potential landing sites, types of data that should be obtained at the landing site, and the criteria for a successful lander mission.

Talk Highlights:

- Scientific goals for Venera-D lander:
    - Chemistry of the surface
        - Major/trace elements
        - Stable isotope ratios
    - Surface-atmosphere interactions
    - Geology of local landforms
- Success Criteria for Venera-D lander:
    - Controlled, safe landing
    - Instruments, communications all working
    - Data that will address important questions in Venus science
    - Landing Site Selection Criteria:
        - Safe landing (requires plains materials)
            - Regional volcanic plains (+canali)
            - Volcanic Shield Plains
            - Shield Clusters
            - Lobate plates
            - Smooth volcanic plains
            - Ridge and groove belts
- Broad applicability to the rest of Venus (not someplace unique)
- Orbital dynamics allow sufficient communication between lander, orbiter, & Earth
- Science questions:
    - Are Venusian regional plains (rp_1 and rp_2 as mapped by Ivanov and Head) comparable to Earth's Large Igneous Provinces (LIPs)? How could we test that hypothesis with a lander?
    - What is the composition of tesserae? If we landed on an impact parabola on the plains that was created by impact into adjacent tesserae, could we safely start to answer the question about tesserae composition?
    - What is the age of the Venusian surface (anywhere)? The current Venera-D lander configuration doesn't address that question, but it would be fantastic to try.

Presenter: Giada Arney

Talk name: The DAVINCI Mission to Venus and Connections to Venus Habitability

Summary: The upcoming DAVINCI mission will address several key questions about the atmosphere of Venus. This data will be fundamental for our understanding of Venus' evolution and its potential to have hosted liquid water and microbial life.

Current Launch Date: 2029

Payload:

- Venus Mass Spectrometer (VMS)
- Venus Tunable Laser Spectrometer (VTLS)
- Venus Atmospheric Structure Investigator (VASI)
- Venus Descent Imager (VenDI)
- Venus Oxygen Fugacity Experiment (VfOx)
- Venus Imaging System for Observational Reconnaissance (VISOR)
- Compact Ultraviolet to Visible Imaging Spectrometer (CUVIS)

Fundamental questions that DAVINCI is designed to answer include:

1. Why did Venus and Earth diverge in their evolution?
2. Did Venus have oceans, and did those oceans contain life?

Talk Highlights:

- The spacecraft will perform two flybys where it will study Venus using IR and UV cameras before dropping the probe
- The probe will address all science goals in the approximate 1-hour descent to the surface
- If the probe survives, it will have power left to transmit data for another 17-18 minutes
- Probe will descend over Alpha Regio (tessera)
- Noble gases (He, Kr, Ar, Xe), D/H ratio, isotopes, major and minor gases, and several phosphorus-bearing compounds will be measured
- Science Team is looking for community input on adding an additional laser to measure PH3
- Obtained data will inform on Venus' past, as well as on planetary evolution of exoplanets

https://svs.gsfc.nasa.gov/20351

https://www.nasa.gov/feature/goddard/2021/davinci-vms

Presenter: Thomas Widemann

Talk name: Atmospheric Studies with the EnVision Mission

Summary: The EnVision mission will be investigating multiple aspects of Venus using a suite of different instruments. It will be obtaining data on atmospheric compounds and cloud dynamics, geophysical and geochemical data of the surface, and data that will be relevant to the investigation of the interior. The mission will address many key questions of the past and current environment of Venus and may provide clues on the potential habitability of the clouds.

Launch date: 2031-2032

Payload:

1. Venus High Resolution Spectrometer (VenSpec-H)
2. Venus Ultraviolet Spectrometer VenSpec-U
3. Venus Pushbroom Multispectral Imager (VenSpec-M)
4. Venus Synthetic Aperture Radar (VenSAR)
5. Subsurface Radar Sounder (SRS)
6. Radio Science Experiment (RSE)

Highlights:

- EnVision is slated to be active for 4 years
- The spacecraft will be inserted into a polar orbit
- SRS will obtain data from hundreds of meters in depth which can be used to study craters and tesserae
- VEM will be used to determine bulk surface composition and detect volcanic activity
- VenSpec-H will make atmospheric measurements in IR above and below the clouds to measure SO2, H2O, and various isotopes
- VenSpec-U will map temporal distribution of SO2, SO
- RSE will determine the global gravity field at 200 km spatial resolution and provide atmospheric sounding to constrain temperature structure and distribution of sulfuric acid

https://sites.lesia.obspm.fr/envision/files/2019/03/Proposition_M5_5oct2016.pdf

15.2.2 Measurements, Instruments, and Missions Concepts to Venus (Part 1)

Presenter: Konstantin L. Vodopyanov

Talk name: Trace Molecular Sensor Based on Mid-Infrared/ THz Frequency Combs

Summary: The talk discusses a dual-frequency comb instrument for mid-IR spectroscopy to detect the molecular signature of NH_3 and H_2O. 3-5 µm range detect isotopes in Venus atmosphere. Real-time detection of trace gases could be provided by the instrument.

Talk highlights:

- New concept for in-situ trace gas detection based on laser frequency combs
- Molecule signature in the mid-IR
- Detect molecules including their isotopes all within a few seconds
- Molecular detection with mid-IR/THz combs can be done based on intra-pulse difference frequency generation (IDFG) and electro-optic (EO) sampling
- Can be used to detect numerous gases/isotopes including several NASA relevant (and some Venus) gases (H_2O, HDO, SO_2, H_2CO, HCN, PH_3)
- Conclusion
    - Real-time detection of molecules and isotopes
    - Spectral coverage from MIR to THz; total band 2,800 cm^-1
    - Sub-Doppler (at 300K or 735K spectral resolution)
    - Can detect new atmospheric trace gases on Venus
    - Can measure isotopic composition (3-5 µm range)
    - Can measure the vertical and horizontal distribution of gases

The talk relates to the session goals in the following ways:

The proposed method can be used to detect molecules and isotopes in the atmosphere of Venus in real-time using Mid-IR spectroscopy.

future needs/recommendations given within the talk were:

Did not discuss

Key takeaways of this talk:

- THz Frequency dual-comb based instrument can be used for Mid-IR range spectroscopy for detection of trace gases in Venus atmosphere
- The proposed method can be used to detect molecules and isotopes in the atmosphere of Venus in real-time.

Ways in which future missions may impact the conclusions of the talk, as defined by the speaker:

Did not discuss

Comments during Q&A

- This method requires that a gas sample is collected, therefore it must be sent into the atmosphere of Venus.
- Average time for analysis is 1 second, but it will depend on your desired signal to noise ratio
- Needed for accuracy or oscilloscope
- Can be linked to GPS for precision
- In-situ, for atmospheric descent

Presenter: Kirby Simon

Talk name: Real-Time Cloud Composition Profiles with an Optofluidic Instrument

Summary: The talk discusses the development of optofluidic instruments for real-time measurement of cloud composition. Venus analog samples are tested and spectra are generated using SERS and LIBS. The instrument is being proposed for Venus exploration.

Talk Highlights:

- VOLTR
    - Identify unknown UV absorber
    - Characterize atmospheric constituents at ppb level
    - Assess habitability or detect traces of life
- Goals
    - Collected cloud aerosols
    - Acquire ultrafast surface-enhanced Raman (SERS) and laser-induced breakdown spectra (LIBS)
    - Analyze and interpret spectral data in real-time during the descent
- SERS
    - Ppb-level detection of organic functional groups in real-time
    - Ultra-low SWaP-C compatible with SIMPLEx small spacecraft
    - TRL 5 in 2022
    - Issues
        - Low sensitivity
        - Issues with fluorescence
        - Longevity and Architecture
            - The substrate can be contaminated or could oxidize in ambient. Also random homogeneities can cause issues
                - Good at qualitative, not quantitative
    - Solutions
        - Nanofabrication techniques
            - Incorporating nanoparticles which can enhance the scattering effect which greatly enhances peak intensity
            - Using different materials to enhance uniformity of substrate which will allow for quantitative data
        - Using different SERS-active materials
- Has been tested on Earth
    - Cloud fly-through con-ops
        - sub-ppb geothermal fluids
- Funded by
    - NASA MatISSE
    - NASA SBIRs
    - ARC Center Innovation Funds

The talk relates to the session goals in the following ways:

An optofluidic instrument has been proposed for the real-time detection of atmospheric constituents. VOLTR can be used to investigate aerosols, the UV absorber, and organics.

Future needs/recommendations given within the talk were:

Did not discuss

Key takeaway of this talk:

- The presenter proposes an optofluidic instrument based on SERS and LIBS methods for the analysis of atmospheric aerosols and gases
- VOLTR can be used to investigate atmospheric constituents including aerosols, the UV absorber, and organics. It will almost be flight-ready and can analyze samples in real-time.

Ways in which future missions may impact the conclusions of the talk, as defined by the speaker:

Did not discuss

Comments from Q&A:

- With funding, the next step would be to do cloud testing
- It has only been tested with liquid/wet aerosols and not dry ones
- The instrument can do point measurements or raster across an area. It would take a few tens of seconds to a minute and can obtain 1000s of data points in a 1x1cm grid
- The substrate is single-use. Currently exploring how to make it multi-use
- Ideally, VOLTR would best serve on a probe because it will force the material through the mesh
- Single point measurements of seconds or tens of second-order
- The number of substrates constrain the measurements
- Options being explored for balloon or probe-based platform

15.3 Day 3

15.3.1 Measurements, Instruments, and Mission Concepts to Venus (Part 2)

Presenter: Oleg Sedykh (Lavochkin Representative)

Talk name: Update on Venera-D

Summary: The updates on the Venera-D mission concept and science objectives are discussed in detail. The science objectives of different modules i.e. orbiter, landing module, and atmospheric module are put forward from design perspectives.

