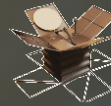
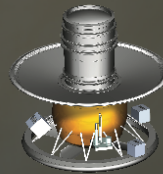
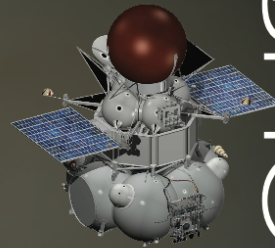
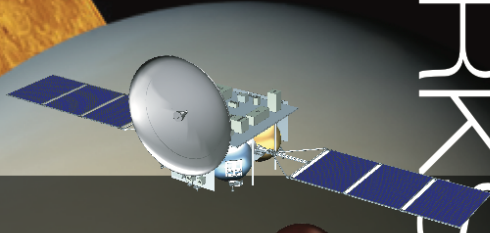


WORKSHOP REPORT

Venera-D Landing Sites Selection and Cloud Layer Habitability Workshop Report

IKI MOSCOW, RUSSIA
OCTOBER 2–5, 2019

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





**Venera-D Landing Sites Selection and Cloud Layer Habitability
Workshop Report**

IKI Moscow, Russia

October 2-5, 2019

**Space Science Research Institute (IKI), Russian Academy of Science,
Roscosmos, and NASA**

<http://venera-d.cosmos.ru/index.php?id=workshop2019&L=2>

<https://www.hou.usra.edu/meetings/venera-d2019/>

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Introduction

The multi element Venera-D mission concept has been under development for at least 4 years, with the goal of advancing the investigation of *Venus' atmosphere, surface and interior and the processes that link them as a system*. The baseline Venera-D mission includes an orbiter, a VEGA like lander and one long life surface station (LLISSE); among the potential mission augmentations it may include more LLISSEs, 2 small seismic stations, a variable altitude aerial platform or perhaps one or two sub-orbiters. (*please see the Phase II report www.iki.rssi.ru/events/2019/Venera-DPhaseIIFinalReport.pdf*).

During the 2018 meeting of the Roscosmos/IKI-NASA Joint Science Definition Team for Venera-D Mission, the Directors Dr. Lev Zeleny and Dr. Lori Glaze agreed that a workshop was a good next step to discuss potential landing sites and to consider investigations related to the habitability of the global cloud layer. The workshop was held 2-5 October 2019, the week preceding the 10th Moscow Solar System Symposium at Space Research Institute (IKI), Moscow, 7-11 October 2019. Space Research Institute (IKI) and the Vernadsky Institute (GEOKHI) of the Russian Academy of Sciences were the host of the workshop. NASA Headquarters offered workshop travel support for 6 early career scientists and experts. The workshop information was distributed via Venus Exploration Analysis Group, VEXAG (ipi.usra.edu/vexag/), the Planetary Exploration Newsletter (planetarynews.org), via the NASA astrobiology research network and IKI web site. IKI also created a website (<http://venera-d.cosmos.ru/index.php?id=workshop2019&L=2>) for the workshop, “Landing Sites and Habitability of the Cloud Layer” to collect abstracts.

The 2019 Venera-D workshop had two themes; *Theme I: Potential Landing Sites; and Theme II: Cloud Layer Habitability*.

Twenty-one (21) abstracts were received for the Landing Sites theme of the workshop (2-3 October 2019) and twenty-three (23) for the Cloud Layer Habitability theme (4-5 October 2019) from scientists residing in Russia, US, Japan, UK, Austria, Poland, and India. In addition, Dr. Mary Voytek (NASA HQ Astrobiology Program Scientist) and Dr. Adriana Ocampo (NASA HQ Venus Lead) also attended. Two presentations were made remotely via video and all presentations were recorded. A team of six scribes (shepherded by Dr. K.-L. Jessup) took detailed notes for each presentation and the distillation of their notes makes up this report. The notes include the main points from each presentation, a brief summary of the presentation and any discussion following each presentation (see Appendix A).

A description of the themes is below:

- 1) Theme I: Potential Landing Sites:** Input from the Venus community was provided on criteria for scientifically desirable landing sites for the Venera-D lander which could be accessible from the approach trajectory, given the known engineering constraints; and the criteria for synergies between the lander and other potential landing elements—such as multiple small stations for weather, surface boundary

chemistry and dynamics, and/or seismic studies. Science priorities for the landed elements of the Venera-D mission are:

surface morphology, mineralogy, aeolian processes, surface-atmosphere chemical and dynamical Interactions, elemental abundances of rocks, seismology, and electrostatic charging processes

The abstracts were divided in the areas of: landing sites targets; geology, mineralogy, surface morphology, seismology, atmospheric boundary studies

2) Theme II: Cloud Layer Habitability: Input from the broader community was provided on the key altitudes, latitudes, methods and suitable platform options for completing habitability studies. Long-duration aerial platforms were discussed as well as measurements that may be made from the Venera-D baseline elements which could answer key or ancillary questions in support of the study of Venus' habitability present and past.

The driving science questions for these discussions were:

- *What species can survive/thrive in the clouds of Venus?*
 - How do we know, what should we look for?
- *Where may life at Venus have come from?*
 - If it migrated from the surface to cloud –what are the tracers, what should we look for, where should we look for it?
 - If it was delivered to Venus —what are the tracers, what should we look for?

The abstracts were divided into four categories- (i) Possibility of life in the habitable zone in the clouds, (ii) Potential risks to short- and long-term survival in the clouds, (iii) Potential biosignatures, and (iv) instruments and platforms required to support the search for biosignatures.

Dr. Sanjay Limaye coordinated with the Astrobiology Journal to publish a collection of papers related to the habitability of the Venus cloud layer, and about a dozen are in the process of being submitted to the journal for peer review. A list of tentative titles and lead authors is included in this report. The Special Collection of papers is targeted for publication towards the end of 2020. Additionally, Dr. Tracy Gregg is coordinating a review paper on Venus landing sites.

We thank Dr. Lev Zelenyi, Dr. Ludmila Zasova and Dr. Anatoly Petrukovich for hosting the workshop and NASA HQ, Roscosmos and Lavochkin N.P.O for supporting the workshop. Dr. Elena Vorobyova was critical in publicizing the workshop within Russia. Dimitry Gorinov provided excellent logistical support for most critical aspects of the workshop and also developed, and regularly updated, the workshop information on the web. The scribes worked diligently to take notes and were critical in producing this report.

Travel support from NASA HQ was critical in ensuring good participation from the US science community. Volunteer scribes enabled the production of this report. Finally, we thank all the participants from the different countries for contributing their ideas and dialogue in the vigorous discussions which enabled a very successful workshop.



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Final Agenda

Venera-D Landing Sites Selection and Cloud Layer Habitability Workshop

2 – 5 October 2019

IKI RAS

Landing Site Theme

Day 1: 2 October 2019

10:00 – 10:20 L. Zelenyi, Welcome (from IKI)
Welcome to Conference: L. Zasova, A. Ocampo & T. Gregg

LS-Session 1: Engineering/Convener: Gregg & Kremic

10:20 – 10:40 Zasova: Venera-D update, including landing site constraints from orbit solution

10:40 – 11:00 Sedykh: The Venera-D Lander

~~11:00 – 11:20 Eismont: Venera-D Orbits, landing site constraints~~

11:20 – 11:40 *Break*

11:40 – 12:00 Gerasimov and Economou: Venera-D lander payload instruments

12:00 – 12:20 Zelenyi and Polyansky: Venera-D Cameras/TV

12:20 - 12:50 *Discussion*

12:50 – 12:55 Logistics–Gorinov & Jessup

12:55 – 14:00 *Lunch*

LS-Session 2: Instruments and simulations/Convener: Gregg & Economou

14:00 – 14:20 Kremic: LLISSE (Venera-D Long Life Element) and SAEVe (Potential Contributed Element)

14:20 – 14:40 Treiman: CheMin-V,A Definitive Mineralogy Instrument for Landed Science on Venus

14:40 – 15:00(remote)Schroder: MIMOS II, miniaturized Mössbauer spectrometer for Venus surface investigation

15:00 – 15:05 Izenberg: APL's Venus Environment Chamber (AVEC) (*poster intro–lightning talk*)

15:05 – 15:10 Kremic: Glenn Extreme Environment Rig (GEER) (*poster intro–lightning talk*)

15:10 – 15:30 *Break (Scribe Meeting)*

15:30 – 16:30 *Discussion*

LS-Session 3: What do we know already? /Convener: Gregg & Ivanov

16:30 – 16:35 Izenberg: VEXAG documents, 2019 revisions (*poster intro–lightning talk*)

16:35 – 16:55 Esposito: VEXAG Landing Targets (2014 VEXAG workshop)

16:55 – 17:15 Economou: What do we know about Venus chemical composition ?

17:15 – 17:35 Berger: Surface-atmosphere interaction influences on in-situ Venus surface analyses

17:35 – 18:15 *Discussion*

18:15 – 18:30 *Day 1 Wrap-Up, Invitation to a.m. Posters*

Day 2: 3 October 2019

9:00 – 10:00 *Poster Session in main meeting room*

10:00 – 10:10 Welcome to Day 2 Oral Session & Logistics: Misha I. and Dima G.

LS-Session 4: Landing Site Selection/Convener: Economou & Kremic

10:10 – 10:30 **Mikhail Ivanov:** Landing Site Constraints

10:30 – 10:50 **Richard Ghail (presented by D. Titov):** Envision, European Concept of a Mission to Venus

10:50 – 11:10 **Jason Rabinovitch:** Global Characterization of Safe Landing Sites Using Venera Panoramas & Magellan

11:10 – 11:30 **Mikhail Ivanov:** High priority of tessera terrain for in situ analysis

11:30 – 11:45 **Tracy Gregg:** Potential landing site hazards in Venus' volcanic plains

11:45 – 12:00 *Break*

12:00 – 12:20 **Richard Ernst:** Evaluation of Landing Site Targets in the Alpha Regio Quadrangle

12:20 – 12:40 **Paul Byrne:** Mobile crustal blocks as landing site targets

12:40 – 13:00 **Patricia Beauchamp:** Potential landing sites for a complementary US Venus Flagship Mission

13:00 – 13:20 **Richard Ernst:** Site selection for geological testing of global warming models on Venus

13:20 – 14:20 *Lunch*

14:20 – 14:40 (remote) **Piero D'Incecco and Iván López:** Olapa Chasma – Idunn Mons: investigating recently active terrains

14:40 – 15:00 **Allan Treiman:** Cleopatra crater: Granite Mountains and Tellurium Snow?