Talk Highlights:

- Venera-D:
    - Orbiter module – 16 instruments
    - Landing module – 11 instruments
    - TAM – 3 instruments
    - Aerostatic module
        - Potential for NASA participation
    - Autonomous seismic stations (SAEVe) – 2
        - Potential for NASA participation
    - Autonomous scientific stations (LLISSE) - 2
        - Potential for NASA participation
- Overview of spacecraft's planned approach to Venus
- Orbital module characteristics and tasks
    - Overview of component masses, orbital parameters, data rate, energy requirements
- Descent module characteristics and tasks
    - Overview of component masses, orbital parameters, data rate, energy requirements
    - Aerostatic module requirements
    - TAM requirements and injection process
- Landing site options
    - Constrained by launch window: Nov 2029
- Landing module overview
    - Requirements for landing payload
- Conclusions
    - COMPLETED:
        - Scientific objectives of mission are developed
        - Scientific payload composition priority determined
        - Budgets fixed
        - Component requirements defined
    - CURRENTLY UNDERWAY:
        - Scientific payload conceptual design
        - Design and layout solutions
        - Operation logic
        - Selection and development of required components

- EXPECTED IN FUTURE:
    - Budgets confirmation
    - Definition of components' interfaces
    - Confirmation of design solutions
    - In-depth development of DM and LM EDL profile
    - Determination of test scope and test equipment
- Phase A to be completed by February 2023
  - Orbiter module
    - Dynamics and nature of superrotation of the atmosphere
    - Heat balance and nature of the greenhouse effect
    - Thermal structure of the atmosphere
    - winds, heat tides and solar-related structures
    - The atmosphere composition, clouds, their structure and composition, microphysics and chemistry
    - The composition of the lower atmosphere and clouds, measurement of the surface emissivity
    - Searching for volcanic activity on the nightside
    - Upper atmosphere, ionosphere, electrical activity, magnetosphere, dissipation of atmospheric components and interaction with the solar wind
  - Landing module
    - Landing site potentially somewhere in the SW quadrant of the planet
    - Obtaining and exploring samples of atmosphere during descent
    - Surface filming during descent
    - Analysis of elemental and mineral composition of the surface and the subsurface layer (depth of several cms), including radiogenic elements Analysis of surface/atmosphere interaction
    - Analysis of structure and chemical composition of lower atmosphere, level of trace gases and inert gases, as well as of isotope ratios of elements
    - Direct chemical analysis of aerosol particles
    - Geological performances of ground forms given for different scales
    - Search for thunderstorm and seismic activity, volcanic activity and volcanic lightning.
  - TAM
    - demonstration of materials technologies, aerostat injection and maintenance of variable altitude
    - demonstration of technologies for the transfer of scientific data and experiments
    - TAM aerostat repeatedly changes altitude from 53 -57 km for more than 20 days. Ascents to 60 km and descents below 45 km
  - Aerostatic module inside the descent module
    - direct observations of the atmosphere inside the cloud layer;
    - measurements of aerosol particles, wind velocity, UV absorbers
    - investigation of clouds possible habitability
  - 2 SAEVe (seismic stations)- NASA GRC
    - Seismic measurements of surface at the landing sites;
    - Measurements of temperature, pressure and wind velocity;
    - Measurement of scattered solar and intrinsic radiation at the surface of the planet;
    - Measurement of the gas composition of the atmosphere
  - 2 LLISSE (long-lived in-situ Solar System Explorer)- NASA GRC

        - measurements of temperature, pressure, solar radiance, wind velocity and direction, and atmospheric chemical composition

The talk relates to the session goals in the following ways:

The talk provides an update on the current status of Venera-D and the different components of the mission

Future needs/recommendations given within the talk were:

Progress on the Venera D mission is underway. An overview and update on each spacecraft system were given

Key take-aways of this talk:

- Progress on Venera-D is underway:
    - 1)The scientific objectives of the mission are developed.
    - 2)The priority composition of the scientific payload has been determined, conceptual design is under development.
    - 3)Budgets are fixed.
    - 4)The requirements for the components are defined.
    - 5)The design and layout solutions and the operation logic are under development.
    - 6)The selection and development of the required components and materials are in progress.
- Phase A Completion date –February 2023

Ways in which future missions may impact the conclusions of the talk, as defined by the speaker:

They were not discussed in the talk

Comment from Q&A:

- Frequencies for the VLBI transmission from the balloon is 405 MHz
    - The Huygens Probe used 2. 1 GHz and the Vega balloons 1.665 GHz. US VLBI does not have a receiver for 405 MHz and could not participate in 405 MHz VLBI.
- Lifetime of the balloon is currently minimum of 20 days, but will likely be longer
- Due to limited payload mass the TAM cannot do balloon seismology, however, the NASA contributed balloon could do it.
- There is still an opportunity to propose instruments. Please contact the Venera-D science team
- The mechanism for altitude change on the TAM is physical. It will drop ballast to rise
- Astronomical launch window is Nov 2029
- Samples handling system in the lander will be a VEGA-type sampling system, but more compact and connected to a sample distribution system among three instruments inside the vessel. The sampling system lead is M. Gerasimov at IKI
- Would like to restart work on integrating LLISSE/SAEVe as soon as possible

Presenter: Satoshi Sasaki

Talk name: Fluorescence Microscopic Observation of Model Microorganisms Suspended in Sulfuric Acid

Summary: The talk discusses the results of fluorescence microscopy in sulphuric acid environments. The methods of sample preparation and interaction of dyes with microorganisms are explained. Further, a sample collection based on an impactor-based system is proposed for Venus exploration.

Talk Highlights:

- Introduction
  - Observation of microbes suspended in sulfuric acid was performed using fluorescence microscopes and stains
  - Life-signature Detection Microscope (LDM) can obtain morphological information that can discriminate biotic/abiotic signal
- Background information
  - SYTO 15 and propidium iodide (enters only dead cells, stains red)
  - Live cells appear as green, dead cells appear as red
  - Dye still viable at high temperatures and irradiation schemes
- Model organism for this study: *Acidithiobacillus ferrooxidans*
  - 80-90% sulfuric acid above what could be found on Earth
  - Cells cultured at pH = 2, SYTO 15 still worked
  - Cells suspended in solution at pH = -0.4, SYTO 15 didn't work and/or cells were degraded
  - Cells suspended in solution at pH = 7, potential non-biological autofluorescence (of dye)?
- Objectives
  - Characterization (fluorescence image viewpoints) of Acidithiobacillus ferrooxidans as a model bacterium
  - Proposal of alkali addition (to observe fluorescence)
  - Observation of fluorescence attenuation (to minimize false positive)
  - Experiments
    - pH 2
      - SYTO mix was added to culture and it bound to DNA (fluorescence)
    - pH -0.4
      - culture was suspended in H_2SO_4 and SYTO was added
      - either SYTO mix can't work or DNA is lost at this pH
    - pH 7
      - culture was suspended in H_2SO_4 then NaOH was added then SYTO was added
      - Fluorescence was observed, however, this dye mixture is imperfect
- Points
  - Sample collection is done with an impactor-based idea
  - Collect samples, sulfuric acid
- Conclusions
  - Alkali addition was effective, fluorescence/attenuation was observed

        - Carry alkali solution to Venus?
- Observation of microorganisms suspended in sulfuric acid was performed using a fluorescence microscope and fluorescence stain. Ways to reduce false positive was reported
- Experiments
        - pH 2
            - SYTO mix was added to the culture and it bound to DNA (fluorescence)
        - pH -0.4
            - culture was suspended in H_2SO_4 and SYTO was added
            - either SYTO mix can't work or DNA is lost at this pH
        - pH 7
            - culture was suspended in H2SO4 then NaOH was added then SYTO was added
            - Fluorescence was observed, however, this dye mixture is imperfect
- If the sample is irradiated attenuation can help with determining between biotic and abiotic

The talk relates to the session goals in the following ways:

The presenter discussed a potential way to differentiate between abiotic and biotic sources in the clouds of Venus using fluorescence microscopy

Future needs/recommendations given within the talk were:

Did not discuss

Key take-away of this talk:

The presenter discussed a potential way to differentiate between abiotic and biotic sources in the clouds of Venus using fluorescence dyes and a microscope. The presenter is currently using different fluorescence dyes to improve their technique and also to eliminate false positives. They also tested the bacterium and fluorescence dyes in various pHs to observe the results. Further, they have suggested the application of fluorescence microscopy to detect life in Venusian clouds.

Ways in which future missions may impact the conclusions of the talk, as defined by the speaker:

Did not discuss

Comments from Q&A:

- Stains have not been tested on spores
- The lower limit for particle size is 1 micron in diameter

Presenter: Kevin H. Baines

Talk name: Venus Cloud Explorer –Understanding Venus's Habitable Zone (VHZ) via a Long-Lived In-Situ Aerial Observatory

Summary: A mission concept of the aerial observatory for performing in-situ analysis of Venus atmosphere is pitched for Venus exploration. The scientific goals for the mission are understanding atmospheric chemistry, the composition of clouds, dynamics, and surface geological processes.Objectives include the identification of UV absorbers and determining potential habitability.

Talk Highlights:

- Proposed New Frontiers mission
    - Orbiter + aerobot
    - Aerobot allows for in situ sampling of gases and aerosols
- Goals
    - 1. Understand the chemistry, composition, and habitability of Venus clouds over range of altitudes, latitudes, and times of day
        - Measure gases and aerosols to characterize photo-and thermal-chemistry
        - Determine composition of UV absorber
        - Assess potential habitability by characterizing biogenic signatures and measuring H_2SO_4 acidity, associated water activity, and isotopic variations
        - Candidate instruments
            - Venus Aerosol Mass Spectrometer (VAMS)
            - Tunable Laser Spectrometer (TLS)
            - Nephelometer
            - Regional orbital imagery for context
            - UV and NIR imagers
        - Gas/Aerosol-Sampling Instrument Package
    - 2. Understand dynamics that transports materials within, into, and out of the Venus cloud environment
    - 3. Understand near-surface geophysical processes indicative of surface emission of materials that influence habitability
        - Methods
            - Infrasound measurements for seismometry
            - Orbital nighttime near-infrared time-lapse imaging for volcanism
            - Magnetometer onboard aerobot for early dynamo, measured over ancient highlands
            - Sub-cloud near-IR nighttime multi-band surface imaging from aerobot, probe, or tow-body (TBD) for surface composition and age
- Primary science disciplines involved

- Atmospheric chemistry/astrobiology
- Atmospheric dynamics and radiative transfer
- Geophysics –seismology (via infrasound)
- Geophysics –remanent magnetism
- Geology –visible and near-IR imaging
  - If budget allows
- Essentially samples aerosol and measures its composition
- Predictions for abundances of HCl/H2SO4 in aerosol particles

The talk relates to the session goals in the following ways:

This mission would allow for a better understanding of Venusian habitability with regards to chemical and physical parameters, transport mechanisms, and near-surface geophysical processes.

Future needs/recommendations given within the talk were:

Did not discuss

Key takeaway of this talk:

This talk outlines a proposed Venus orbiter/aerobot mission that would provide an extensive characterization of parameters relevant to habitability via in situ samplings.·

Ways in which future missions may impact the conclusions of the talk, as defined by the speaker:

Did not discuss

Comment from Q&A

- The presenters are potentially interested in talking to Vodopyanov about their Mid-Infrared/THz Frequency Combs
- An optical microscope has been considered, however carrying fluid dyes adds complications
- Infrasound method has been proposed for Venera-D
- How long would this last? 1 Venus day (~120 earth days?)

Presenter: Mark A. Bullock

Talk name: Sustained In Situ Exploration of the Habitability of Venus' Clouds

Summary: A mission concept based on a dynamic soaring-based aerial flight in Venus clouds is analyzed. The aerodynamic coefficients and power budget are computed for Venus's atmosphere. The activity of water is discussed in relation to past and present habitability. In addition, the potential payloads including aerosol mass spectrometer and nephelometer are proposed for the aerial platform.

Talk Highlights:

- Dynamic soaring in the Venusian atmosphere
  - Dipping in and out of shear layer near the surface would be efficient
  - Propulsionless flight in the Venusian atmosphere would be possible
    - Glider would need to be CL/CD = 50
    - Venus designed aircraft has CL/CD = ~70
- Solar power
  - Aircraft would fly with the wind, encountering 2.5 days of sunlight and 2.5 days of darkness
  - Parameters for solar power and battery usage given
- Flexible science payloads from Black Swift Technologies
  - Configuration: core science payload with 1-2 major instruments
  - Core science payload
    - Solid-state pressure, temperature, and 3D acceleration sensors (100mg, 100mW)
    - 12 MEMS gas composition sensors for measurements of specific gases at ppb concentrations (10mg/10mW each)
  - Major science instruments
    - Venus aerosol mass spectrometer
    - Aerosol polarizing nephelometer
    - Venus life detection microscope
  - Two science targeted missions
    - Venus Aerosol Explorer (VAE) Core payload (P,T, acceleration, MEMS composition sensors) plus Aerosol Mass Spectrometer
    - Venus Life Explorer Aircraft (VLEA) Core payload (P,T, acceleration, MEMS composition sensors) plus Venus Life Microscope
  - Can elucidate unknown photochemistry, trace gases
- Two science-targeted missions
- Low water activity in Venus's clouds: how significant is this limitation for life?
  - Life does not exist on Earth for water activity less than 0.6 – is this because life never needed to solve this problem on Earth?
  - Increase in metabolic energy required for life scales as log of water activity, thermodynamically
  - Assuming that low water activity was just another evolutionary problem to solve, 1.5x the typical metabolic energy would be needed for a putative Venusian microbe
  - Arguing that this possibility is worth exploring
- Conclusions
  - Dynamic soaring in Venusian atmosphere supports weeks or months-long in situ investigations of Venus's clouds

    - Dynamic soaring aircraft can provide 110 W of continuous power for navigation, operations, communications, and science instruments
    - Dynamic soaring aircraft can navigate to regions of interest

The talk relates to the session goals in the following ways:

The presentation discusses the dynamic soaring mission concept for an aero platform to navigate the clouds of Venus. They discussed two different science targeted missions with potential instruments

Future needs/recommendations given within the talk were:

Did not discuss

The key takeaway of this talk was:

- An aero platform that dips into and out of a shear layer requires very little energy expenditure.
- Dynamic Soaring in Venus' atmosphere supports weeks or months-long in situ investigations of Venus' clouds
- Dynamic Soaring aircraft can provide 110 W of continuous power for navigation, operations, communications, and science instruments

Ways in which future missions may impact the conclusions of the talk, as defined by the speaker:

Did not discuss

Comments from Q&A

- A single aircraft can be dropped off from a Venus flyby
- Information on the MEMS for this talk was not discussed, however LLISSE (NASA GRC) has been funding MEMS sensor development. MAKEL engineering is a commercial US source and is also developing them
- Tracking the aircraft on the Earth-facing side will be completed. Perhaps with a VLBI beacon for interferometric tracking. An ultrastable oscillator may be necessary.

Presenter: Larry W. Esposito

Talk name: Investigating the Venus Clouds from Balloon and Orbit

Summary: Two mission concepts of Venus exploration: VASE and HOVER are discussed to study the cloud region of Venus. A balloon-based hybrid probe is proposed to measure the composition of noble gases, trace gases and perform descent imaging.

Talk highlights:

- Venus Atmosphere and Surface Explorer (VASE)
  - Science objectives
    - Measure noble gas and light-stable isotopes to constrain theories for planetary formation and evolution
    - Image surface through descent
    - Procure atmospheric structure profile from clouds to surface (temp, pressure, wind)
    - Measure trace and reactive gas compositions
  - Mission description
    - Hybrid mission: deep atmosphere probe is carried on balloon for one circumnavigation, then dropped
    - Balloon mission: 6-8 days
    - Dropped probe: 1-2 hours
    - Trip to Venus: 4 months
    - Direct-to-Earth telecommunications via S-band
    - Balloon and probe can be tracked from Earth
  - Flight system elements
    - ~900kg launch mass (with contingency)
    - Simple carrier spacecraft
    - Single-string architecture
    - Probe and balloon delivered inside PV-like aeroshell, 2.2m diameter
    - 7m super pressure balloon, 0.3m probe
    - Instruments
      - Mass spectrometer
      - Tunable laser spectrometer
      - Descent imager
      - Atmospheric structure (T, P, wind)
  - Hyperspectral Observer for Venus Reconnaissance(HOVER)
    - Allow for better understanding of the mechanisms of Venus's climate
      - What makes the clouds?
      - What is the role of the surface?
      - How does Venus compare?

        - Spacecraft hovers over balloon, takes high-res images (on the order of km) in multiple wavelengths
        - Could be integrated into New Frontiers proposal –HOVER BUS
            - Astrolabe heritage
    - VASE + HOVER summary
        - Better observations and models can explain Venus climate mechanics
        - Orbit and payload for simultaneous high-cadence, high-resolution imaging and spectroscopy provide a comprehensive, global data set
        - In situ balloon and probe measurements provide ground-truth and characterize the cloud environment
        - Orbiter investigations: UVCAM, IRCAM, UVPSEC, IRSPEC, ROCC
        - Ballooninvestigations: mass spec, TLS, IR spec
        - Probe investigations: descent imager, atmospheric structure, tracking
        - Can compare results to Earth and extra-solar planets
            - Atmospheric structure (T, P, wind)

The talk relates to the session goals in the following ways:

The presenter discussed the possibility of combining two potential mission concepts with the potential to better-understand Venus's climate and planetary history.

Future needs/recommendations given within the talk were:

Did not discussed

The key takeaway of this talk was:

The presenter discussed the possibility of combining two potential mission concepts that have been studied in the past. By combining them,even more science of the atmosphere and the surface can be completed than if sent individually.

Ways in which future missions may impact the conclusions of the talk, as defined by the speaker:

Did not discussed

Comments from Q&A:

Lifetime? Would sync with the balloon for ~1 week (prime mission), then would contact Earth (pause). If the balloon survives, the mission would continue upon reconnection.

Presenter: Vladimir V. Sorokin

Talk name: Conversion of Living Matter to Inanimate Material as the Method of Detection of Life Signs: Application to Venera-D Mission

Summary: The presentation discusses a method of detecting life using biocidal destruction of cell walls followed by gravimetry, UV-Vis spectroscopy, and chromatography. A lab on chip format is suggested for the analysis. The concept is proposed to detect proteins in the sample.

Talk Highlights:

- The concept for life detection
  - Life detection by detecting life's ability to lose its signs of life
  - Biocidal processing of the samples will result in the destruction of cell walls/membranes which can be used to detect the presence of life
- Steps
  - Collect cells from clouds
  - Destroy membranes under controlled conditions – ultrasound processing, set of different lysing solution, sharp changes in temperature or acidity of the medium
  - Release of cytoplasmic components and intracellular structures
- Analytical methods
  - Gravimetry: separate based on mass
  - Thin layer chromatography: separate components
  - Spectroscopy: confirm whether the sample contains DNA, proteins, etc.
- The presence of earth-type acidophiles in cloud samples is likely to be registered by changing the pH of a medium after the membrane's destruction

The talk relates to the session goals in the following ways:

This talk provides an overview of a potential method for life detection on Venus.

Future needs/recommendations given within the talk were:

Did not discuss

Key take-away of this talk was:

This talk proposes a concept for life detection to break open a cell and release its internal components and then look for/analyze these components to determine if it is organic, then analyze those through gravimetry, chromatography, and spectroscopy.

Ways in which future missions may impact the conclusions of the talk, as defined by the speaker:

Did not discuss

Comments from Q&A:

- Would prevention of contamination be possible?
  - Probably not.
- If the cell is dead, would you be able to determine that it had been a living cell?

    - Only live cells would work on this.
    - Residual enzyme activities and the presence of labile metabolites could be clues to recent life activity.
    - Due to the Vulnerability of the dead cell (compared to a living cell) in the acidic environment, there is a limited amount of time to do such detections.
- What are the characteristics of an instrument to do this (in terms of size, mass, and measurement times)?
    - Size: possible to construct for this task
    - Mass: “not large mass”
    - Measurement time: “in a short time”
- Since the different biological components have different sizes, unknown if this would prevent any clogging in the instrument

Presenter: Iouli E. Gordon

Talk name: HITRAN2020: Deciphering Spectra from the Cytherean Atmosphere

Summary: The presentation discusses important changes in the HITRAN database including the addition of new line-by-line data and comparison with experimental data. The applications of the HITRAN database are discussed in reference to the goals of Venus exploration.

Talk highlights:

- Spectroscopy is critical for interpreting results from a Venus mission, lots of work on how to decipher targets still needs to be done.
- HITRAN database is available for spectroscopic analysis, would benefit from more information.
    - Sister database contains information at higher temperatures relevant for Venus.
- HITRAN2020
    - Line lists for several molecules were updated (H_2O, SO_2, CO_2, NO_2, O_3, and many many more)
- The modern structure and interface is at www.hitran.org
- Improved parameters, new bands, and isotopologues (e.g. SO2) have been added
    - Significantly increased spectral coverage from HITRAN 2016
    - Validated against laboratory spectra
- New molecules relevant to Venus have also been added (e.g. SO)
- Major update of CO_2
    - Line positions and intensities
    - Line shape parameters – every line now has Voigt and speed-dependent Voigt parameters
- Planetary broadened were added, with gases relevant to rocky planets and gas giants
- SO2 as an example of taking something from “worst” case to “good” case
- They want to expand and add UV data in the future
- The data within the database has been cross-referenced for accuracy and includes both theoretical and experimental data
- Python libraries are available to download from the website
- They are working on updating a sister database that has spectra obtained at high temperature
- Added “planetary” broadeners to HITRAN

The talk relates to the session goals in the following ways:

The presentation discusses the updates in the HITRAN database and its application to the Venus atmosphere. The database is useful for future experiments, models, and instrument testing

Future needs/recommendations given within the talk were:

The database is updated, spectral signatures are under certain gas conditions (e.g. CO_2 being added). Lots of work on how to decipher spectroscopic targets still need to be done before a Venus mission.