15:00 – 15:20 *Break (Scribe meeting)*

15:20 – 17:30 *Discussion (Panel lead by Noam Izenberg; intro comments about camera from T. Gregg)*

17:30 – 18:30 **Workshop Welcome Reception in the Exhibition Hall**

Cloud Habitability Theme

4 October 2019 (Day 3)

10:00 – 10:15 **Ivan Polyansky: Landing Site Special Presentation: Descent Cameras**

10:15 – 10:20 **Welcome to Cloud Habitability Sessions: Elyena & Ocampo**

CH-Session 1, Habitability at Venus/ Conveners: Jessup & Zasova

10:20 – 10:40 **Michael J. Way: Ancient Venus climate & Observational Constraints**

10:40 – 10:50 **Shawn Domagal-Goldman: Venus as an Exoplanet (lightning talk)**

10:50 – 11:10 **Sanjay S. Limaye: Case for Search of Bio-signatures on Venus**

11:10 – 11:30 **Oleg Kotsyurbenko: Terrestrial microorganisms from extreme environments as analogues to hypothetical microbial forms inhabiting Venus' clouds**

11:30 – 11:50 **David H. Grinspoon (remote): Considerations of energy, biomass limits and cloud microphysical implications of a putative Venus cloud biosphere**

11:50 – 12:10 **Break**

12:10 – 12:30 **Vladimir Kompanichenko: Evaluation of Possible Origin of Life in Early Venus in Case of Available Liquid Water**

12:30 – 12:50 **Valeriy Snytnikov: Chemical basis of a hypothetical life on Venus**

12:50 – 12:55 **Logistics-- Jessup & Gorinov**

12:55 – 14:10 **Lunch**

CH-Session 2, Viability (Candidates and Processes)/ Conveners: Elyena & Oleg Kotsyurbenko

14:10 – 14:30 **Jaime A. Cordova: Investigating the Viability of Microorganisms in a Venus Cloud Analog**

14:30 – 14:50 **Rakesh Mogul: Venus' Spectral Profiles and the Potential for Microbial Life in the Clouds**

14:50 – 15:10 **Arif Husain Ansari: UV-absorbance and survival mechanism of potential bacteria in Venus clouds**

15:10 – 15:30 **Mark Bullock (remote): Venus atmospheric chemistry and possible metabolic pathways for microbial organisms**

15:30 – 15:50 **Tetyana Milojevic: Metallophilic extreme thermoacidophiles: potential biosignatures in the Venusian clouds**

15:50 – 16:10 **Break (Scribe meeting)**

16:10 – 16:20 **Discussion Preamble**

16:20 – 17:30 **Discussion**

17:30 – 17:40 **Discussion Review**

17:40 – 17:50 **Break**

CH-Session 2b, Venera-D Spacecraft Support and a.m. Poster Invitation/ Convener: Jessup

17:50 – 18:05 **Anastasia Kosenkova, Poster Preview Talk: Venera-D: Spacecraft and Orbits (lightning talk)**

5 October 2019 (Day 4)

9:00 – 10:00 *Poster Session across from main meeting room*

CH-Session 3, Origin and Survivability/ Conveners: Limaye & Oleg Kotsyurbenko

- 10:00 – 10:20 **Anatoli Pavlov:** Permanent infecting of the Venus upper atmosphere by transfer of terrestrial microorganisms through the ejected dust particles from Earth and Mars.
- 10:20 – 10:40 **Margarita Kruchkova:** High stability of mycobiota from desert soils to the impact of ionizing radiation (100 kGy) at low temperature and pressure
- 10:40 – 11:00 **Grzegorz Słowik:** Observation of the life cycle of extremophilic bacteria of the genus *Acidophilus* under the conditions of the reconstituted Venus atmosphere
- 11:00 – 11:20 *Logistics (pizza money collection, dinner head count) & Break*
- 11:20 – 12:30 *Discussion*
- 12:30 – 13:30 *Pizza lunch in main session room*

CH-Session4, Detection Mechanisms/ Conveners: Limaye & Jessup

- 13:30 – 13:50 **David J. Smith:** Methods for sampling bioaerosols in Earth's troposphere and stratosphere
- 13:50 – 14:10 **Diana M. Gentry:** Bioaerosol Sampling Considerations for In Situ Analysis
- 14:10 – 14:30 **Satoshi Sasaki:** Life-signature Detection Microscope for Cloud Layer Particles
- 14:30 – 14:50 **Mark Bullock (*remote*):** Venus atmospheric chemistry and possible metabolic pathways for microbial organisms
- 14:50 – 15:00 *Break*
- 15:00 – 15:15 **Kevin Baines:** Aerosol Mass Spectrometer for characterizing the Venus Cloud Habitability Zone
- 15:15 – 15:30 **Jason Rabinovitch:** Aerobots to Explore Venusian Clouds
- 15:30 – 15:50 *Break (Scribe Meeting)*
- 15:50 – 16:10 *Plenary: Mary Voytek: Venus Astrobiology Exploration, NASA perspective*
- 16:10 – 17:30 *Discussion of Big Questions, Panel lead by Voytek, Jessup & Kotsyurbenko*
- 17:30 – 17:45 *Break*
- 17:45 – 18:15 *Meeting Wrap Up, Review of Actions and Next Steps*
- 18:15 – 19:00 *Take Metro to Celebratory Dinner @Mama Gochi, Bolshaya Dmitrovka 5/6 s.1*
- 19:00 – 21:00 *Celebratory Dinner*

Posters:

- Zasova et al. the Venera-D Mission Concept Fact Sheet
- Gilmore et al. NASA Venus Flagship Mission Concept
- Hall et al. the NASA Aerial Platform Study: *Aerobots to Explore Venusian Clouds*
- Izenberg et al. APL's Venus Environment Chamber (AVEC)
- Izenberg et al. Venus Exploration Analysis Group (VEXAG) roadmap documents
- Kremic et al. Glenn Extreme Environment Rig (GEER)
- Belov et al. Multiple stress-tolerance of culturable bacteria from extreme habitats: astrobiological implication

An archive of the meeting abstracts for the Landing Site theme is posted at:
http://venera-d.cosmos.ru/uploads/media/Landing_Sites.zip

An archive of the meeting abstracts for the Cloud Habitability theme is posted at:
<http://venera-d.cosmos.ru/uploads/media/Habitability.zip>

An archive of the presentations from both themes is posted at:
http://venera-d.cosmos.ru/index.php?id=vmw2019_presentations&L=2

Summaries of the meeting presentations for the Landing Site and Cloud Habitability themes follows the technical report, listed as shown on the agenda.

Astrobiology Special Collection of papers from the workshop

Prior to the work, the Editors of Astrobiology journal were approached regarding potential publication of a few papers expanding on some of the presentations at the Venus cloud habitability workshop and the response was very promising. The Chief Editor encouraged inviting a few to be Guest Editors for the Special Collection of papers to be published in late 2020 following the peer-review and revision process. Presenters were encouraged to form collaborations to focus on a few topics of interest and significance for further research relevant to the cloud layer habitability. A tentative list of lead authors and topics is presented below.

#	Lead Author	Tentative Title
1	Baines, Kevin	Cloud Aerosol Spectrometer
2	Bullock, Mark	Population dynamics of possible microbial life in Venus' clouds
3	Cockell, Charles	The Venusian Cloud Layer: What we need to know about one of the Solar System's most interesting uninhabitable environments
4	Izenberg, Noam	Equation of Life for Venus
5	Kompanichenko, Vladimir	Origin of life in oscillating extreme environment (application to Venus and other planets)
6	Kotsyurbenko, O.R.	Exobiology of Venus clouds: terrestrial analogs and methods of detections
7	Limaye, Sanjay	Venus, an Astrobiology Target
8	Milejevic, Tetyana	Potential Bioavailability of Phosphorous in Venus Clouds
9	Mogul, Rakesh	Venus' Solar Flux and the Potential for Photosynthesis in the Clouds
10	Sasaki, Satoshi	In situ bio/chemical characterization of Venus cloud particle using life-signature detection microscope
11	Treiman, Allen	Supply of volatiles to the Venus atmosphere

Guest Editors for the Special Collection: S.S. Limaye, O. Kotsyurbenko, R. Mogul, A. Ocampo

Technical Report: Venera-D Landing Site and Cloud Habitability Workshop

1.0 Missions to Venus

1.1 Past and Present

A summary of Venus missions was presented during the plenary portion of the workshop.

1.1.1 Available Instruments and Lessons Learned Surface Geology

Direct measurements of the composition of the Venusian surface are limited to the Soviet-era Venera and Vega landers. Veneras 8, 9, 10, 13 and 14 and Vega 1 and 2 returned compositional data (e.g., Treiman, 2007, and references therein, for a review of Venus surface composition). Vega 1 and 2 contained an X-ray fluorescence instrument to measure bulk composition of major elements at the surface. The Venera landers contained gamma-ray spectrometers that measured the abundances of K, Th and U in Venusian surface materials. Information about the rock and regolith mechanics were obtained by observing and measuring interactions between the landers and the Venusian surface.

Aside from the compositional measurements made by the Venera 8 lander, the measurements of the Venusian surface are consistent with tholeiitic basalts (Treiman, 2007). Venera 8 measurements revealed K, Th and U contents that suggest a more alkalic--and therefore magmatically evolved--composition. Interestingly, a flat-topped, circular, steep-sided “pancake dome” rests within the Venera 8 landing ellipse, and there has been speculation (Basilevsky et al., 1992) that the Venera 8 craft landed on, and sampled, this dome material.

Other information available for the surface composition come from emissivity measurements obtained using the visible and near-infrared (VNIR) spectrometer on board Venus Express (Drossart et al., 2007). These measurements reveal that, at the 1.1-micron wavelength, the tessera are distinct from the surrounding plains (Gilmore et al., 2017). Anomalously high emissivity values have been interpreted to be caused by young ($1 - 10^6$ years old) lava flow fields on the surface (Smrekar et al., 2010; Filiberto et al., 2020).

The proposed instruments that would be included on a Venera-D lander to measure surface composition include an active Gamma-ray spectrometer (GRS), an X-ray fluorescence (XRF) spectrometer, and possibly an alpha-particle X-ray spectrometer (APXS) (VDJSDT, 2019).

Our understanding of Venusian surface processes is dominated by the near-global coverage of the Magellan Synthetic Aperture Radar (SAR), which imaged the surface at resolutions >75 m/pixel. Magellan also provided altimetry (topographic) data, which were collected with a horizontal resolution of 10 - 30 km/pixel and a vertical resolution of 80 - 100 m. These resolutions are too coarse for detailed morphologic analyses.

Locally, Magellan stereo data can increase the horizontal resolution to 1 - 2 km/pixel (Herrick et al., 2012), which is still too low for detailed analyses of volcanic flow features and plains, for example.

1.1.1.1 Open Questions

- **Is Venus still volcanically and tectonically active?** Recent investigations suggest that specific volcanic terrains might be only a few years old (Filiberto et al., 2020). The small number of impact craters on the Venusian surface (<1000) suggests an average surface age of ~750 Ma, but the complicated surface geology leaves the possibility of locally much older--or younger--terrains.
- **How do the surface and the atmosphere chemically interact?** High temperatures and pressures at the surface of Venus, combined with the CO₂-rich atmosphere (and a minor amount of highly reactive sulfur compounds) are similar to some terrestrial low-grade metamorphic environments. It is likely that there are chemical interactions between the surface and the atmosphere, but the available data do not provide tight constraints on rock/regolith or near-surface atmospheric compositions.
- **What is the composition of the tesserae?** Locally, tesserae terrain represents the highest and most deformed (via faulting) materials on the Venusian surface. Cross-cutting and superposition relations are consistent with tesserae representing some of the oldest materials on Venus' surface. Characterizing the chemical and mineralogical composition of the tesserae is essential to constraining the thermal, mechanical and chemical evolution of the interior and surface of Venus.
- **What minerals exist on the surface of Venus?** Although the Venera and Vega landers measured the abundances of elements within the surface samples, there are no in-situ measurements of surface mineralogy. Identifying the minerals present on Venus is vital for understanding interactions between the surface and atmosphere, as well as the most recent volcanic and igneous processes.
- **What is the nature and rate of chemical interactions between the surface and atmosphere?** There are no direct measurements of the Venusian atmospheric composition or wind speed at the planet's surface. Without this information, we cannot accurately interpret any remotely sensed data of the surface.

1.1.2 Available Instruments and Lessons Learned for Cloud Habitability

A wide variety of instruments have been employed to obtain *in situ* atmospheric measurements on Venus, including mass spectrometry, gas chromatography, large probe mass spectrometry (LMNS), and UV spectroscopy. Johnson and Oliveira (2019)¹ present a comprehensive summary of all *in situ* measurements gleaned from previous flyby, lander, and orbiter missions. Several questions concerning the habitability of the

¹ Johnson, Oliveira (2019). "Venus Atmospheric Composition In Situ Data: A Compilation." *Earth and Space Science* 6. <https://doi.org/10.1029/2018EA000536>

Venusian cloud layer exist. Some of the major outstanding questions are described in 1.1.2.1.

1.1.2.1 Open Questions

- **What are the unknown spectral absorbers?** Approximately 20 potential candidates have been identified, several of which are organic. However, all of the candidate compounds have either been disproven or have not yet been studied. Microbes have been experimentally shown to produce the observed spectral absorption pattern. This observation posits the exciting possibility of life on Venus. However, much more experimentation and measurement is necessary to investigate this possibility.
- **Can microbes reproduce in aerosols? Can the atmosphere host a viable ecosystem, even if surface conditions are inhospitable?** Viable microbes have been detected in the Earth's atmosphere, but it is not known whether they are consistently able to grow, metabolize, and replicate while aerosolized. If terrestrial microbes are found to not just survive, but thrive, in the Earth's atmosphere, this would inform habitability assessments for the Venusian cloud layer.
- **What is Venus' climate history?** Given the high level of similarity between the two planets, what caused Earth and Venus's climates to diverge so drastically?
- **Do environmental parameters in the cloud layer fit our current definitions of habitability?** Specifically, could life as we know it survive the ranges of temperature, pressure, pH, and chemical composition present in the Venusian atmosphere? Certain important life-limiting factors, including water activity and levels of UV radiation, are not yet well-elucidated in the Venusian cloud layer.
- **Are any terrestrial organisms capable of surviving Venus-like conditions?** Various terrestrial microorganisms are known to be capable of surviving different environmental stressors (e.g. low pH, atmospheric transport) present in the Venus cloud layer. Additionally, certain aspects of the cloud layer (e.g. temperature, pressure) may not be very stressful to life. No terrestrial organisms have been identified that are polyextremophilic towards Venus' unique set of conditions as currently identified. Furthermore, it is important to note that terrestrial possibilities do not set the limit for extraterrestrial possibilities.
- **What are the energetic and biomass limitations on a potential Venusian biosphere?** Living things require chemical disequilibrium (conferring the potential for energy utilization) and sufficient biologically available elemental abundances, among several other requirements.
- **What measurements would be most indicative of life in the Venusian clouds?** Direct detection or observation of microorganisms would be extremely difficult given the current state of technology and hardware limitations for a Venus spacecraft, so a wide variety of biomarkers/biosignatures should be identified for future astrobiological investigations of Venus
- **How can these necessary measurements be obtained?** Which instruments, platforms, and sampling methods would be best suited to further understand the Venusian cloud layer?

1.2 Future Missions

A brief list of (near term and long term) Venus proposed missions were mentioned:

- Decadal Venus Flagship Mission, US (investigations: distant, surface, technology demonstration)
- Venus Mobile Explorer, US (investigations: surface, technology demonstration)
- Venus Observing System, US (investigations: long term, surface, technology demonstration)
- Venus Origins Explorer, US (investigations: long term)
- Venus Sample Return Mission, US (investigations: surface, soil sample return, technology demonstration)
- Shukrayaan-1, ISRO IN (target launch date 2023, investigations: near term)
- VERITAS, US (target launch date 2025, investigations: currently under competition)
- Davinci, US (target launch date 2026, currently under competition)
- EnVision, EU (target launch date 2032, investigations: long term)
- Venera-D, RU-US (target launch date 2029-2032, investigations: long term, surface)

1.2.1 Proposed and Recommended Architectures for Advancement in Surface Geology

Any potential architecture for a surface lander will need to measure the atmospheric composition at the surface-atmosphere interface, over the day-night transition. Thus, a long-lived lander should land in the local daytime, and continue to characterize the atmospheric temperature, pressure, wind speed (and velocity, if possible), and composition during that time. At the surface, we need to know the major- and trace-element composition as well as the mineralogy of weathered materials in contact with the atmosphere, and pristine materials at depth. We learned from the Vega and Venera landers (as well as decades of subsequent exploration of Mars) that precise knowledge of the landing site location is required to place these analyses in a geologic context. To achieve this, a lander must be equipped with cameras to image the landing site during descent and after landing. Finally, determining the nature and rate of surface weathering requires (weathered) sample collection at the surface, and (pristine) samples from depth (tens of centimeters).

1.2.2 Observational Targets and Instrument Requirements for Advancement in Surface Geology

Lessons learned from the Venera and Vega landers illuminate the requirements to accurately interpret data collected from the Venusian surface. First, descent imagers and at least one panorama camera are needed to morphologically assess the landing site and to place it in a geologic context. Much of the controversy surrounding the interpretation of Venera and Vega data results from the large (300-km-diameter) landing ellipse and the wide range of geologic terrains contained within it. Experience from Martian landers clearly reveals the importance and ability of descent imagers combined with panoramic images collected after landing to pinpoint the precise landing site.

Second, determining both the major-element compositions and the mineralogical compositions are vital to unraveling Venus' magmatic and volcanic history. Venera and Vega lander data, providing either major-element abundances or only abundances of K, Ur and Th, leaves a lot of room for interpretation. With both geochemical and mineralogical compositions of landing site materials, we can most accurately assess Venus' igneous processes. Thus, instruments capable of measuring both mineralogy (such as the ChemMin instrument on the Mars Curiosity rover) and major-element composition (such as the APXS on Curiosity) are required.

Third, determining the nature and rate of surficial weathering on Venus is vital for constraining the resurfacing rate and age of the Venusian surface. The best way to assess the weathering rate is to analyze samples collected from the surface, and those collected from depth for comparison.

Although the tesserae are of enormous scientific interest, current landing technologies preclude a safe landing on the tesserae. Therefore, viable landing targets are restricted to the vast Venusian plains.

1.2.3 Proposed and Recommended Architectures for Advancement in Cloud Habitability

Potential future architecture concepts were discussed, focusing on successful Earth-based platforms as well as propositions for Venus aerial platforms. Aerosol sampling techniques have been successfully used on airplanes and high-altitude balloons to sample atmospheric microbes on Earth. However, such studies require sample return to the ground, followed by extensive laboratory analysis. *In situ* aerobiological analysis capabilities could offer much to a future Venusian life detection experiment. Various platforms were proposed for a future Venus mission, including aerobots, balloons, and gliders. In evaluating these platforms, it is important to consider whether active or passive sampling would be desired. Passive sampling runs the risk of providing data that is not representative of the Venusian atmosphere as a whole. Active sampling, on the other hand, is much more difficult to implement.

1.2.4 Observational Targets and Instrument Requirements for Advancement in Cloud Habitability

Observational targets and instrument requirements for *in situ* cloud habitability analysis could be determined from desired measurements identified by the working groups. These desired measurements can be found in the respective spreadsheets generated by the working groups.

2.0 Lab and Experimental Studies, Current and Future Needs for Science Advancement in Venus Surface Science

2.1 Motivation for new and on-going Venus surface science studies

Current understanding of the processes operating on the Venusian surface is dominated by analyses of Magellan Synthetic Aperture Radar (SAR) data. Although the Magellan mission returned near-global coverage, the SAR spatial resolution is low (generally >100 m/pixel). Where there are SAR stereo images, topography can be obtained with a horizontal resolution of ~2-3 km/pixel (Herrick et al., 2012); elsewhere the Venusian topography has a horizontal resolution of 10 - 20 km (Ford and Pettingill 1992). Compositional data is limited to the Venera and Vega landing sites, although recent studies have attempted to obtain compositional information using the 1-micron emissivity data obtained from Venus Express (Gilmore et al., 2017), but the spatial resolution is poor and 1-micron emissivity data are equivocal. Furthermore, the precise emissivity behavior of silicate minerals at Venus temperature and pressure conditions are not yet quantified.

2.2 Results from Current and On-going Work

The ongoing scientific work is broadly divided into three categories: 1) further analyses of Magellan SAR data; 2) analyses of surface emissivity data collected from the VIRTIS instrument on Venus Express (see Gilmore et al., 2017); and 3) high-temperature laboratory measurements of mineral spectra at various wavelengths. Ongoing engineering studies include development of high-temperature and pressure (hTP) facilities to test the viability of instrumentation at Venusian surface conditions.

2.3 Goals for Future Work

Most of the Magellan SAR data have been exhaustively mined; future progress in resolving scientific controversies about Venusian geology (and geologic history) requires additional data of the surface. High-resolution SAR, topography and compositional information are needed.

Available technology requires that the next Venusian landing site be located on the plains. More input from the international Venus community is needed to evaluate and select specific potential landing sites.

2.4 Requirements and Recommendations to meet Future Goals

It is suggested that for future Venus landing sites workshops and to maximize science return consideration be made to the arguments presented here as a result of this workshop (i.e. such as the need to be made for plains overall, their interception with other terrains and a specific type of plains, etc.). The workshop participants recommend that working groups be established to study the potential science return from the different plains terrains identified during the workshop. These plains types are: 1) stratigraphically oldest plains; 2) stratigraphically youngest plains; 3) lobate plains; and 4) canali-fed plains. We recommend that a working group be assigned to each plains

type. Outcomes of these working group studies would be: 1) GIS-based maps showing where these plains crop out on the Venusian surface, based on Magellan SAR data; 2) justification for selecting each plains type, and specifically what scientific questions can be answered by landing on that particular plains; 3) a consensus of the most scientifically robust 3 - 5 landing site locations on Venus.

Engineering studies, investigating how instruments will behave for hours, days, weeks and months on the Venusian studies, need to continue. Similarly, investigations into the weathering behavior of likely minerals and rocks on the Venusian surface, at Venus temperature-pressure-composition conditions, need to be conducted so that measurements made at the surface (or of the surface from orbit) can be interpreted in context.

3.0 Lab and Experimental Studies, Current and Future Needs for Science Advancement in Venus Cloud Habitability Studies

3.1 Motivation for new and on-going Venus Cloud Habitability Studies

Habitability analysis on Venus requires further characterization of the range of environmental conditions that living things can survive, as well as further studies of the chemical, meteorological, and physical conditions of the cloud layer. Advancements in aerobiological sampling techniques would be helpful for any future attempts at *in situ* life detection.

3.2 Results from Current and On-going Work

Terrestrial microbes are capable of surviving some combinations of Venus cloud-like conditions. However, some of these conditions are comparable to the harshest environments on Earth. Here, microbes are often merely surviving, with little to no activity.

Detecting, collecting, and identifying microbes in the atmosphere is possible, but technically difficult. Multiple collections, at different spatial and temporal resolutions, of large volumes of air are required to obtain a signal, and samples must be returned to the lab before any genetic, molecular, or microbial analysis can be done. It is even more difficult to characterize microbial activity in the atmosphere: most stratospheric samples appear to be dormant or dead, and samples begin changing immediately following collection.

3.3 Goals for Future Work

A number of fundamental questions need to be addressed through experimental studies and Earth-based atmospheric sampling in order to better inform the future of Venus cloud habitability studies. Microbial tolerance, or even preference for Venus-like conditions, needs further characterization. It is essential to determine whether atmospheric microbes on Earth are capable of metabolic activity in aerosols to support growth and reproduction, and if they are utilizing the space to create a viable ecosystem

or are simply being transported. Biomass, energy, and nutrient limitations need to be constrained in order to determine whether the ingredients and conditions necessary to sustain life are concurrently available on Venus so that a viable long-term ecosystem could potentially exist and therefore, be observed and sampled.

3.4 Requirements and Recommendations to meet Future Goals

Additionally, development of *in situ* microbial analysis would be helpful for both terrestrial aerobiology and Venusian astrobiology. Further studies are needed in the lab and in Venus analog environments. Additionally, it is imperative that stakeholders across disciplines work closely together to ensure that science and engineering needs and goals are being met.

4.0 Role of Modeling in Venus Exploration Planning at the Surface

4.1 What's happening Now

Current Venus modeling efforts are focused on atmospheric studies, because the most recent missions (Venus Express and Akatsuki) to Venus were designed to study the atmosphere. The best data available for the Venus surface remains the Magellan SAR. In spite of the general lack of surface data, however, there are specific ongoing efforts to coax more geologic information from Venus.

Rabinovitch and Stack (2019) are using panorama images collected from the Venera and Vega landers, combined with detailed analyses of SAR roughness information to quantify the presence of boulders at the Venera and Vega landing site. By extrapolation, the safety of potential landing sites for future landed missions could be modeled and assessed in a similar way.

Chemical interactions between the Venusian surface materials and the atmosphere have not yet been measured in-situ; ongoing efforts in specially designed laboratories are underway to collect chemical and spectral information from geologic materials exposed to Venus conditions (e.g., Filiberto et al., 2020). These laboratory simulations will help to decipher the limited 1-micron emissivity measurements obtained from VIRTIS (on board Venus Express) (Gilmore et al., 2017).

The Glenn Extreme Environments Rig (GEER) and the NASA Glenn Research Center is a unique facility that enables investigation into how both natural and man-made materials will react while being exposed to Venus surface temperature, pressure and atmospheric composition (see <https://geer.grc.nasa.gov/geer-overview/overview-of-geer/>) (Kremic et al., 2019). The Johns Hopkins University Applied Physics Laboratory (JHUAPL) has developed a similar, but smaller, apparatus for examining gas-solid reaction chemistry: the APL Venus Environment Chamber (AVEC) (Izenberg and Lessis, 2019). These facilities are available to members of the community interested in testing natural or manmade materials at Venusian surface conditions.