Key take-aways of this talk:

- HITRAN is a spectroscopic database that is freely available to everyone and can be used to compare with acquired data or can be incorporated into models. They have made numerous updates to the database to increase accuracy as well as applicability to other planetary bodies.
- The HITRAN database is being updated with spectroscopic information relevant for the exploration of Venus.

Ways in which future missions may impact the conclusions of the talk, as defined by the speaker:

The speaker did not discuss, however perhaps future data collected from Venus could be added to the database

Comment from the Q&A:

- What temperature range will this data be accurate for? Also, do you plan to include any UV spectra/cross-sections/quantum yields?
  - SO can be used for at least 3000K. SO_2 to about 500K, but in some regions higher, but OCS probably less than 400K, although it would also depend on the band.
  - We do have a number of UV line by line spectra (OH,O_2) and a few in cross-sections (SO_2,H_2CO, O_3, etc), but for HITRAN2020 we plan to substantially expand UV cross-sections
  - The temperature range for some molecules could be 100s to 1000s of Kelvin

15.3.2 Poster Lightning Talks

Presenter: Thibaut Pouget

Talk name: Vesper: Multi-Experience Transport Mission Architecture in the Venusian Environment

Talk category: Mission Concept

Talk Highlights:

- Offer customers (research institute, university, private company) service to transport their payload to a target on Venus without having to design a complete space mission
- Targets proposed by the mission are a heliocentric orbit, a high Venusian orbit, a low Venusian orbit, an atmospheric entry near Phoebe Regio, or an atmospheric entry on a point selected by the customer
- Payloads meet the cubesat format from 1U to 12U

Presenter: Thomas Voirin

Talk name: EnVision: The New Medium-Class ESA/NASA Mission to Venus

Talk category: Missions

Talk Highlights:

- EnVision is M-class mission being developed in partnership with NASA
- Suite of 6 complimentary instruments and experiments intended to collect data from core to atmosphere over 4 full Venus cycles (4 Earth years)
- Launch in 2031 with Ariane 62
- Science payload
  - VenSpec-U: mapping SO, SO2, UV absorber
  - VenSpec-H: near surface atmosphere
  - VenSpec-M: mineralogy by surface emission
  - SAR: surface morphology
  - SRS: subsurface radar down to 1000m depth, 10m resolution
  - RadioScience: mapping, gravity field, occultation

Presenter: Arina Shimolina

Talk name: Magmatic History of North-East Part of Theia Mons, Beta Regio, Venus

Talk category: Surface Mapping

Talk Highlights:

- Mapping of Theia Mons
  - Identify sources of all flow units
  - Integrate emplacement of flows with graben system emplacement and central caldera collapse
  - Characterize relationship with triple junction rifting
- Results:
  - Mapping of flows and grabens-fissures in the NE quadrant indicate multiple generations and suggest rifting postdate emplacement of flows
  - Two different directions of flows from the central caldera and from the grabens to the north of it

Presenter: Danil G. Malyshev

Talk name: Dyke Swarm History of Sanodiva Mons Region, Devana Chasma Quadrange V-29, Venus

Talk category: Surface Mapping

Talk Highlights:

- Study underway to better understand lava flows in Samodiva Mons Region
  - 5 graben systems interpreted to overlie dyke systems
- Goals
  - Detailed mapping of fissure systems
  - Grouping of systems into sets
  - Revealing of relative ages of dykes by crosscutting relationships
- Further objectives
  - Mapping of lava flows and identifying sources
  - Timing of caldera collapse
  - Age relationships between flows and grabens
  - Geological history of Samodiva volcano and surrounding area

Presenter: Ekaterina Antropova

Talk name: A Newly Recognized 2000 km long Bolide Airburst Chain, Phoebe Regio, Venus

Talk category: Surface Mapping

Talk Highlights:

- A new airburst chain has been identified in Phoebe Regio
    - 12 splotches with clear linear trend
- Blast from explosion resulted in recognizable features
    - 3 main types of splotches: small dark center, large dark center, and dark center with crater-like structures
- Potentially from bolide airburst (meteoric explosion)
    - Similar processes observed on Earth (e.g. 1908 Tunguska event and 2013 Chelyabinsk event)
- Splotches are very young features

Presenter: Carlos H. G. Braga

Talk name: Preliminary Results and Timing Constraints from the Geological mapping of the Volcano Atria Mons, Beta-Atla-Themis (BAT) Region, Venus

Talk category: Surface Mapping

Talk Highlights:

- Geologic mapping of the BAT region
- Results:
    - Summit units are younger than flank flows
    - Caldera collapse happened late in volcano's history
    - Arcuate fracture system on E is younger than most flows on that flank
    - Large volumes of lava emplaced during the volcano's early history
    - Atira mons' volume allows us to classify it as a large igneous province (LIP)

Presenter: Vadim E. Rozhin

Talk name: History of Volcanism in Northern Asteria Regio, Venus

Talk category: Surface Mapping

Talk Highlights:

- Studied Polik-Mana Mons and Kono Mons
- 4 graben swarms identified
    - B-Z linera swarm – source unknown
    - NW-SE swarm -belong to rift or Kono mons?
    - Fan-shaped swarm -probably belongs to the "U" center along the rift to the south

    - Radial swarm - belongs to Polik-mana mons

Presenter: Hafida El Bilali

Talk name: Dyke Swarm History of Atla Regio, Venus: Insights into a Large Plume Head Event

Talk category: Surface Mapping

Talk Highlights:

- Atla Regio graben systems were mapped
- Plume head size determined from radius at which radiating swarm swings into linear trend
- All the centres (Ongwuti, Unnamed centre, Ozza, and Maat and possibly Sapas) are likely linked to a single plume head, 2400 km in diameter centered on Ozza Mons.
- Conclusion: Atla Regio is still at the plume head stage consistent with gravity anomaly

Presenter: Grzegorz Slowik

Talk name: Selected Terrestrial Microorganisms as an Example of Potential Analogues of Venusian Microorganisms

Talk category: Present Habitability

Talk Highlights:

- Important to study extremophiles on Earth to determine if/how life could potentially proliferate in the atmosphere of Venus
- Types of microorganisms that might be useful to study experimentally in simulated Venus environment:
    - Acidophilic bacteria
    - Electric bacteria
    - Cable bacteria

Presenter: Leah Nakley

Talk name: Venus Atmosphere Simulation with the Glenn Extreme Environment Rig

Talk category: Experimental Lab Equipment

Talk Highlights:

- Glenn Extreme Environment Rig (GEER) at NASA Glenn is able to replicate Venusian surface conditions (temperature, pressure, gas composition)
    - Can also be configured for other planets
    - Available for government and public use
    - Mini-GEER is almost ready for operation
- Science benefits and applications
    - Risk reduction through ground-based testing
    - Planetary research (geology, chemistry, atmospheric science)
    - Material testing
    - Large test articles and subsystems
    - Integrated testing
    - Technology demonstrations
    - Qualification testing

Presenter: Elizabeth L. Kimmel

Talk name: Exploring the Venus Atmosphere with a Venus Aero Vehicle (VAV): A mission concept for Low Cost, Multi-year Venus Atmospheric Exploration

Talk category: Mission Concept

Talk Highlights:

- A multi-year lifetime solar powered VAV with direct insertion from interplanetary trajectory into the atmosphere of Venus
- Cruise phase:
    - VAV will cruise just above cloud layer (70km)
    - Charge with solar panels and communicate with Earth
    - Will stay around equator but can make excursions north and south
- Dive phase:
    - Descend into cloud layer regularly (50km)
    - Sensing and sampling

Presenter: Daniel Sokol

Talk name: Development of Cloud Mirco-Organism Census Sampling Platforms

Talk category: Mission Instrument Concept

Talk Highlights:

- Motivation: Develop an autonomous in-situ sampling Astrobiology platform initially focused on Venusian flight
- Approach: Model development on prior Mars rover sampling missions
- Use Earth as instrument/long duration astrobiology platform/in-situ sampling system development surrogate
- Aerial Platform with Basic Particle Size and Distribution Suite and Advanced Life Detection Suite

Presenter: Isabel R. King

Talk name: Tape and Roller Sampling System for Flexible Venusian Atmosphere Aerosol Capture and Delivery

Talk category: Mission Instrument Concept

Talk Highlight:

- Tape-based system for aerosol sampling
    - sampling system is comprised of a tape wound between
    - two spools
- Venusian air containing aerosols is directed, either actively or
- passively to tape, then tape is fed into analytical instrumentation
- After analysis, samples stored in spool
- Multiple samples can be obtained
- Drive motor could be reversed to analyze a sample a second time
- Very adaptable to different circumstances
- From Honeybee Robots design heritage: Rock Core subsampling system

Presenter: Masatoshi Yamauchi

Talk name: Venus Laputa: A sustainable N2-filled platform in the Venus atmosphere

Talk category: Mission Concept

Talk Highlights:

- Sustainable (> 1 year) platform inside/below cloud
    - Cloud/atmospheric chemistry and dynamics
    - Surface, lower atmosphere, and lightning
- N2 based buoyancy
    - Separation of N2 from atmosphere
- Challenges

- Low-power separation of N_2 gas in the CO_2-rich atmosphere
- Long-term power generation in a tough environment (low light, acid)
- Control trajectory => Propulsion (propeller + wing)?