Models are being developed and employed to understand specific questions about Venusian geology. For example, Gregg and Sakimoto (2019) used multiphysics computational modeling to improve our understanding of how Venus canals formed.

4.2 Hope for the future, and needs to meet those goals

4.2.1 Tools

Continued investigation into the behavior of natural and manufactured materials at Venus surface temperature, pressure and composition conditions is essential for a successful landed mission. Before potential landing sites can be selected, the final instrument list for the Venera-D landing craft need to be identified, and their capabilities fully described.

4.2.2 Data

Existing data from the Magellan mission are housed at the Planetary Data System and can be found here: <https://pds-geosciences.wustl.edu/missions/magellan/index.htm>. GIS-ready data products (such as global SAR image mosaics) can be downloaded from the USGS Astrogeology Branch here: <https://astrogeology.usgs.gov/search/results?q=MAP2&k1=target&v1=Venus>, and imported into GIS software such as ArcGIS for mapping and spatial analyses.

High-resolution topography (~2-3 km/pixel) obtained from Magellan SAR stereo (Herrick et al., 2012) can be found here: <https://sites.google.com/alaska.edu/robertherrick/resources/stereo-derived-topography-for-venus>.

5.0 Next Steps for Venus Cloud Exploration

5.1 What's happening now

No in-situ exploration of the Venusian clouds is taking place. However, remote studies of the cloud layer are taking place using JAXA's Akatsuki and ground based telescopes. Additionally, observations will be made by ESA and JAXA's BepiColombo during its flybys of Venus on 15 October 2020 and 11 August 2021.

Groups established during the workshop are working to refine the guiding recommendations for the next steps for the exploration of the Venus clouds. These recommendations include: 1) developing an understanding of the interactions between surface geology and the near surface atmosphere; 2) define terrestrial microbes that may be used in Venus cloud simulation studies; 3) measuring the atmospheric conditions and composition at varying altitudes, latitudes and times of day; and 4) conduct biomass constraint measurements. It should be noted that while the working groups were established at the workshop, the goals detailed below were formalized during post-workshop dialogue amongst the groups.

In addition to these guiding recommendations, several presenters from the workshop have formed collaborations and are writing papers to be submitted for publication in a special collection of the Astrobiology journal to be published in late 2020. These papers focus on various areas of interest discussed during the workshop, with the goal of further defining areas of research critical to understanding habitability in the clouds.

5.2 Needs to meet these goals

5.2.1 Tools

Continued investigations into the atmospheric conditions are needed to not only develop proper models, but also to simulate environments at high resolutions. To increase this understanding tools such as a particle counter and a nephelometer are needed to measure the cloud aerosol density and bulk composition, respectively. Specifically, for cloud habitability, tools for the detection of biosignatures are needed, such as the life-signature detection microscope discussed during the workshop (Yamagishi et al., 2018). Research and development in regard to the use of microscopes for such detection is still in its infancy. Additional candidate instrument needs are listed below.

- UV-NIR spectrometer for measuring spectral signatures of different species in the atmosphere at a resolution of > 100 and higher
- Raman Spectrometer for aerosols/cloud particles
- Venus Organics Analyzer
- Chemical analyzers for specific species (e.g. what SAEVE/LLISSE will carry)
- Aerosol/Gas spectrometer
- Meteorological measurements (pressure, temperature, humidity/acidity, wind components)
- Bioaerosol sampler
- Good platform for sampling and taking measurements

5.2.2 Data

5.2.2.1 Mission Data

The working groups have provided recommendations on data desired from future missions. From the atmospheric conditions working group, desired measurements are listed below to be conducted at an altitude range of 45-70km during the morning, mid-day and night. These measurements are desired to take place at latitudes of $0-90^\circ$ ~ every 15° .

- Cloud aerosol density and the size distribution across multiple vertical profiles.
 - Desired range:
 - Cloud aerosol density: $0.1-10^4/\text{cm}^2$; 10%
 - Size distribution: $0.01-10 \mu\text{m}$ rad; 10%
- Aerosol bulk composition: H_2SO_4 acidity
 - Desired range: 50-99.9%; $\pm 0.5\%$

- Cloud particle and atmospheric environmental composition levels (aerosol mass spec. sensitivity: 2 ppb in 300 s.) of:
 - HCl, HF, HBr, daughter species
 - Elemental sulfur (S_n)
 - Hydrocarbons
 - Phosphorus, PO₄ and other P species.
 - Isotopic ratios:
 - $^{13}\text{C}/^{12}\text{C}$, $^{15}\text{N}/^{14}\text{N}$, $^{18}\text{O}/^{16}\text{O}$, $^{17}\text{O}/^{16}\text{O}$, $^{34}\text{S}/^{32}\text{S}$, $^{33}\text{S}/^{32}\text{S}$, D/H
 - H₂O (atmospheric environments composition)
 - Fe, Mn, Cu, Co, etc. (cloud particles)

From the habitability constraints and biosignatures group, the preliminary primary desired measurements for habitability were of aerosol composition, including chemical compositions, elemental abundances (e.g. CHNOPS), and isotopic abundances. The primary desired measurements for life detection are regarding the presence of organic compounds, (e.g. organic carbon vs total carbon), lipids, amino acids, etc.; if they are present, understanding their chirality and molecular complexity (chemical structure formation that requires biological processes) is critical. Finally, measurements regarding photoenergy, including energy transfer through the cloud layer and chemical energy/disequilibrium, are desired. As mentioned above, these are preliminary desired measurements, the working groups will work towards detailing measurements specific to the unique Venus atmosphere.

5.2.2.2 Laboratory Data

The microbiology working group seeks to incorporate mission data regarding the atmospheric conditions into simulations of the Venus cloud layer to test the viability of terrestrial microorganisms. With this data, the group looks to develop greater understanding of what terrestrial microorganisms should be used as analog organisms and what analog facilities are available to replicate these environments. Additionally, the group desires to model metabolic activities in the Venus-like conditions and develop a list of potential ancient microorganism characteristics that will potentially allow for panspermia to be taken into consideration. Finally, to truly understand how life could be floating in the clouds of Venus, greater understanding is needed of microorganisms' viability and reproduction in an aerosolized form. The habitability constraints and biosignatures group seeks to understand the potential sources and lifetimes of water and bioavailable CHNOPS in the Venus cloud layer, as well as the durability of the potential ecosystem that could be supported in such conditions (dry, acidic, irradiated) given estimated aerosol residence times. Lastly, this group also seeks to understand the stability and absorbance of major biomolecules such as lipids, amino acids, nucleic acids, pigments, etc. in simulated Venus conditions and aerosols, and the concentrations necessary to produce a signal that could be detected in the Venus spectral data.

6.0 Summary of Workshop Outcomes

6.1 Landing Site

The complete instrument suite for the proposed Venera-D lander has not yet been finalized. To maximize the science return from a lander, it is essential that the instruments, and their requirements, are known. For example, the general community consensus is that an instrument capable of measuring minerals and their abundances, as well as a one that measures absolute elemental abundances, are necessary for the most complete interpretation of the observed geology. In the current (non-final) instrument list for the lander, there is not yet an instrument capable of measuring mineral abundances. Thus, for landing site selection to be optimized, the lander instrument list needs to be finalized.

Although there is broad scientific interest in learning more about the tesserae, current technological constraints require that we land on the plains. Four main types of plains terrains were identified as scientifically interesting and viable landing sites: 1) the stratigraphically oldest plains; 2) the stratigraphically youngest plains; 3) lobate plains; or 4) canali-fed plains. The recommendation is that a working group be established to map, investigate, and explain the science return that could be obtained from each terrain type. The next step would then be a safety assessment (see Rabinovtich et al., 2019) to help constrain the landing site selection.

More input from the international community is needed to advance this topic. The majority of participants at the Landing Site Selection workshop were from the U.S.A.; from the attendees there were not sufficient numbers of international scientists to populate the landing site working groups.

6.2 Cloud Habitability

A wide variety of topics were covered in relation to cloud layer habitability and the potential for life detection in the Venusian atmosphere, raising many questions about whether life as we know it could exist on Venus and what studies need to be done so that we can work to answer these questions.

The discussions stemming from these presentations highlighted potential areas for future focus. Biological perspectives need to be better integrated into mission design. One frequently echoed opinion among workshop participants, particularly those with backgrounds in biology, was that although the idea of life on Venus is extremely interesting, in situ life detection is not a good goal for the Venera-D mission. Instead, further characterization of the atmosphere would be extremely helpful. Certain unknown environmental parameters, including UV levels and the presence of water throughout the atmosphere, carry major ramifications for whether the Venusian cloud layer is habitable to life as we know it. It is important to note that while a habitable environment is necessary for life, the detection of biosignatures and characterizing an environment's habitability are not the same thing.

7.0 Next Steps: Future Workshops

It is recommended that the science themes for future Venera-D workshop consider building on the questions and topics identified in this and other workshops. From the 2019 workshop at least four (4) working groups (WG) were formed to follow up on the findings summarized below. In 2020 the Venera-D workshop will be part of the IKI **Solar System Symposium** <https://ms2020.cosmos.ru/>

The Working Groups established identified key questions in assessing cloud habitability (HWG) and landing sites (LSWG). These WGs will work to determine what data has already been measured, what can be investigated by laboratory experiments, what technology developments are needed and what direct measurements (either via remote or in situ measurement) are required. The guiding questions of these working groups are mentioned above in section 2, 5.2.2.1 and 5.2.2.2. The Working Group leads are identified below:

Working Groups -

- *Landing Sites*, Leads: Dr. Paul Byrne, Dr. Misha Ivanov, Dr. Tracy Gregg,
- *Microbiology*, Leads: Dr. Oleg Kotsyurbenko, Jaime Cordova
- *Venus Atmospheric Conditions*, Leads: Dr. Kevin Baines, Dr. Larry Esposito
- *Habitability Constraints and Biosignatures*, Leads: Dr. Diana Gentry, Jordan McKaig, Margarita Kryuchkova

Summary of key themes for LSWG and HWG are:

LSWG - The landing site working group identified the needs as stated in section 2 and summarized here to be:

- Maximize science return consideration for plains overall, their interception with other terrains and a specific type of plains.
- Study the potential science return from the different plains terrains identified during the workshop.
 - These plains types are:
 - 1) stratigraphically oldest plains;
 - 2) stratigraphically youngest plains;
 - 3) lobate plains; and
 - 4) canali-fed plains.

Outcomes of the landing site working group (LSWG) studies would be:

- 1) GIS-based maps showing where these plains crop out on the Venusian surface, based on Magellan SAR data;
- 2) justification for selecting each plains type, and specifically what scientific questions can be answered by landing on that particular plains;
- 3) a consensus of the most scientifically robust 3 - 5 landing site locations on Venus.

HWG - The 3 Habitability Working Groups (Microbiology, Venus atmospheric conditions, and Habitability Constraints and Biosignatures) identified areas of focus, as stated in section 5.2 and summarized here (not listed based on priority), to be:

- 1) Instrument development to increase understanding of 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.

In addition to an increased understanding of the Venus atmosphere, the outcomes of these goals support the goals to:

- 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.