Presenter: Romi Rishit George

Talk name: Hypothesizing Possible Life Forms in Venusian Clouds

Talk category: Present Habitability

Talk Highlights:

- Bottom-up approach for hypothesizing life: studying extremophiles and predicting the existence of biomolecules (e.g. proteins)
- Some extremophiles on Earth produce enzymes that help them become acid and heat resistant
- Some extremophiles on Earth have resistant nucleic acids
- Best model: anaerobic, polyextremophilic, sulfate-reducing chemoautotroph, because it matches cloud chemistry composition and energy availability

15.4 Day 4

15.4.1 Putative Origins of Life and Past Habitability of Venus

Presenter: Steve Benner

Talk title: Limits of organic life in the solar system: From cold Titan to Hot Venus

Summary: Life can occur where there is energy, reduced carbon and a solvent. There is a lower limit for solvent in which life can exist however it can adapt to that lower limit. Life on Venus may be composed of a biochemistry that is not found on Earth yet shares a universal agnostic bio signature of biopolymers composed of informational units that all have the same size and structure within a supporting backbone with a repeating charge. An Agnostic Life Finder (ALF) is a suggested method to extract and identify polymers with a repeating charge in a solvent to detect life on Venus and other planets.

Talk Highlights:

- Life can occur where there is energy, reduced carbon and a solvent
  - Life is a chemical system capable of thermodynamic processes
  - Carbon-carbon bonds drive metabolism
  - Aldol reactions occur at near neutral pH (ie: Terran metabolism), C=N replaces C=O at high pH (ie: icy moons and gas giants), at low pH C=C replaces C=O (ie: Venus environment)
  - Fluid environments allow molecules to move around and interact
- Universal agnostic bio-signatures in water
  - Informational units must all have the same size and structure and the interchanging units do not change the overall structure or molecular properties
  - Backbone supporting informational units must have a repeating structure
  - A backbone with a repeated structure with a charge allows for small changes in the information unit that will not change the overall molecular properties or solubility or precipitation
  - Informational units must fit into a Schrodinger aperiodic crystal structure
  - Alien DNA in a solvent may have 4, 6, 8, 10 or 12 units but to evolve, they must be of similar sizes and shape
- Agnostic Life Finder (ALF)- uses polycharges to extract polyanions and polycations in counter current free flow electrophoresis and can mine a flowing solvent
- Water activity is a metric to assess livability in water
  - Life can exist and adapt to low fluid water activity
  - Venus cloud fluid has very low fluid activity composed of H_2SO_4
  - Our understanding of organic chemistry does not offer good intuitions into how chemistry will behave in that environment
  - $HCHO + H_2SO_4$ creates C13-C13 bonds. C13 has an electron spin that leads to the bonding of carbons.

    - CH202 + CH202 —> $C_2H_4O_2$ (current understanding of molecular chemistry does not explain reaction)
- Challenges in understanding Venus: 1) Terran style life emerged finding a way to continuously evolve to survive in its solvent replacement. 2) Overcoming Earth based chemistry bias to understand how organic chemistry is occurring on Venus.

Future directions:

Agnostic Life Finder (ALF) is a suggested method to extract and identify polymers with a repeating charge in a solvent and characterizing these polymers may yield life on Venus and on other planets. Suggested low cost add-on. Studying non-Earth based chemistry yields insight into alternative ways to support life including informational biopolymers with the necessary structural requirements

Comments from Q&A:

If alien life is silicon based, C-Si-O bonds are more likely than Si-Si bonds. Darwinian evolution is universal then, an informational biopolymer is universal.

Presenter: Noemie Globus

Talk title: Homochirality, Cosmic Rays and Venus

Summary: Cosmic rays from supernovae may be an evolutionary pressure for homochirality as a biosignature. Homochirality may be a phenomenon only produced by life and can be an unambiguous biosignature. Development of instrumentation capable of detecting homochiral molecules can be used to detect biosignatures.

Talk Highlights:

- Supernova explosions occur once every 30 years in our Galaxy.
    - Cause shock waves that accelerate cosmic waves up to 10,000 years after the explosion and diffuse heavy elements
- Cosmic ray showers
    - Cosmic rays interact with planets' atmospheres and induce mutations and promote natural selection
- Muons dominate cosmic rays at sea level
    - Portals interacting in the atmosphere have three main components:
    - electromagnetic, hadronic and muonic
    - Muonic dominates on Earth
    - Polarization of muons arise from weak decay of neutrinos
    - Polarization of the muon flux occurs at sea level
- Cosmic ray origin for biological homochirality
    - Muons (polarized cosmic rays) act as an evolutionary pressure on homochirality.
    - Polarized muons dominate in the middle cloud layer between 50-57 kilometers.
    - During supernova explosions the rate of muon polarization can be boosted for 100-10,000 years.

Further directions:

Develop and identify instrumentation capable of detecting homochiral molecules in Venus clouds. Study chirality in sample return missions from planetary bodies. Irradiate biological samples with polarized beams.

Presenter: Dennis Höning

Talk title: Habitability of an early stagnant-lid Venus

Summary: The carbonate silicate cycle could have preserved liquid water on Venus for 0.9gyr. After which the heating of carbonates may have led to metamorphic crustal decarbonation and the release of CO_2 resulting in increased atmospheric CO_2 partial pressures leading to an increase in surface temperature and a runaway green house effect.

Talk Highlights:

- Plate tectonics
  - Earth- Carbon dioxide is degassed from volcanoes from the interior into the atmosphere which reacts with rainwater to form carbonic acids which dissolves in silicate rocks and is washed into the ocean and then subducted in subduction zones.
  - The lithosphere is a part of the convecting mantle
- Stagnant lid
  - Venus and Mars- Lack plate tectonics and convection occurs underneath the lid. Mars is a single lid planet and Venus has very limited features consistent with tectonic activity and unclear if Venus ever had plate tectonic activity.
  - The stagnant lid is an independent layer above the convecting mantle. Carbon sediments are not recycled, they accumulate on the surface.
  - Lava flows and sinks bury carbonated crust. The temperature of the carbonated crust heats up with depth and at some depth, the carbonate becomes unstable and is released as CO_2.
- Carbon fluxes and reservoirs during the first 1.5gyr on Venus
  - As degassing becomes more active, the carbon concentration in the atmosphere increases at the same time. The surface temperature also rises with subsequent evaporation of liquid water.
- Model that combines interior atmosphere evolution and 3D general circulation to generate planetary albedo and surface temperature
  - Evolution model: The atmospheric carbon dioxide at specific times can be used to model the planetary albedo and Venus surface temperature
  - 3D GCM: The planetary albedo and surface temperature benchmark can be used to model the atmospheric carbon dioxide
  - Combined: Carbonate silicate cycle could have preserved liquid water on Venus surface for about 0.9gyr after which metamorphic crustal decarbonation trigger runaway greenhouse and the rise of carbon dioxide

Future directions:

The model utilized to calculate CO_2 partial pressures used global mean surface temperature. If varying surface temperatures (ie: differences in surface temperature due to lake precipitation, carbonate deposits at poles) were used then the distribution of carbonates may be different.

Presenter: Erika Kohler

Talk title: Stromatolites on Venus - An experimental look into their stability and where to investigate

Summary: Stromatolites are ancient fossils created by photosynthetic organisms with distinct visual layering features and identifiable morphology. When stromatolite samples are subjected to Venus stimulated atmosphere conditions, there are virtually no changes to the samples visually, chemically or in mineral composition with the exception of the disappearance of kaolinite. Future missions to Venus can search for structures with similar features to stromatolites.

Talk Highlights:

- Stromatolites are created by photosynthetic organisms (ie: cyanobacteria) and are the oldest fossils on earth. Characterized their identifiable morphology and chemistry to facilitate search for similar structures as evidence of extinct life in future missions.
- Two different stromatolites choose
  - Neoproterozoic carbonate: ~780Ma. Composed of dolomite, argillite and shale. Originated in Murchisonfjord, Svalbard, Norway. Deposition- marine, glacial.
  - Tumbiana formation: ~2.7Ga. Composed of dolomite, silica (diagenetic). Originated in Hamersley Basin, Western Australia. Deposition- very shallow marine or lacustrine environment.
- 3. Stromatolite samples were subjected to Venus stimulated atmosphere under the following conditions:
  - Powdered and whole, 460C/95 bar, 96% CO_2, 155ppm SO_2, 4% N_2 for 100hrs and analyzed with XRD and SEM
  - Results: Virtually no changes to samples visually, chemical or mineral composition except for disappearance of kaolinite
- 4. Morphology may be more important for recognition of stromatolites than chemistry
  - Stromatolites have distinguishing features at the micro and macro scale
  - Evidence for past Venusian life may still be preserved today in tesserae

Future directions:

Mission launches can be constrained to better search in areas that could have harbored life. Veritas, EnVision and DaVinci missions will allow for IT, local imaging of Venus.

Comments from Q&A:

- It is unknown if stromatolites are resistant to sulfuric acid rain.
- Tesserae may contain some ancient fluvial features.
- Best way to recognize highly deformed stromatolite units is an open question.
- Stromatolites may arise from somewhere else aside from the Tessalor region.

15.4.2 Biosignatures at Venus

Presenter: Heather Graham

Talk Title: The limits of parsimony: Agnostic modes for designing life detection

Summary: Graham discusses various biosignatures that are an indication for life. Concentrating geochemically distinct scarce elements into discrete metastable entities, favoring of lighter isotopes, and homochirality were suggested as principal biosignatures. Agnostic biosignatures explore the possibility space for life, rooted first in knowledge of life

Talk Highlights:

- Agnostic biosignatures
    - Agnostic biosignature is an indication of past or present life that does not presuppose a molecular makeup or metabolism based on life on Earth.
    - An agnostic biosignature is derived from fundamental observations rather than analogy. Thinks about fundamental commonalities of biological systems irrespective of their origin or machinery, it explores the possibility space for life
    - With limiting N=1, looking for life is not a comparison to existing life but rather how biological actions can be recognized
- Organisms are open systems with fluxes of matter and energy that are far from equilibrium thermodynamic
    - Homeostasis is essential to promote metabolic processes
    - Life concentrates scarce elements into discrete metastable entities that are geochemically distinct -- provides a convenient way in life detection to describe what we might see as an example of life. Regardless of metabolism since life can be described as just this one process
    - This definition is general enough to build search patterns based on elemental abundance that can then could be transferred to really unfamiliar systems:
        - C12 bonded to N14 in the cell allows for the visualization of metastable entity geochemically distinct from its environment
        - P31 also allows for chemical distinction from the environment upon sequestration of the element in the cell
        - Cu63 is less charismatic but still linked to metabolism so it allows for geochemical distinction from its surroundings
- Fluxes can be generalized as ecological stoichiometry
    - These concentrations are metastable because there are fluxes with the environment and our responding to their ecosystem
    - Redfield ratio: near constant ratio of carbon nitrogen phosphorus found in oceans all around the world. The bulk chemistry of our oceans is being driven by the biology in these oceans and it provides a way of identifying life. The difference between other bodies of water indicates that there is something fundamentally different in terms of biology there
- Ecological stoichiometries