In addition to the goals developed by the working groups, areas of focus for future workshops include:

- Surface and atmospheric interactions (including in relation to habitability)
- Using upcoming Venus Gravity Assist Science Observation (VeGASO) opportunities for furthering the understanding of the escape rate of water
- Understanding the lifetime of phosphine, a possible biosignature, under Venus conditions (Sousa-Silva et al., 2020)
 - It is important to note that no such source has been found on Venus, nor has such a biosignature been detected. Such a biosignature requires a large source of biomass, currently unknown to be present on Venus. This focus area is proposed as to what such a possible biosignature *may* look like under Venus conditions.
- Investigating the phosphorus chemistry taking place and a possible biogenic source of methane (Andreichikov et al., 1987; Donahue and Hodges, 1993)

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Appendix A. Summary of Workshop Talks

Landing Site Selection Workshop Notes

Compiled from notes taken by workshop scribes: Paul Byrne, Jaime Cordova, Diana Gentry, Anastasia Kosenkova, Margarita Kruchkova, Jordan McKaig, Jason Rabinovitch

Day 1: Landing Site Session 1: Engineering

Presenter: Ludmila Zasova

Talk title: Venera-D Update, Including Landing Site Constraints from Orbit Solution

Talk category: Mission development

Notes from talk:

- Venera-D baseline mission = orbiter + lander
- Lander + LLISSE (attached)
 - Lander will operate >2 hours
 - LLISSE will operate >2 months
 - 14 instruments (excluding LLISSE), including some chemical analysis package
- Potential augmentations
 - SAEVe (1 or 2)
 - Variable altitude aerial platform
 - Subsatellites at L1 or L2
 - LISSE (1 or 2)
 - Augmentations not yet prioritized
- Orbiter
 - Focus on atmospheric science
 - >2 years operation
 - 17 instruments (preliminary accommodation)
- Launch, orbit, landing
 - Angara 5 launch vehicle
 - 2026 launch: 180-190 days transfer
 - High northern latitudes for landing site best for orbiter/lander/LLISSE communication

Presenter: Oleg Sedykh

Talk title: The Venera-D Lander

Talk category: Mission development

Notes from talk:

- Spacecraft will be 6 – 7 tonnes for Venus
- Lander mass = 1577 kg; 120 kg for payload
- Lander will operate ~3 hours on surface (Venera & VEGA heritage)
 - Depends on orbiter view of lander
 - And on precise surface conditions
- Asks for instrument interface specifications to enable design
- Discussion, questions, answers
 - Don't yet have details on how material will be transferred to the instruments inside the lander; Lavochkin must be involved in these discussions
 - Interior of lander will be pressurized to maintain Earthlike conditions
 - Lander can function on slopes $<30^\circ$ and with a rock clearance of 30 cm
 - Brake shield will be jettisoned at 63-64 km altitude; atmospheric sampling can begin there

Action for the Venera-D Team: determine how to respond to Lavochkin's request for information about instrument subsystems.

Presenter: Mikhail Gerasimov (& Tom Economou)

Talk title: Venera-D Lander Payload Instruments

Talk category: Mission development

Notes from talk:

- Lander will perform science investigations during atmospheric descent and on surface
- First 4 high-priority science objectives are atmospheric:
 - Composition during descent
 - Composition at surface
 - Structure & meteorology
 - Physical properties of aerosols
- Next high-priority science objectives are geology & geophysics:
 - Descent cameras
 - Microscopy at surface (~1 mm resolution)
 - Surface elemental composition
 - Surface mineralogy
- Considered using a gamma-ray spectrometer through a window to avoid ingesting samples, but not as useful
- Additional (lower priority) geology & geophysics objectives: seismicity and EM wave package
- Notational lander payload = 120 kg; 35 kg for sampling device

- Improvements over legacy soil sampling systems can be considered
- Discussion, Questions, Answers
 - Could the entry profile be modified to enable higher detachment of brake shield so UV absorbing layer could be sampled at higher latitudes? Or could the descent through the cloud layer be slowed to allow for more discreet sampling? How will the lander attitude be determined upon landing?
 - And on precise surface conditions
- Asks for instrument interface specifications to enable design
- Discussion, questions, answers
 - Don't yet have details on how material will be transferred to the instruments inside the lander; Lavochnik must be involved in these discussions
 - Interior of lander will be pressurized to maintain Earthlike conditions
 - Lander can function on slopes $<30^\circ$ and with a rock clearance of 30 cm
 - Brake shield will be jettisoned at 63-64 km altitude; atmospheric sampling can begin there
 - Important to develop a timeline for all required analyses given the short operational lifetime of lander
 - Possible to measure C, N bondings of surface crust? No.
 - Possible to measure gaseous light hydrocarbon gases via GCMS? Yes, during descent (not at surface)
 - When does the IR spectrometer work? During descent.
 - How much time is required for all the analyses? Not yet known because specific instrument selection has not yet been made.

Presenter: Anastasia Kosenkova

Talk title: "Bonus" talk (untitled)

Talk category: Mission development

Notes from talk:

- Baseline design: balloon (variable altitude aerial platform) not included inside lander
- Lander can accommodate slopes $<30^\circ$
- Descent takes ~60 min
- Limitation: radio link duration
- Longitudinal range: 200 km (range from atmospheric entry to landing point)
- Instrument container temperature: $+50^\circ\text{C}$ to -50°C during flight; -50°C before atmospheric entry; T (at surface) = $30^\circ \pm 10^\circ\text{C}$; internal temp = $90^\circ - 120^\circ\text{C}$ during surface ops
- Worst-case scenarios landing for transmissions = 5 hour (toward pericenter); 4 hour, 40 minutes (towards apocenter)
- Orbiter:
 - Orbit altitude = 300 – 500 km to 60,000 – 70,000 km
 - 3 years in orbit
- Lander will detach from orbiter ~4 days prior to landing

- Prospective technology
 - Maneuverable entry vehicle (MEV)
 - Shrink landing ellipse
 - Enable more landing sites
- Discussion, Questions, Answers
 - How many ports or penetrations are planned in baseline lander for thermal modeling? Heating not controlled by number of ports
 - Have landing sites been determined yet? Estimates can be more detailed depending on expected coordinates of atmospheric entry
 - How much air volume can be sampled during descent? How quickly? Good experience with VEGA, but no details or designs yet.
 - How is the 30° slope tolerance determined? What wind speeds are assumed during descent and landing?
 - Is aerosol/atmospheric sampling being carried out by lander during descent? What does that look like if the aerial platform isn't flown? (We don't yet know.)
 - Has someone calculated density of aerosols? Question is being looked at carefully.
 - Surface elemental composition
 - Surface mineralogy

General Discussion

What kinds of strategies can be employed to minimized lander tipping? Surface winds are pretty low, and there was much success with Venera landers.

Drag plate puts lander down at ~10 m/s and will keep the lander from wobbling; lander has a low center of mass.

Venera landers seem to have bounced; is that a consideration for Venera-D? Damper system should help to minimize bounce: use what worked!

If slope is >30°, lander will tip over. Some instruments will still work but coms won't (Venera 7).

Is 3-hr communication window with orbiter a function of horizon to horizon? What happens if the lander ends up in a graben? Best-case scenario is for communication for horizon-to-horizon; comms time can be reduced by topography.

Whose responsibility is it to design the sample system?

Day 1: Landing Site Session 2: Instruments and Simulations

Presenter: Tibor Kremic

Talk title: LLISSE (Venera-D Long-Life Element) & SAEVe (Potential Contributed Element)

Talk category: Instrumentation

Notes from talk:

- Long-Lived In-situ Solar System Explorer
- Small (~10 kg, 20 cm)
- Flexible
 - Dropped by a balloon or
 - Set from a lander
 - Doesn't depend on lander at all
- Leverages simple high-T electronics, low-data-volume measurements, meteorology and atmospheric composition
- Can be thought of as a “beacon:” periodically turns on, takes a measurement, broadcasts data in real time (no on-board data storage)
- SAEVe:
 - Enhance LLISSE, take away mass constraint: what could we do with a more capable LLISSE?
 - Based on LLISSE: more battery, more instruments, extend surface ops to full Venus solar day (120 Earth days)
 - 2 -3 SAEVes, 300 – 800 km apart, operating for 120 days
 - Station would transmit periodically, triggered by a seismic event
 - Could carry cameras for descent and soon after landing
- Landing site requirements:
 - Any site!
 - First LLISSE on plains
 - If multiple LLISSEs, different altitudes, latitudes, near major geologic features, other locations
 - For SAEVe, places near large flat areas with potential activity (Atla/Beta Regio)
 - Comms with orbiters are important
- Discussion, Questions, Answers
 - How are chemical species detected? Solid-state detectors, each species has unique configuration, all are in ppm or better
 - Can you go beyond 60 days? Power is the constraint: battery design, communication frequency, etc. all drive power consumption and thus duration
 - Options for batteries? HOTTech, and possibly wind-driven

Presenter: Allan Treiman

Talk title: CheMin-V, A Definitive Mineralogy Instrument for Landed Science on Venus

Talk category: Instrumentation

Notes from talk:

- Miniature XRD
- K-alpha x-rays from cobalt, passes through sample; x-rays strike CCD sensor, cooled to -30° to -40°, can pick out specific species
- Piezo-actuated sample cell rotates/excites sample to give a representative measurement
- Used for 20 – 30 analyses on MSL successfully; has detected clays formed in an aqueous environment
- CheMin on Mars takes 20 – 30 hours for analyses; on Venus it might only take 40 min
- CheMin-V could take 2 decent samples in 15 min with mineralogy down to ~1%
- Current setup negatively impacts ability to pick up Na and Mg measurements
- Discussion, Questions, Answers
 - Possible to sample rock surface outside lander, or must a sample be ingested? A drilled sample must be powered, delivered inside, and vibrated; must be done inside because the atmosphere will absorb light elements
 - How to handle complex sample prep? Venera approach was simple and could be adapted for CheMin-V
 - How deep to get past the weathering rind? Or is that what you want to measure?

Presenter: Christian Schröder

Talk title: MIMOS II: Miniaturized Mössbauer Spectrometer for Venus Surface Investigation

Talk category: Instrumentation

Notes from talk:

- Small (<500 g, 4 W)
- ID iron-bearing mineral phases & Fe-oxidation states; quantitative distribution between mineral phases and oxidation states: give elemental and mineralogical surface composition.
- Most successful application: MER (also flown on Beagle 2, Phobos-Grunt)
- MIMOS-IIA, for Venus, developed to return measurements faster (~30 min) than on Mars
- Considerations for Venus: only 1 – 3 spectra collected in short ops time available
- Instrument currently operational at -120°C to 30°C
- Sample temperature must be stable: spectra are temperature-dependent; pressure adjustments may be needed?
- Simultaneous XRF and Mössbauer measurements

Presenter: Noam Izenberg

Talk title: AVEC

Talk category: Instrumentation: Lightning Talk #1

Notes from talk:

- Small chamber (6 cm x 23 cm cylinder) can reach 500°C and ~10 MPa (Venus conditions)
- Designed for gas-solid reaction chemistry experiments
- Can gas chemistry be monitored during experiments? (Yes and no) Experiments can be run for up to weeks at a time.

Presenter: Tibor Kremic

Talk title: Glenn Extreme Environment Rig (GEER)

Talk category: Instrumentation: Lightning Talk #2

Notes from talk:

- Designed to support Venus community, experiments
- Recently added a small chamber (miniGEER) to run faster experiments
- GEER has 811L volume (can fit a full-size LLISSE)
- Gases are mixed so can hit any part of the Venus atmosphere up to 70 km and can vary gas mixture through time

Day 1: Landing Site Session 3: What Do We Already Know?

Presenter: Larry Esposito

Talk title: VEXAG Landing Targets (2014 VEXAG workshop)

Talk category: Previous Work

Notes from talk:

- Finding: substantial science returns from landing in low-risk plains regions; best plains are those that are older because they are likely to be devoid of impact ejecta
- Top Targets: tessera, plains, young lava flows, active (young) volcanoes (e.g., Maat Mons)
- Major focus is geochemistry and mineralogy of surface targets. Divided objectives into “needs” (major elements, S, Cl, heat-producing elements, mineralogy) vs. “wants” (trace elements, Fl, Fe-O states)
- GRS could measure abundances of K, Th and U for comparisons with previous lander measurements
- Good idea to make atmospheric measurements during descent
- Nested images during descent helpful for creating Magellan radar context
- Questions, Answers, Discussion
 - How much water in Venus’ history? Is it worth taking elemental measurements from 2 or more places?
 - Recommended instruments for these measurements? Mars exploration provides a template, but Venus isn’t Mars and instruments would need to be adjusted accordingly
 - Is it enough to measure K at 10% precision? No: these numbers are indicative, not prescriptive
 - Need radiogenic Ar abundance to a few % to really get at the question of degassing
 - Also need to measure escape rates, which we don’t have for Venus.

Presenter: Tom Economou

Talk title: What do we know about Venus' chemical composition?