    - The consequence of variation in elemental composition among organisms and between organisms and their environment
    - Moving elements in and out of cells is an energy dependent process and indicative of a biological imperative. Evidence of energy transfer (an electron looking for a place to rest) is one of the best ways to describe life in the most general sense possible
- Redistribution of materials represents energy and selection mechanism
    - Smaller isotopes are more likely to be incorporated by organic life because it's easier, faster, and energetically favorable
    - Metabolite production also reflects energy and selection mechanisms. unlike a biotic organic material, biotic organic material has a strong preference for chirality and severely lacks structural diversity
- Physicochemical gradients create non equilibrium redox conditions that influence evolution and diversity
- Particular metabolism in a system has to be diagnosed with respect to the peculiarities of that location because it is an economic energy system where there are choices made based on redox gradients of that system
- Life reflects a record of adaptation, unrecognizable without the context of deep time
    - Networks and metabolism don't just arrive de novo on a landscape. By looking at a fossil we cannot determine what current living organism evolved into
- Possibilities space versus habitability
    - Relying entirely on habitability metrics can be a trap. it makes it hard to predict life based on analogy and it doesn't work sometimes even on Earth
    - The presence of life doesn't solely rely on biotic composition or conditions on coordinated communities determined by mobility or the ability to even get into that niche
- Life is everywhere but the environment selects
    - When looking for life, are you looking for life or appropriating patterns from earth? Let the environments drive those investigations

Future needs/recommendations given within the talk:

There is a need to reformulate habitability and biosignatures based on fundamental principles of chemistry and thermodynamics. Relying entirely on Earth based habitability metrics can be problematic.

Presenter: Janusz Pętkowski

Talk Title: Towards an explanation for Venusian cloud anomalies and implications for the habitability of the cloud

Summary: Pętkowski's talk presents sulfuric acid concentrations and scarce water content as the principal environmental challenges that need to be overcome by Venusian life. The speaker hypothesizes that ammonia is possibly synthesized by life in the clouds and acts as a neutralizing agent in the acidic environment of Venusian cloud droplets. Thus, ammonia could be a biosignature and by adding ammonia to future models, it can explain SO2 profile, H2O profile, O2, H2S below the clouds, and the unusual shape of the mode 3 particles.

Talk Highlights:

- Two environmental challenges pose major issues for life in Venusian clouds
    - High concentrations of sulfuric acid in which life has yet to be discovered on Earth
    - Water content 50 times drier than the Atacama, the most driest place on Earth
- Three emerging strategies for life to mitigate these challenges
    - New biochemistry: Life on Venus rely on sulfuric acid instead of water
    - Membrane: Evolution of acid resistant membrane structures
    - Biological neutralization: Life modifies its environment through neutralization of acid to acceptable levels
- Venus atmosphere anomalies
    - The presence of an anomalous UV absorber in the top clouds that absorbs over 50% of all UV light that falls into the planet
    - Mode three particles play a role in anomalous detection of "non spherical droplets" in the mid-low cloud deck
    - Anomalous detections of atmospheric gases in the clouds
        - ammonia, various nitrogen species, 20 ppm oxygen in the clouds, phosphorus, hydrogen sulfide below the clouds, abundance profile of sulfur dioxide and water, hydrocarbons deemed contaminants
- Building a model to explain Venusian anomalies
    - Considers diagnostic chemistry, thermal chemistry and various other chemical processes
    - Paul Rimmer's model: A new model that integrates ammonia and clouds revised by program does not require artificial constraints
    - Addition of ammonia can be used to explain the gases, the oxygen int he clouds, the profile of sulfur dioxide depletion in the clouds, the water vapor profile, hydrogen sulfide anomalies, the existence of mode 3 particles
    - The source of ammonia it could be explained by the presence of microbial life in the clouds
- Ammonia has a neutralizing agent of the Venusian cloud droplets
    - If ammonia acts as a neutralizing agent in droplets on Venus, it would mean that the clouds maynot be as acidic as previously thought

- The challenge of the concentrated sulfuric acid environment may just be an illusion and life may have adapted to it thus it's no longer an issue
- However low water activity may still be an issue

Ways in which future missions may impact the conclusions of the talk, as defined by the speaker:

To send a future mission to Venus to determine which previous atmospheric measurements were true, which were errors, and to search for sources of life. In situ measurement to understand cloud aerosols, PH3 and UV absorber.

Presenter: Sean Jordan

Talk Title: Metabolic Signatures of an Aerial Biosphere in the Clouds of Venus: A Self-Consistent Photo-Bio-Chemical Model

Summary: Jordan discussed how the SO2 depletion observed in the clouds of Venus could be a biosignature. Three metabolic processes using SO2 could explain SO2 depletion in Venusian clouds but the presenter could not determine which metabolic pathway would give results that match observed data. The presenter hypothesizes that either SO2 depletion is due to a currently unknown metabolic pathway or that our current understanding of the lower-atmosphere composition of Venus is wrong and there is no life on Venus affecting the atmospheric chemistry.

Talk Highlights:

- Metabolism links life to the chemistry of its environment
  - The metabolic feeds being consumed from the environment controls the potential to survive and thrive and given sufficiently high biomass it will imprint diagnostic signatures
  - Thus suggested metabolisms for life on Venus provide testable predictions of life's presence given current observations
- Three plausible metabolisms have been proposed for life on Venus to extract energy from its environment and raise the possibility that life is responsible for unexplained sulfur chemistry observed in the atmosphere
  - Anoxygenic phototrophic: utilizes hydrogen sulfide, carbon dioxide and light energy to synthesize carbohydrate, water and sulfur
  - Chemotrophic: utilizes hydrogen, carbon monoxide, sulfur dioxide to produce carbon dioxide and hydrogen sulfide
  - Chemotrophic: utilizes carbon monoxide and sulfur dioxide to produce carbonyl sulfide and carbon dioxide
  - Sulfur chemistry in the cloud layer is generally relatively well understood except for the order of magnitude of depletion of SO2
- Could life be responsible for sulfur dioxide depletion in the clouds of Venus?
  - Sulfur dioxide is observed to be depleted above the cloud layer relative to the one below. An oxygen molecule is liberated from either sulfur dioxide or carbon dioxide which then goes on to react further with SO2 to form SO3 which reacts with water to form H2SO4. For every one molecule of water consumed either one or two molecules of SO2 is consumed in the reaction pathway
  - This implies that the depletion must be within a factor of two of the abundance and this is not observed. Thus no conclusive solutions can be inferred from this
  - It is reasonable to investigate whether this long unexplained feature of chemistry is actually a diagnostic metabolic feature due to a sulfur metabolizing aerial biosphere
  - If attributed to life it provides a stringent test of sulfur based metabolisms

    - In order to perform this a self consistent photo biochemical model has to be constructed coupling biochemistry through the atmospheric chemistry
- A self consistent photobiochemical model
    - “Argo” a one dimensional gene code that follows a passive gas from the surface to the top of the atmosphere and back down again. it takes the initial chemical composition of the base of the atmosphere and solves the reactions of the chemical network
    - The reaction rates determined by the temperature, the altitude, and the time interval over which chemistry is solved for is determined by the diffusion profile which parameterizes vertical mixing in the atmosphere
    - In order to get photo biochemical kinetic model each metabolism in the atmospheric reaction network needs to be coupled
    - Anoxygenic phototrophic $2H_2S+CO_2+$*hv*à $(CH_2O)+H_2O+S_2$. Needs to be coupled with terrestrial anoxygenic respiration to liberate energy (oxygen replaced by sulfur dioxide instead)– $SO_2+ CH_2O$àCO_2+H_2O+S. Net reaction produced: $2H_2S + SO_2$ à S_2+S
    - Each of the metabolic pathways can now be coupled to the atmosphere network and provide a possible destruction pathway for SO_2.
- In coupling these reactions and effective rate constant also needs to be prescribed
    - In order to comply with the aerial biosphere hypothesis metabolic reactions are exclusively limited to the temperate region of the cloud
    - This is done by imposing a condition on the rate constant such that at any given altitude it's equal to some coefficient k, if the temperature is between 273 Kelvin to 373 Kelvin, this then corresponds to the lower cloud layer
    - Increasing the rate coefficient k represents increasing the bio mass density in the model
- Results: each metabolism can reproduce SO_2 observations
    - SO_2 depletion is due to a currently unknown metabolic pathway
    - Our current understanding of the lower atmosphere composition of Venus needs to be refined
    - Life is not affecting atmospheric chemistry. There is no life in the clouds of Venus

Ways in which future missions may impact the conclusions of the talk, as defined by the speaker:

In-situ measurements of the lower atmosphere and remote sensing based variations in SO_2 will test the chemical pathways and potential reactions as metabolic pathways of life in Venus.

Presenter: Jane Greaves

Talk Title: Update on phosphine in Venus's atmosphere

Summary: After input from the community and reanalysis of the data, Greaves et al. conclude that detection of PH3 was definitely detected in the atmosphere of Venus and consistent with the acquired spectra from various instruments. More work needs to be done to determine if it is present in the cloud layers. Attaining data regarding infrared, millimeter spectra and chemical profiles can help understand the concentration and stability of PH3 in Venus.