Talk category: Previous Work

Notes from talk:

- XRF successfully used on Venera 13, 14 and Vega 2
- Vega 2 measurements cannot resolve Mg, Al, Si, S, Cl
- Multi-channel GRS successfully used on Venera 8, 9, 10; Vega 1, 2
- Venera 13 returned higher abundance of K₂O than for other landing sites
- No mineralogy for Venus
- APXS is instrument of choice for elemental chemical composition
 - Flown on Soviet Surveyor mission
 - Also on MSL
 - Compare MER results with Venera 13

Presenter: Gilles Berger

Talk title: Surface-atmosphere interaction influences on in-situ Venus surface analyses

Talk category: Previous Work

Notes from talk:

- Essentially a summary of the following paper, and the highlights from this paper are listed below.
- Berger, G., A. Cathala, S. Fabre, A. Borisova, A. Pages, T. Aigouy, J. Esvan and P. Pinet, 2019, Experimental exploration of volcanic rocks-atmosphere interaction under Venus surface conditions, *Icarus* 329, pp. 8-23, <https://doi.org/10.1016/j.icarus.2019.03.033>
- Samples were altered at 475°C, typically 1 week and 90 bars, in Venus-like gas
- Only olivine and glasses show signs of oxidation/alteration
- In dry gas, olivine is coated by Fe-oxides and glass is oxidized (magnesioferrite)
- Ca, Na, Mg were transferred from glass to the gas phase or mineralized as sulfate
- In wet gas (early Venus), glass alteration rate is modeled by a shrinking core model

Day 2: Landing Site Session 4: Landing Site Selection

Presenter: Mikhail Ivanov

Talk title: Landing Site Constraints

Talk category: Landing Sites

Notes from talk:

- Found geologic sites on Earth that might be equivalent to Venus terrains to better understand landing site constraints
- Safety first!
- Identifies the following criteria for a successful landing site:
 - Safe (flat, few rocks)
 - Scientifically valuable
 - Representative of Venus geology
 - Simplest geochemical signal (magmas/lavas that are as close to primary magmas/lavas as possible)
- Using global geologic map (Ivanov and Head) identifies “regional plains 1” (rp₁) as representing a good likely sample of the upper mantle, and numerous solutions allow for landing ellipses in many places within this unit
- Discussion, Questions, Answers
 - Who makes the decision for where to ultimately land? We’ll likely need more discussion and additional workshops to start to narrow down potential sites. (In the NASA system, the project manager ultimately decides.)
 - If the landing ellipse shrinks, does that open up new possibilities? Yes.
 - Might be good to talk with EnVision team and coordinate with them and their “regions of interest”

Action item: EnVision-Venera-D coordination for considering landing sites.

Presenter: Dimitry Titov

Talk title: EnVision, European Concept of a Mission to Venus

Talk category: Landing Sites

Notes from talk:

- Titov begins by summarizing Venus knowns. EnVision is interested in understanding how active (volcanism, tectonism) Venus is today. There are 4 objectives for Venus activity.
- There are 6 objectives for Venus evolution
- There are 3 objectives for understanding what has made Venus' climate so hostile
- Currently working to understand if EnVision can resolve cm-scale deformation
- EnVision will carry out geodesy, including planetary ephemerides (GR, GM, J) and spin rate
- VenSpec-M will also fly using NIR spectral windows (1 micron)
- EnVision will also use subsurface radar to penetrate to 10 cm depth
- Gravity field will be measured <200 km; mesosphere T profiles, H₂SO₄ vapor and liquid water concentrations
- H₂O, HDO in upper atmosphere
- Discussion, Questions, Answers
 - 20% of the surface will be imaged with cm-scale resolution radar. Have those locations been finalized yet? No.

Presenter: Mikhail Ivanov

Talk title: High priority of tessera terrain for in-situ analysis (“Tessera as a high-wish site”)

Talk category: Landing Sites

Notes from talk:

- Tesserae are oldest preserved units on Venus—is it tertiary crust?
- Might there be plains terrains in the tessera that predate the tectonic deformation in tessera? Some spectroscopic data suggest that the tessera are not basalt—maybe sedimentary?
- Smooth deposits within tesserae are morphologically identical to basaltic plains outside of tesserae, suggesting similar compositions
- Tesserae are not safe landing sites, but future controlled landing may help
- Questions, Discussion, Answers
 - Festoon flows maybe basaltic? Perhaps, but festoon flows are very, very rare
 - Tesserae are a fantastic landing site, but the very youngest sites might also be high-priority for science.
 - Other LIPS on Earth, only trace elements really attest to country rock interaction; mafic dikes on Earth don’t seem to melt much of the granitic rock around them—probably the same for Venus.
 - Tesserae are important but they require a controlled landing technology.

Presenter: Tracy Gregg

Talk title: Potential landing site hazards in Venus' volcanic plains

Talk category: Landing Sites

Notes from talk:

- Venus canali as potentially hazardous sites within otherwise “safe” volcanic units
- Canali are 1 – 5 km wide, morphologically similar to lunar sinuous rilles, lava delivery systems
- Are exotic lava compositions required?
- Two end-members for formation: slow, steady eruption making canali collapsed lava tubes or rapid emplacement with high effusion rates requiring thermal and/or mechanical erosion.
- Canali may have fed the smooth plains, so it would be great to land close to (but not in!) a canali.
- Discussion, Questions, Answers
 - Why are the canali similar widths along their lengths? We see this on Earth; seems to be how channels develop.
 - Does the high surface temp on Venus make a difference? Helps laminar lavas flow great distances
 - If Venus had much higher surface temperatures in the past, does that make a difference? Not really.
 - Let's land on canali-fed plains.

Presenter: Richard Ernst

Talk title: Evaluation of Landing Site Targets in the Alpha Regio Quadrangle

Talk category: Landing Sites

Notes from talk:

- V-32 Alpha Regio quadrangle mapped in detail; 77 units identified
- Plains cover 55% of V-32
- Subtle differences in reflectivity (radar brightness), cross-cutting/infilling/superposition relations used to distinguish different flow units
- Five potential landing site targets identified in V-32
- Expansive, digitate volcanic flows are good sample sites: bigger than terrestrial LIPS and maybe representative of mantle-derived melts
- Coronae are key features and not yet sampled. Newly discovered giant circular dike swarms on Earth may be analogous to Venusian coronae
- Extensive flow field associated with Fatua Corona
- Two landing sites within plains, 2 within volcanic flow fields and 1 within a corona
- Discussion, Questions, Answers
 - Concentric dikes: recognized in several places? Yes. Possible analogs to Venus? Yes. Any changes in deposits inside and out? Not clear yet.

Presenter: Paul Byrne

Talk title: Mobile crustal blocks as landing site targets

Talk category: Landing Sites

Notes from talk:

- Tectonic mapping reveals that Venus' lithosphere is fragmented and mobile
- Groove belts (rift zones) and ridge belts (orogenic zones)
- Large low-lying undeformed regions surrounded by deformation belts
- Sigmoidal extensional and compressional features
- Perhaps jostling like blocks in pack ice on Earth
- Suggests that tectonic activity may post-date some plains units, and would indicate potential landing sites for SAEVes.

Presenter: Pat Beauchamp

Talk title: Potential landing sites for a complementary US Venus Flagship Mission

Talk category: Landing Sites

Notes from talk:

- Flagship mission study
- Flagship mission goals:
 - Study volatiles/liquid water history
 - Composition of surface & atmosphere & how they interact
 - Geologic history of Venus and whether it is active today
- Decadal Survey (2023-2032) so this would launch during that time.
- 1 orbiter, 2 orbiting smallsats, 2 landers/probes, 1 balloon and 1 long-lived lander (LLISSE)
- 3 landers, 2 sites: short-lived on plains and tesserae; LLISSE on plains
- A lot of data for Venus are single-point data; how reliable are these points?
- Lander goals: composition, origin of layering and sediments
- Discussion, Questions and Answers
 - What is the timeline for this project? Needs to be done by the end of June.

Presenter: Richard Ernst

Talk title: Site selection for geological testing of global warming models on Venus

Talk category: Landing Sites

Notes from talk:

- Global climate change on Venus
- Tesserae may date from before the onset of Venus' runaway greenhouse effect
- Is the massive volcanism with no CO₂ sinks responsible for climate change on Venus? If so, tesserae are from "pre-warming" times
- Are tesserae formed at depth and are tectonically unroofed? Is there a set of "missing basalts" that are covered by more recent flows?
- What about ancient wind erosion? Could glaciers have existed on Venus?
- Discussion, Questions, Answers
 - How deep would one need to drill to find the older terrain?
 - If EnVision generates new, better topography, will those data help this project? Yes, that would probably be sufficient resolution to fully test out the erosion pattern concepts.
 - For the erosion patterns, how do you know it's water and not some other liquid? Only real alternative is lava, but the erosive structures don't look like they were formed by lavas

Presenter: Pierre D’Incecco (remote presentation)

Talk title: Olapa Chasma—Idunn Mons: Investigating recently active terrains

Talk category: Landing Sites

Notes from talk:

- Region of VEX discovered high-emissivity areas on Venus on Idunn Mons, probably 2 million – 2000 years old
- See D’Incecco et al. (2017) Planetary and Space Sci. 136:25-33.
- Does this region also have active tectonic activity? Fractures and flows crosscut each other
- The “safe” part of this system is a volcanic flow field, which is not a high scientific priority, but if its recent, then there would be little weathering and could be a useful place to estimate volatile contents of “recently” erupted lavas.
- Might also be a safe place to deploy SAEVes.
- Discussion, Questions, Answers
 - There are upper and lower parts here, and we can’t land on the upper part. Does the advantage of landing near the upper part require specific imaging capabilities? What does “as close as possible” really mean?

Presenter: Alan Treiman

Talk title: Cleopatra crater: Granite mountains and tellurium snow?

Talk category: Landing Sites

Notes from talk:

- Based on Herrick (2014) VEXAG targets workshop
- Cleopatra impact crater on Maxwell Montes
- Surface-atmosphere interactions can be studied here
- Is Maxwell Montes granitic? If so it would require water (like continents on Earth)
- Indirect geophysical evidence for low-density rock at Maxwell Montes (or dynamic support)
- NIR emissivity of some highlands is lower than basalt, consistent with more silica-rich rocks
- High backscatter at high elevations, indicating a “snow-line” that could be tellurium? Or chalcogenides (S) or pyrite (FeS)?
- Topography for Cleopatra crater is poor
- Some potential landing sites for Cleopatra crater includes interior plains, the plains between the rim and the central ring, or near the exterior to Cleopatra
- But geology is poorly known, topography not well constrained, relatively small landing area. Would need better maps, radar, evaluation of risks, etc to land here
- Discussion, Questions, Answers
 - Is the interior (darker) material basaltic? Possibly.
 - Can we rule out A-type granites? Possibly
 - Long-lasting lander at high elevation is compelling. Are the winds stronger at higher elevations? Yes.
 - Why tellurium? It's rare, but not clear why it was picked by Pettengill originally; but whatever it is needs to be a semi-conductor or semi-metal

Landing Site Discussion

Coordinate with ISRO and EnVision

Premise: remove all engineering constraints from the discussion (for now), to motivate where we may want to go from science only—and then start ranking sites.

Tessera

Removing tesserae engineering constraints, tesserae could be crustal or mantle material but may provide information about crustal evolution.

Which tessera? Ovda Tessera: the largest, possibly the safest. Fortuna Tessera is a favorite. Tellus Tessera: planar strata exposed by erosion.

Tesserae are fundamental to understanding the history of Venus. Would be interesting to land near a tessera that's been embayed by younger flows. That way, we're safely not landing in the tessera itself, but we're seeing the plains-tessera relations.

Maybe tessera are impossible for the main lander, but could be tractable for something small (LLISSE or SAEVe).

Canali

The source will tell us a lot about how the plains were emplaced (graben, central volcano, shield field, corona), so if we ultimately decide on the plains, **landing near a channel** is important.

Plains

If we land in one of the oldest plains, we might be able to pick up the climate transition. This argues for the stratigraphically oldest plains (say in Alpha Regio, which also has a corona).

The most recent flows would be interesting: Mielikki Mons (one of the high-emissivity flows identified by Vex). Landing here, info could be coordinated with remote sensing data.

Plains within crustal blocks, particularly if a SAEVe is involved.

Craters

Landing inside an impact crater (e.g., Cleopatra crater) might reveal stratigraphy in the plains.

Rotation Rate

What is the momentum exchange on Venus? Wind speed is important, and we'd like to know wind speed where it's not affected by local topography. Argues that LLISSE should be placed on the lowest slope possible. Also supports landing multiple SAEVs at different latitudes. Priorities for SAEVe would be: 1) flat plains; 2) high altitude; 3) higher latitude; 4) near a topographic feature.

Active Tectonics

SAEVe (or some other seismic package).

Scientific Intersections

- 1) A lava plain that's near a source or near an embayed tessera, would provide sampling of one and imaging of the other—if technology allows such a landing. How far could the descent imagers see? How far could the panorama camera see? Not known yet.
- 2) Is there an area that would include older plains, younger plains, and be proximal to areas of “recent” tectonic activity? (Idunn Mons?)

General

Having a landing site with multiple objectives might be dangerous, and may provide non-unique outcomes.

What about putting the main lander someplace safe, and one of the small ones (SAEVe or LLISSE) in the tessera? Tesserae remain risky because we don't know what they really look like at the lander scale.

Comms prefer a high-latitude site in the northern hemisphere.

Dropping the lander outside of Cleopatra crater, for example, would address the "snow line" question, and could put a small lander on the other side of the snow line. Cleopatra and Maxwell Montes would satisfy comms requirements. Are there astrobiological implications for a possible tellurium layer?

What about the augmentations?

We'd like 300–800 km between SAEVs

Main lander in a young volcanism/outflow channel area, then one SAEVe in a tessera, and another inside a mobile block, that might help us address numerous science goals

If we had multiple LLISSEs, we could chance one or two in a tessera; perhaps less so for SAEVe

We have substantial uncertainty regarding weather rates, differences in starting composition, etc., when it comes to lava being "young" or "old"

Good idea to place augmentations at as different altitudes as possible, to assist GCMs because of key data for atmospheric circulation; it's important to measure wind speed and directions

SAEVe and LLISSE could be deployed independently, with smaller landing ellipses than for the baseline large lander

Possible to characterize the tesserae from orbit before deploying the lander/augmentation(s)? the big lander has to be deployed *before* orbit, but the smaller thingies *can* be

Could pick a safe, baseline site (or sites) that would be scientifically justifiable, but put off the decision until more technical information about the spacecraft and the planet are known

Possible to do terminal guidance?? (something to encourage folks to think about)

Engineering constraints will always override science; so if the tesserae become the preferred site(s), then a robust scientific justification is needed, as well as a backup site(s) with a clear narrative for what science will be lost by not going to the primary choice

So, other than the tesserae, what is there? **Young plains, old plains, lobate plains, plains associated with channels/feeder systems**

Venus flows may well have glass rinds, which weather really quickly, and so the weathered surface will be cm thick

Vesicularity will change as a function of atmospheric pressure, though perhaps not by very much

Shortlisting our (types) of sites

Action item: Identifying additional plains sites (others people are studying) that would make good candidates?

Action item: Four types of plains unit could be assigned to four people/groups + tessera as a target site for an augmentation?

Action item: Develop a well-written and robust justification for why these terrain units are scientifically valuable target sites

Action item: Advertise requests for folks to join these splinter groups (e.g., VEXAG listserv, PEN?)

Action item: Write up a charter for these splinter groups, for the end of the workshop
We could then discuss the outcome of that work at the next workshop (~October 2020)

Venus Terrain Subgroups Charter:

- produce among their deliverables a map (shapefile) of the terrain type
- use a baseline mission architecture first and then use augmentation options as described in the Phase @ JSDT Report (see VEXAG report website)

Young plains *Larry Esposito, Kevin Baines*

Old plains *Richard Ernst, Kathryn Stack*

Canali-fed plains *Tracy Gregg, Allan Treiman*

Lobate plains (flow field) *Richard Ernst, Tracy Gregg*

Tessera (augmentation) *Mikhail Ivanov, Paul Byrne, Allan Treiman*

Risk analysis *Jason Rabinovitch,*
(to be carried out after the combined shapefiles are produced)

Cloud Layer Habitability Workshop Notes

Compiled from notes taken by workshop scribes: Paul Byrne, Jaime Cordova, Diana Gentry, Anastasia Kosenkova, Margarita Kruchkova, Jordan McKaig, Jason Rabinovitch

Prepared by: Jordan McKaig

Day 3: Landing Site Session 4: Landing Site Selection

Presenter: Ivan Polyansky

Talk title: Landing Site Special Presentation: Descent Cameras

Talk category: Instrument

Notes from talk:

- Major tasks
 - Synoptic views, descent imaging system (resolution: a few meters/px up to tens of centimeters/px)
 - 360° panoramic images
 - Close-up views
 - Obtain as many images as possible
- Contents
 - Descent cameras (2 pcs)
 - Panoramic cameras (resolution: centimeters/px)
 - Microscopic cameras (resolution: millimeter/px)
 - Common mass memory and data compression unit
- Scientific and practical goals
 - Navigation usage of the cameras
 - Surface morphology at meter scale.
- Cameras
 - Panoramic cameras: observation at centimeter scale (the surface texture, rocks and loose materials)
 - Microscopic cameras: observations at sub-millimeter scale (fine-scale characterization of the sampling point, identification of traces of weathering, fine-scale texture of rocks)
 - The only optical images available are panoramas acquired in Soviet Venera-9...14 landers mission (1975-1981).
 - Multicamera approach – a number of tiny similar cameras with different lens and common Mass Memory and Control Unit.
 - Lifetime is approximately 3 hours
 - Prototype has same configuration as ExoMars-2020 surface platform
- Essential that the engineers understand exactly what data scientists need
- Discussion
 - Recording can begin in the upper atmosphere

Main Points: This talk discusses a potential Venera-D lander imaging system, providing a full imaging system overview.

Day 3: Cloud Habitability Session 1: Habitability at Venus

Presenter: Michael J. Way

Talk title: Ancient Venus climate and orbital constraints

Talk category: Theory

Notes from talk:

- 2 key constraints on ancient Venus habitability
 - Liquid surface water (unknown whether this existed)
 - Slow rotational rate (allows for high insolation, supporting liquid water)
- Geological history of Venus
 - Magma ocean □ first stable climate □ present-day Venus
 - How did Venus and Earth's climates diverge?
 - Longevity of magma ocean is crucial: Venus maintained its magma ocean for 1-2 Gya longer than Earth. If the magma ocean is present for ~100 Myr, the water photodissociates and the planet ends up dry.
 - There is some debate concerning the longevity of Venus's magma ocean. Detecting primordial water may help resolve this outstanding question and strengthen climate models.
 - If Venus had surface liquid water 4.2 Gya, then some unknown factor, not solar luminosity, defined its climate evolution.
- In-situ observations of volatile gases in the atmosphere can strengthen conclusions about Venus's geological history
 - Venus's history may also constrain possible exoplanetary climates – more surface studies are needed
 - Helpful measurements that could be taken
 - In situ He/Ne/Ar/Kr/Xe
 - Radiogenic noble-gas isotopes reflect processes that occurred over one or two half-lives of the parent species, and therefore a suite of isotopes sensitive to different time scales
 - Need to be able to correctly model the atmospheric escape processes. Deuterium/hydrogen ratios at various altitudes could help constrain this.
 - NGIMS (Neutral Gas and Ion Mass Spectrometer) on a prospective lander could yield data needed to answer these questions
- Discussion: no time for questions

Main Points: This talk discusses how climate modeling allows for greater understanding of Venus's climate history. In order to have been habitable, the ancient Venus would have needed surface liquid water and a slow rotational rate. In-situ measurements can corroborate such climate modeling – a Neutral Gas and Ion Mass Spectrometer (NGIMS) instrument is recommended for inclusion on a future spacecraft.

Presenter: Shawn Domagal-Goldman

Talk title: Venus as an Exoplanet

Talk category: Theory

Notes from talk:

- Why Venus?
 - Venus is a compelling astrobiological target for its ability to help us understand habitability
 - An opportunity to study how habitability is the result of interacting processes on a planetary scale
 - We don't know where the inner edge of the habitable zone region lies
 - Venus can help us with this
 - Most important place for exoplanet scientists to go for the next 10-20 years
- Major questions and knowledge gaps
 - Why did Venus turn into something very different from Earth?
 - What interactions occur between the surface and the atmosphere?
 - Need greater characterization of the microenvironment of the clouds in order to look at cloud layer habitability
- Proposes a systems-based approach for Venus exploration
 - Comprehensive, global measurements to understand climates
- Implications on exoplanet studies
 - Lots of Venus-like worlds that could be investigated
 - More likely to transit the star (closer)
 - Give good S/N ratios for observations
 - Further study of biosignature detection, habitability analysis, outcomes of terrestrial planet evolution
- Regardless of the cloud layer's habitability, Venus is an essential astrobiological target for understanding habitability and planetary evolution
- Discussion: no questions

Main Points: Domagal-Goldman's talk highlights Venus's utility to the field of exoplanet research. Domagal-Goldman asserts that Venus could answer many questions about habitability, terrestrial planet evolution, and biosignature detection. He proposes a systems-based approach for Venus exploration, seeking to understand the planet as a global entity.

Presenter: Sanjay S. Limaye

Talk title: Case for Search of Bio-signatures on Venus

Talk category: Theory

Notes from talk:

- Themes for the search for Venusian life
 - Where there is water, there is life (on Earth)
 - Liquid water could have existed on Venus's surface for up to 2 billion years. Could there have also been life on Venus?
 - As liquid water was lost from the surface, life could have migrated to the habitable niche in the clouds where it could be extant today
 - Life on Earth can survive in the clouds and in very acidic conditions similar to that of the Venusian cloud layer
 - There is an unknown solar radiation absorber in the Venusian atmosphere. It could be one of several possible chemicals, or it could be microorganisms, as many terrestrial specimens have similar spectral absorption as seen on Venus.
 - There is also chemical disequilibrium and an inexplicable level of methane in the atmosphere.
 - Absorption takes place throughout the electromagnetic spectrum, not just in the UV range. This cannot be entirely explained by Rayleigh scattering.
 - The only possible absorber that has been spectroscopically detected is sulfur dioxide (SO₂) and the amount of SO₂ detected is not enough to cause all the absorption.
- Unanswered questions and knowledge gaps
 - Are microorganisms able to reproduce within the atmosphere?
 - Are the required abundances of nutrients and liquid water consistent?
 - Capable aerial platforms are needed to sample cloud layer for extended periods
- Discussion
 - How has collaboration with the exoplanet research community been?
 - Abiotic radiation absorbers should be first considered before potential biotic explanations.
 - Collaboration with exoplanet scientists to identify the unknown absorber has been difficult – several candidate species have been tested and none of them work.
 - How long would volcanically-ejected water vapor stay in the atmosphere?
 - Unknown, would require modeling
 - Majority of water would be quickly picked up into H₂SO₄

Main Points: Limaye's talk discusses the mysterious radiation absorber present in the Venusian cloud layer and explains the theory that this absorber is biotic in origin. Several possible abiotic explanations have also been postulated, but all tested candidates have not been able to explain the observed radiation absorption. Further

understanding of terrestrial aerobiology and the chemical composition of Venus's atmosphere are necessary to assess the habitability of the Venusian cloud layer.

Presenter: Oleg Kotsyurbenko

Talk title: Terrestrial microorganisms from extreme environments as analogues to hypothetical microbial forms inhabiting Venus' clouds

Talk category: Theory

Notes from talk:

- Habitability is defined as a series of physiochemical requirements coming together at the special scale of an organism so that it can be present in a given environment
 - Appropriate conditions for habitability: energy, solvent (water), CHNOPS and other trace elements, and appropriate physicochemical conditions
 - Need to consider the temperature, pressure, and pH of Venus's cloud layer, relative to what terrestrial microorganisms can survive.
 - Conditions at the lower cloud layer of Venus (47.5–50.5 km): 50–60°, 0.4–2 atm, pH <0.5, presence of sulfur and ferrous compounds, and CO₂
 - Putative Venusian microbes could survive by driving different metabolic processes based on redox cycles in the atmosphere. These include reduction and oxidation of iron and sulfur compounds, oxidation of hydrogen and methane, reduction nitrate and fixation of CO₂ through the phototrophic or chemolithotrophic oxidation.
 - Extremophilic microorganisms found on Earth have been observed to be capable of withstanding conditions similar to those of Venus's clouds.
- Additional aspects of habitability
 - Microorganisms can survive in microniches
 - Examples of microniches on Earth include permafrost, anaerobic syntrophic reactions, and Antarctic ice
 - Venusian organisms can have a combination of properties of different types of terrestrial microbes
 - Consider lithotrophy and thermophily for potential Venus microbes
 - Developing a database of relevant terrestrial analogues, biosignatures, and metabolic features/survival
- Contribution of microbiologists to the mission
 - Selecting and studying terrestrial analogs or environments with key features relevant to the conditions in Venus's clouds
 - Studying specific properties of such life (metabolism, biochemistry, physiology)
 - Modeling and simulating experiments with selected microorganisms
 - Producing biotechnology applications and suggestions for astrobiology missions to Venus's clouds
- Discussion
 - Scientists should pay attention to organisms that can survive in arid environments, perhaps focusing on extreme desert areas.
 - It is important to consider pressure, as biochemistry behaves differently under different pressure conditions.