Talk Highlights:

- Project Outline
    - The project was dedicated to searching biosignature specifically.
    - Phosphine is produced by anaerobic microorganisms on Earth, especially not by abiotic roots -- led to the hypothesis that Venus clouds or a possible habitat for anaerobic acidophiles microorganisms
- The project was initiated with a instrumental approach in mind rather than a biological one
    - a search for ground state rotational transition phosphene and absorption and Venus is highlight atmosphere against a quasi continuum generated at 55 kilometers altitude
    - Phosphine molecule undergoes rotation about its symmetry axis and has a rotational transition wavelength of 1.1 millimeters between zero and one rotation states – I.e. it is the longest wavelength at which it absorbs readily and goes deepest into the clouds
    - In the presence of phosphine, an absorption line against the bright broadband signal that's generated by the warmer deeper layers in Venus atmosphere would be seen
    - Used James Clerk Maxwell telescope and ALMA
- Why is this challenging in practice?
    - Venus at mm wavelength is a very bright source that the telescopes are not readily designed for.
    - However, an absorption of about 1 part in 10,000 in the spectrum provides a very high dynamic range that causes the telescopes to do some undesirable things
    - Instrumental "wiggles" in the spectrum when looking at very high continuum-to-line dynamic range
- Some misconceptions about the results
    - the detections are by chance slightly bigger or wiggles
        - the statistical test used is not amplitude but is very precise to 10^-6 coincidence of observed and expected wavelength
        - there are now three independent datasets for phosphene 1-0 all observing the same rotational axis with different instrumentation that all passed this test --the absorption is always very close to the expected wavelength

        - data processing has moved towards no subjective user intervention
    - The detections are much more likely to be a high rotational state transition of sulfur dioxide
        - not only does this violate the wavelength coincidence test but other sulfur dioxide transitions were observed as well
        - the energy it would take to get the sulfur dioxide molecules to this high rotation state is two to three times hotter than the energy for the characteristic temperature of the atmosphere
    - The narrow lines indicate the absorption is all coming from the cold mesosphere with none from the warmer clouds
        - it is currently hard to distinguish the cloud and mesosphere together from the mesosphere only region because of the loss of line wings when cleaning up the wiggle
- Robustness of phosphine detection
    - Attain strongly detected feature from a simple average of the Spectra from all three epochs
    - superposed is a simple radiative transfer model for 20 parts per billion of phosphine at all altitudes 55 to 90 kilometers, which was post process to mimic the handling of the real data
    - true fit is uncertain (there is no usable information on line wings, no lab based information on phosphine carbon dioxide line broadening coefficient etc)
- Variation of phosphine
    - different areas and illuminations were seen in each observation differences in fitted Lorentzian line profiles are likely just due to modest signal to noise
    - No clear temporal or spatial variations
- Future
    - Acquire a new spectrum perhaps phosphine 2-1. model phosphine with various patterns lifetimes etc
    - Reconcile all data including infrared and millimeter Spectra and in situ mass spectra with chemically plausible altitude profiles
    - The main goal is still to find out if phosphine has cloud origin

Future needs/recommendations given within the talk:

- Observe Venus with Sofia
- Acquire new spectra (proposed for JCMT Large Program in 2022/2023)
- Model phosphine with various drift patterns, lifetimes, etc
- Reconcile all data (infrared + millimeter spectra + in-situ mass-spec) with chemically-plausible altitude profile

Ways in which future missions may impact the conclusions of the talk, as defined by the speaker:

DAVINCI mass spec will provide a chemical profile of Venus clouds to confirm the presence of PH_3 or related P-bearing compounds in Venus. EnVision will study the variation of SO_2 in Venus

15.5 Day 5

15.5.1 Evolution of the Venusian Atmosphere

Presenter: Michael J. Way

Talk title: Did an Ancient Habitable Venus Provide the Seeds for Life Today

Summary: A new view of Venus habitability supported by model stimulation combines two previous viewpoints to yield a habitable Venus with a short-lived magma ocean or late water delivery from 4.2Ga to 1Ga that underwent volatile cycling and transitioned to a hothouse Venus at 1Ga through today. Clouds and rotation rate may have played a key role in Venus' climate by contributing to the formation/loss of surface liquid water in Venus's history. The great climate transition from temperate to hot house is not due to (traditional) increasing solar insolation, may have been due to an impactor or large scale volcanism. Further direct observations and imaging by DAVINCI and IR imaging by VERITAS/EnVision can provide higher resolution of Venus' topological features with further modeling to quantitate day-night cloud asymmetry preventing early ocean formation on Venus is needed.

Talk Highlights:

- Venus' atmosphere provides insights into how early Venus formed, its cloud formation and if conditions for life exist.
    - Venus' radiation has increased from 1900W/m^2 4.2Ga to 2601W/m^2 today relative to Earth's radiation has remained constant at 1361W/m^2
    - What was unique on early Venus when considering its relation to the inner edge of the habitable zone?
    - Modern earth with 40% or more incident radiation will cause Venus like conditions on Earth
- Two traditional views of Venus habitability
    - Long lived magma ocean- existed for 1-5Myr and ultimately lost due to proximity to sun and became very dry for 4+ Gyr
        - H2 escapes to space as water vapor (H20 + hv —> O- + H_2)
        - O2 absorbed in magma ocean
        - PV D/H from this epoch is high relative to Earth
        - No plate tectonics
        - Doesn't explain why a thick 92 bar atmosphere is still present with the lack of a magnetic field on Venus
    - Short lived magma ocean- existed for 1-5Myr. After the planet cooled and water condensed on the surface, a 1Gyr habitable phase began. During which the sun luminosity increased over time leading to a runaway greenhouse effect.
        - Doesn't explain present state or where O2 went
- 3-D view of Magma Ocean Atmosphere.
    - Day-night cloud asymmetry prevents early oceans on Venus but not on earth

        - Subduction may take place in stagnant lid mode
        - Volatile in-gassing could reduce high initial atmosphere and may offer a second chance for late water delivery in late veneer
        - Water retained in terrestrial magma oceans and carbon rich early atmospheres
        - Numerous chondritic impactors and oxidized magma ocean sets Earth's volatile depletion
        - Collision chains among terrestrial planets. Due to asymmetry between Earth and Venus.
        - Implies more late stage accretion (late veneer) than Earth
- Newer view of Venus
    - Short lived magma ocean or late water delivery at 4.5Gya- then had long term habitability from 4.2Ga to 1Ga after which underwent volatile cycling to transition to a hothouse Venus.
        - Clouds and in concert with rotation rate may have played a key role in Venus' climate and contributed to the formation/loss of surface liquid water in Venus' history
        - Evidence for past surface liquid water on Venus (data provided by Pioneer Venus)
        - High D/H ~150x greater than Earth
        - Ar40 data suggests that its reflecting a hydration of oceanic lithosphere (speculative)
            - Galileo/NIMS- highlands may be composed of felsic rocks
            - Venera 8- identified a greenstone belt that may require water/ocean and sedimentary
            - Tesserae radar mapping- Venus may preserve evidence of fluvial erosion
    - Photochemistry (x-ray, UV, solar particles) of Venusian atmosphere
        - Climatic importance of clouds and effect of rotation rate on planet
        - Slowly rotating planets have cloud decks which allows for increased insulation and shielding from incidental radiation that allows for a slow increase in albidio
        - Fast rotating planets form cloud bands that results in decreased insulation and a fast increase in albidio
        - Venus may have become a slow/retrograde rotator with odd obliquity due to:
            - Large impactor
            - Solid body tidal dissipation
            - Core-mantle friction
            - Atmospheric tides
            - Ocean tidal dissipation
- Could Venus have been habitable?
    - ROCKE-3D: 3D general circulation model

    - Modeled 5 epochs resulting in 5 different scenarios for topography, land/sea and water amount
    - Arid-Venus: Dune works (20cm in soil only) <Late Veneer>
    - 10m Venus: 10m GEL in lakes <Late Veneer>
    - 310m-Venus: 310m GEL in lakes and ocean <Primordial>
    - 158m-Aqua: 158m deep ocean aquaplaned, no land <Primordial>
    - 310m- Earth: modern earth with 310m bathtub ocean <Primordial>
    - Mean of the stimulation produced consistent with cool, magma ocean period for 4.2G (Cool early Venus)
        - Temperate period of unknown duration with surface water
- Where is the ocean remnant oxygen?
    - May have been loss to space
    - Diffusion of hydrogen through photodissociation would take $3x10^5$ yrs to 11Gyr
    - Could have only lost ~30cm of water via atmospheric escape of O+
    - Volcanism may provide mechanism for oxygen loss through large scale resurfacing over 100My
    - Degassing, decarbonation and dehydration

Proposed timeline: Magma ocean lifetime 1-100Mya then, accretion of planetesimals ends and a cool early Venus arose with possible early plate tectonics and volatile cycling and CO_2 dominate atmosphere. Leading to a temperate period characterized by surface liquid water and an increase in solar insulation. Partially through the temperate period, N_2 began to dominate the atmosphere. Then, the LIP period began which transitioned from temperate to hot house state and characterized by CO_2 increase, H_2 escape leading to runaway greenhouse. Then, a resurfacing period characterized by absorption of O_2.

Future directions:

1. Comprehensive study to quantitate day-night cloud asymmetry preventing early ocean formation on Venus but not on earth. How does the cloud and atmospheric circulation feedbacks vary nonlinearly and non-monotonically with rotation period?
2. DAVINCI may provide insights into Venus' history with D/H and noble gas isotopes
3. DAVINCI imagining with Veritas and Envision and Venera-D can provide a higher level of visualization and data collection to provide information for site selection.
4. Identify a large impactor- careful isotopic measurements could identify a large impactor
5. DAVINCI IR imagers on Veritas/Envision can be used to find remains of large igneous provinces or ancient aqueous features that may provide an explanation for the heat-death of Venus-like worlds.

Comments from Q&A:

Q: If the Bower et al. results are correct then couldn't the dichotomy of "Primordial deep ocean" vs "late veneer shallow ocean" be an incomplete spectrum of the possibilities? If, most magma ocean water was ingassed, then might later outgassing have provided a deep ocean which would have avoided the Turbet type destruction of an early ocean?

A: Yes- need more data.

Q: What are the uncertainties dating the resurfacing events? Assuming a temperate pre-resurfacing atmosphere, how fast would the greenhouse take hold once the resurfacing started? Is there an expected transient atmosphere between before resurfacing and after resurfacing?

Q: Do you estimate H2/H20 concentrations at the thermosphere height? Hydrogen escape strongly depends on the hydrogen density at the exobase, and this should depend on upward convection of H20/H2. How much can high temperature enhance it?

Q: Did you test the robustness of the substellar cloud feedback at very high CO2 partial pressures? Ie: 10bar of CO2 or more

- DAVINCI will measure surface reflectivity at Alpha Regio below the clouds which will provide constraints on surface compositions. Veritas, EnVision and DAVINCI will all measure surface emissivity from above the clouds providing global surface composition constraint information.

Q: Isn’t it quite likely that the initial rotation rate was not 243 days but faster with unknown spin axis orientation?

A: We have no constraints on what Venus’ early rotation rate was. It could have been tidally locked from very early on. Because of the stochastic nature of late accretion, we simply cannot constrain it.

Presenter: Matthew B. Weller

Talk title: From Whiffs to Pulses: Links between tectonic evolution, outgassing and atmospheric development

Summary: Venus is considered to be an episodic lid planet that lacks plate tectonics and may be in transition between tectonic and stagnant states. It has undergone extensive resurfacing events that have generated a thick outgassed atmosphere with high pressures suppressing outgassing, and influencing internal temperatures which affects surface mobility. Future missions can provide additional observations to inform Venus' geology and atmosphere to improve models.

Talk Highlights:

- Venus is hypothesized to be an example of a planet in transition in tectonic regimes
  - Young planet emplaced in the last 500-1100 Myr.
  - Volcanoes cover 80% of the planet's surface with current volcanic rates comparable to earth's intercontinental volcanic rate (~0.5-4km^3/yr)
  - Thick atmosphere with high surface temperatures
  - ~92bar, ~96.5% CO2, ~740K
- Suggested to be an episodic lid that alternates between extreme mobility and extreme stagnancy.
  - Greatest atmospheric compositional changes occurred early and are currently reduced
  - No evidence of plate tectonics
  - Atmospheric pressure suppresses outgassing
- Complex feedback in mantle convection leads to instabilities and changes
  - Higher internal heating favors surface immobility
  - Hot lithosphere has smoother flow and able to withstand higher stresses
  - Decreasing internal heating favors surface mobility
  - Faster convection creates more stress that can break lithosphere
- Venus transition from early mobile state to stable single plate through an unstable episodic transitional stage
  - Transition is a stochastic process that is sensitive to amplitude of perturbation
  - Mobility can be decreased through a loss of pore fluids which yields 30% increase in yield strength
  - Increased surface temperatures dries out lithosphere which decreases conductive strength but increases the strength of the lithosphere

Future needs/recommendations given within the talk:
Future missions to let us know more about current venus geology and the atmosphere which will allow us to more precisely models Venus' past
Comments from Q&A:
An overturn event is like a hemisphere/subhemisphere scale LIP event lasting some 60-100Myr per overturn. Not traditional subduction as defined on earth.

Presenter: James Head

Talk title: Formation and stability of the Venus Atmosphere: Insights from the Geological Record and Implications for Evidence of Life on Venus

Summary: Venus may have been characterized by more earth like conditions in early history that may have carried into last 20% of Venus history. The current high atmospheric pressure severely inhibits degassing of mantle-derived S, H_2O and CO_2 brought to the surface by volcanism and respective contribution to the observed atmospheric concentrations observed today. Current Venus atmosphere may be a fossil atmosphere, largely inherited from a previous epoch in Venus history. Further work to answer what the atmospheric pressure, water content and solar insulation tipping point that led to the general stabilization of this fossil atmosphere is recommended.

Talk Highlights:

- Forward models predict that Venus may have been characterized by more Earth-like conditions in early history that may have carried into last 20% of Venus history.
- Volcanism is the primary transfer process of volatiles from mantle to surface/atmosphere
    - Venus has a very high atmospheric pressure (~93 Bar)
    - Current high atmosphere severely inhibits degassing of mantle derived S, H_20 and CO_2 brought to the surface by volcanism and contributes to the atmosphere
    - Severely inhibits pinion explosive explosive volcanic activity that could deliver exsolved volatiles directly into the atmosphere
    - Sufficient to preclude Explosive volcanism requires volatile contents (>3-5% wt%) that is several wt% higher than typical Earth magmas (<1% wt)
- Total volume of lava erupted in the period of global volcanic resurfacing
    - Insufficient to produce the CO2 atmosphere observed today
    - Significant part of the CO2 atmosphere must have been inherited from a time prior to the observed geological record sometime in the first 80% of Venus history
- Amount of water degassed to the atmospheric pressure was only 10% of today
    - Current low atmospheric water content may be an inherent characteristic of the ambient atmosphere and not required enhanced rates to space in the last 20% of Venus history
- Current Venus atmosphere may be a fossil atmosphere largely inherited from a previous epoch in Venus history

Future needs/recommendations given within the talk:

- What was the atmospheric pressure/water content/solar insulation tipping point that led to the general stabilization of this fossil atmosphere?
- Use inverse modeling instead of forward modeling: i.e. using current atmosphere as a baseline and work backwards in time
    - Benefits include the ability to assess:

- Nature and magnitude of the major phases of volcanism
- Style and magnitude of volatile output
- Candidate effects of their volatile release on the observed atmosphere

Comments from Q&A:

Consider that clouds may be actively maintained by green house degassing. Difficult to transport high levels of volatiles into clouds. Most volatile may be trapped in magma and contribute to long term diffusion and may provide variability in SO_2. Big unknown is interaction of atmosphere with surface.

Speaker: Richard Ernst

Talk title: The Implications of Applying a Large Igneous Province (LIP) Context for Volcanism, Tectonics and Atmospheric Evolution on Venus

Summary: Characterizing LIPs on Earth and Venus can help improve our understanding of volcanism on Venus. Further characterization of LIPs by grouping magmatic units into events, using Graben fissure systems as the surface expression of underlying dyke swarm, linking mantle plumes and triple junction rifting can help locate magma reservoirs and sources of lava flows as well as respective ages and relationships. Detailed flow and graben mapping and determining the relative ages can improve modeling of the evolution of the Venusian atmosphere and testing the hypothesis of a Great Climate Transition.

Talk Highlights:

- Terrestrial Large Igneous Provinces (LIPs)
    - Huge volume of mainly mafic magma with a short duration of emplacement
    - Magmatic units can be grouped into events
    - Venusian magmatic units including large volcanoes (mons), coronae, novae, large flow fields (flucti), early plains, minor components (shield fields, canals), are possible within tesserae
    - Venusian magmatic units can be linked to plumes/diapirs and largest components can be considered LIPs
- Graben fissures as a surface expression of an underlying dyke swarms
    - On Venus giant radiating and circumferential dyke similar to those on Earth
    - Can use dykes and graben swarms to map edge of underlying mantle plume
    - Edge may be identified as radiating transitions to linear or at the edge of a circumferential swarm
- Proposed Great Climate Transition Event on Venus (~700-1000Ma ago)
    - Intense period of LIP volcanism led to dramatic CO_2 release and global runaway greenhouse global warming
    - Possible that Venus had the same history of LIP magmatism as Earth and a sudden random pulse of multiple large LIPs may have caused a runaway greenhouse effect that led to the Great Climate Transition Event
    - On Earth, LIPs were huge mainly balsamic events that caused dramatic climate change
    - Natures barcode

Future needs/recommendations given within the talk:

- How to best distinguish grabens overling dykes from purely extensional graben in the venusian rift system?
- Detailed flow and graben (dyke) mapping of both planitia and younger volcanic centres and determination of relative ages from cross-cutting relationships can constrain the volume v time release of CO_2 and SO_2. This will provide parameters for improved

modeling of the evolution of the atmosphere and testing the model of the presence of an earlier Earth-like atmosphere and the hypothesis of the Great Climate Transition to today's observed decidedly "un-Earth-like" atmosphere

- Understanding on if LIPs can cause a runaway greenhouse effect that changed Venus from Earth-like conditions to current conditions

Comments from Q&A:

LIPs not likely to be related to Lunar Mare on Venus as are not the same thickness due to internal plumbing on Venus. LIPs are more likely to be vertically oriented based on current evidence and understanding.

Presenter: Martin Turbet

Talk title: Day-night cloud asymmetry inhibits early ocean formation on Venus

Summary: 3-D global climate global model simulations of the atmosphere of young, rocky planets reveal the stabilizing role of subsolar clouds. The nightside cloud has a water vapor dominate gas that absorbs incoming heat on the dayside and undergoes cooling to space by thermal emissions resulting in a low albedo. Cloud feedback mechanism prevents early ocean formation on terrestrial planets.

Talk highlights:

- 3-D global climate model simulations adapted for hot water dominated atmospheres reveal stabilizing role of sub solar clouds
    - Day-night cloud asymmetry prevents early oceans on Venus but not Earth
    - Clouds effectively reflect sunlight in daytime
    - Nightside efficiently undergo thermal cooling to space
        - Water vapor (steam) dominates gas-water cloud and preferentially forms on nightside
- Mechanism of nightside cloud formation on planets with hot, water dominated atmosphere and dry surface
    - Water vapor strongly absorbs incoming solar heat on dayside and undergoes cooling to space by thermal emission resulting in a low albedo
    - Cloud formation on nightside creates an efficient greenhouse effect
    - Water condensation leads to decreased surface temperature
    - Cloud feedback mechanism prevents early ocean formation on terrestrial planets
    - No early surface condensation on Venus
- A faint young sun is required to form oceans on earth

Future needs/recommendations given within the talk:

DAVINCI, VERITAS, and EnVision will collect data of the surface and atmosphere of Venus which will allow for more accurate models of Venus' past

Comments from Q&A:

This model does not assume that the rotation rate has remained the same. A slow rotating planet allows for time for water vapor to accumulate and dominate as gas preferentially accumulates on the night side.

Presenter: John E. Hallsworth

Talk title: Venus' Clouds are an Order of Magnitude Beyond the Acidity Limit and Two Orders of Magnitude Below the Water-Activity Limit for Active Life

Summary: Venus cloud when considering limits of life does not allow for habitability of life as we know it. Direct observations and models imply that Venus' atmosphere is dry with Venus clouds' water activity between 0.01-0.0001 at 80-100% sulfuric acid concentration. Data obtained from DAVINCI mission are likely to verify previous measurements.

Talk Highlights:

- Water activity is the effective concentration of water molecules
    - Thermodynamic parameter based on Raoult's law dependent on temperature and pressure
    - Potent determinant of cell function and a key parameter for habitability and planetary protection privacy
    - 0.585 is the water activity limit for active cell division and metabolism for terrestrial life
    - Ie: Aspergillus pencillioides
    - pH= -0.06 is the acidity limit for active cell division and metabolism for terrestrial life
    - Ie: Picrophilus torrid
- Direct observations agree with models that Venus' atmosphere (gaseous phase) is dry
    - Venus' clouds have water activity between 0.01-0.0001 at 80-100% sulfuric acid concentration
- Water activity is independent of the solution details
    - Water activity determines sulfuric acid concentrations of Venus's clouds
    - Sulphuric acid concentration independent of water activity and within clouds concentration dependent on rate of diffusion between gas and liquid
    - Depends only on radius of cloud droplets
    - Sulphuric acid at high concentrations, destroys cellular structures

Future needs/recommendations given within the talk:

The data obtained from DAVINCI will inform on the abundance of water in the atmosphere

Comments from Q&A:

Mode three particles that are non-spherical and likely composed of some unknown material coated with H_2SO_4. Measurements made by Pioneer Venus and Venera probes suggest variations in water vapor measurement. A different complex chemistry might permit different alien life forms. It is possible that a mechanism of adaptation of potential Venus microorganisms to the transition from presumed Venusian water to H_2SO_4.