Main Points: Kotsyurbenko's talk discusses what is currently understood about habitability-relevant parameters in the Venus cloud layer, and what types of microorganisms may be able to survive in such conditions. Extremophilic microbes found in various extreme environments on Earth may contain metabolic, biochemical, and physiological properties similar to those that would be necessary to survive on Venus.

Presenter: David Grinspoon

Talk title: Considerations of energy, biomass limits, and cloud microphysical implications of a putative Venus cloud biosphere

Talk category: Theory

Notes from talk:

- History of Venusian astrobiology
 - Mariner 2 results showed that Venus's surface is too hot and acidic to host life as we know it.
 - Magellan suggested a volcanic world, with cycling atmosphere-surface interactions that would provide potentially interesting thermodynamic considerations for astrobiology.
- Must understand Venus's planetary history
 - Some planets may go through a cycle in which they go from a plate tectonics- to a stagnant lid-regime.
 - Surface volcanism is likely the driver of any biogeochemical cycles.
 - Uncertainties and knowledge gaps include H⁺ and O⁺ escape rates, dynamics, radiative balance, cloud structure for evolutionary climate models, and rate and history of volcanism
 - For 2+ Gyr, the solar system may have had two habitable, terrestrial planets
 - Microbes could have migrated into the atmosphere from a mobile lithosphere, being "blocked" out of a desiccating surface.
 - There was a lot of material transfer between planets in the early solar system, which could have transferred biological material to Venus
- Habitability
 - Microbes can live in very low-pH environments (as low as pH<0)
 - Organisms may affect albedo and radiative properties of clouds, and thus affect dynamics through radiative-dynamic feedback, possibly even affecting super rotation. The absorber could be microbial, something like an algal bloom.
 - Global clouds are much larger and more continuous than those found on Earth.
 - Venus cloud aerosol lifetimes seem to be long enough to sustain microbial replication. It doesn't matter if microbes are falling out of the bottom of the clouds if they're reproducing fast enough.
 - Bacterial endospores could act as cloud-condensing nuclei.
- We must proceed carefully with regard to considering potential abodes of life. However, of the plausible habitats for extraterrestrial life in the Solar System, the clouds of Venus are among the most accessible and the least explored.
- Discussion: no questions

Main Points: This talk discusses the potential for habitable conditions in the Venusian cloud layer, within the context of what is known about Venus's planetary history. Microbes on Earth are capable of surviving similar stressors to those found on Venus,

and can reproduce in aerosolized droplets. Grinspoon argues that life on Venus is possible, and a worthy astrobiological target.

Presenter: Vladimir Kompanichenko

Talk title: Evaluation of Possible Origin of Life in Early Venus in Case of Available Liquid Water

Talk category: Theory

Notes from talk:

- Self-replicating processes could have arisen on Venus
 - Unknown evolutionary jump between RNA/lipid/protein worlds and living things
- Thermodynamic inversion concept
 - Previous experimental attempts to transform prebiotic microsystems into primary life forms were unsuccessful because they did not consider the thermodynamic differences of organizing living and non-living systems
 - Living systems extract free energy, while non-living active systems dissipate it
 - Oscillating physiochemical parameters are required for the origin of life (along with an aqueous medium, available organics, and an energy source)
 - Available prebiotic organic microsystems combined with continuous stress results in an enhanced response
 - Biotic processes arose in prebiotic microsystems at the time of thermodynamic inversion, as an enhanced response to external influences
 - An oscillating medium (such as a hydrothermal system with oscillations on the second-minute scale), could have catalyzed the origin of life
- Venus's compatibility with the origin of life
 - Liquid water (possibly present throughout its history and now)
 - Necessary elements (C, H, N, O, etc.)
 - Energy sources (volcanism)
 - Fluctuations (tectonics and volcanism)
- Consequences
 - The existence of life as we do not know it is encompassed by these theories.
 - Life on early Venus may have originated in the presence of liquid water.
 - Fluctuations in the Venusian atmosphere should sustain any existing microbes.
- Discussion
 - What kinds of fluctuations are possible that could have driven life?
 - Must be short-lived (~30 mins to 3 seconds), given expected lifetime of bacteria (i.e., fluctuations must be much faster than life cycle)

Main Points: Kompanichenko's talk discusses the concept of "thermodynamic inversion" for the origin of life, and its applications for Venus. He argues that plate tectonics and volcanism could introduce environmental oscillations needed to maintain a Venusian cloud-based ecosystem.

Presenter: Valeriy Snytnikov

Talk title: Chemical basis of a hypothetical life on Venus

Talk category: Theory

Notes from talk:

- Environmental parameters and life
 - No stable organic polymers above 550-600°C, sublimation of protein amino acids starts at 500-540°C. Surface temperature on Venus is 462°C.
- Venus “iron sulfur world”
 - Possible “nitrogen life” by N activation
 - Soil contains Fe, SiO₂, Al₂O₃, MgO, CaO, and K₂O is a typical catalyst for N₂ + H₂ > NH₃. N could activate reduced Fe to form the complex Fe_xNH, which participates in the further synthesis of new complex hydrocarbons.
 - Alternative photosynthesis on Venus’s surface
 - Carbonyl sulfide [CO₂] : H₂S + CO₂ <--> [COS] + H₂O
 - Catalytic cycle
 - FeS → FeS₂ → FeS
 - Formation of complex organic compounds with iron-containing catalysts could occur on the surface of Venus
- Data needed from Venera-D
 - Altitude content of gases near the surface (H₂, He, H₂O, C_xH_y, Ne, OCS, H₂S, HCN, Ar, SO₂)
 - C and N compounds on the surface
 - Inorganic surface material
 - Compounds adsorbed on inorganic surface material
 - Composition of dust on the surface
- Studies of chemical catalytic processes on the Venusian surface can have applications for the creation of new chemical technologies and materials for high-temperature uses
 - Fixed bed catalytic reactors and fluidized bed reactor
 - Laboratory capabilities for surface chemical processes
 - Temperature < 1000°C, pressure < 1000 atm
 - Device for producing oxide nanoparticles
- Discussion
 - Could complex reactions on the surface be a source of organic materials?
 - Turbulence and winds could transfer particles higher up into the atmosphere

Main Points: Snytnikov’s talk proposes a potential chemical basis for life on Venus, based upon the formation of complex organic compounds with iron-containing catalysts on the surface. Additionally, a comprehensive list of helpful data that could be collected by Venera-D is given.

Presenter: Jaime Cordova

Talk title: Investigating the Viability of Microorganisms in a Venus Cloud Analog

Talk category: Experiment

Notes from talk:

- Suitability of terrestrial microorganisms for the Venusian cloud layer
 - Altitude of 47.5 – 50.5 km, 60°C, UV radiation, terrestrial-like pressure, acidic
- Which genes ensure survival at these conditions?
 - Recreating Venus cloud conditions (temperature, pressure, and water vapor) in the lab
 - Conducting experimental evolution on microorganisms
 - Species selected based on potential for survival in experimental conditions
 - Also selected species with the ability to oxidize sulfur and fix carbon dioxide
 - Evolutionary timescales taken into consideration
 - RNA sequencing to be used to identify genes responsible for microbial survival
- Further directions
 - Investigate viability of microorganisms in aerosolized form
 - Compare genetic profile of multiple generations
 - Investigate community dynamics of surviving microorganisms
 - Conduct long-term evolution experiment replicating changing Venus conditions
- Discussion
 - Could consider replicating temperatures slightly above the targeted altitude (15°C)
 - Selected bacteria are culturable, experiment will be conducted in liquid media
 - The space community should keep its eyes on the ever-developing technology for microbiology analyses (example: MinION nanopore sequencer)
 - UV radiation should not be discounted in these studies, as it can be a lethal factor

Main Points: Cordova's talk explains an upcoming study seeking to identify which genes enhance survivability in Venus cloud layer-like conditions. Microbial species selected for their pre-existing extremophilic qualities will be propagated in Venus-like conditions in an experimental evolution study, then genes responsible for microbial survival will be analyzed using RNA sequencing.

Presenter: Rakesh Mogul

Talk title: Venus' Spectral Profiles and the Potential for Microbial Life in the Clouds

Talk category: Theory

Notes from talk:

- Photophysical constraints on photosynthesis on Earth
 - Photosynthesis can be oxygenic (using chlorophyll *a*) or anoxygenic (bacteriochlorophyll *a*)
 - Photosynthesis occurs between atmospheric absorption bands (“photosynthetic windows”)
 - Must absorb at peak photon flux, shortest suitable wavelength, and longest suitable wavelength
- Proton flux within Venus clouds
 - Substantial absorption in UV wavelengths as light goes through the Venus atmosphere
- Available wavelengths for photosynthesis on Venus
 - 590-656nm (peak proton flux); 400-485nm (shortest wavelength); 900-1030nm (longest wavelength)
- Habitability for terrestrial organisms
 - Earth life under Venus light demonstrates some absorbance at the peak photon flux, some at the shortest wavelength, and considerable absorbance at the longest wavelength.
 - Thus, the photosynthetic windows on Venus (theoretical) and Earth (real) actually overlap. Largest possibility for photosynthesis on Venus is at 400-700nm.
 - Can make estimates for the hypothetical biomass in the Venus clouds.
- Life detection techniques
 - Raman LIDAR (for organic functional groups and inorganic minerals)
 - Fluorescence LIDAR (for complex biochemicals and organics)
 - Microscope (for aerosol structure and bio/chemical activity and reactivity)
- Discussion
 - UV radiation may be too strong for microbes to survive at higher altitudes than those considered in the study
 - Recommends focusing on an altitude of 55km
 - How sensitive are the Raman and fluorescence life detection techniques?
 - Sensitive enough to detect life at the theorized biomasses
 - Life detection microscope for looking at aerosol structure would be a good way to distinguish biotic from abiotic morphologies.
 - Debate over nitrogen and nitrate detection in Venus's atmosphere

Main Points: Mogul's talk outlines a putative photosynthetic system consistent with Venus's environmental conditions. He outlines the minimum constraints for photosynthesis on Venus and proposes life detection techniques (Raman and fluorescence LIDAR, microscopy).

Presenter: Arif Ansari

Talk title: UV-absorbance and survival mechanism of potential bacteria in Venus clouds

Talk category: Theory

Notes from talk:

- Life can be defined as a set of organic molecules that can interact with its environment and reproduce itself
 - Basic requirements include presence of carbon and liquid water, and temperature normally between freezing and boiling
 - Current conceptions of life and habitability are human- and Earth-centric, but our views of the boundaries of microbial habitats is widening
 - Biology does not need to sit on the surface of the planet
 - Terrestrial microorganisms have different types of defense mechanisms that allow them to be resistant to extreme environmental parameters (high/low pH, salt, desiccation, UV radiation, high/low temperature).
- Reasons to search for life in Venus cloud layer
 - Sufficient H₂O
 - High density of particulates and micron-sized particles
 - Presence of light hydrocarbons
 - Absorbance of attenuated UV, resulting in lower UV radiation
 - Usually life concentrate in niches, and this area of the Venusian atmosphere could be a good niche to support life.
- Discussion
 - Useful measurements include light hydrocarbons, glucose, and amines (things that bacteria use for food), along with isotopic analyses.
 - Most life in the stratosphere is dormant, so it's not a great Venus analog.
 - Need to know what particle density of UV absorber is required to meet the observed spectral absorbances

Main Points: Ansari's talk discusses how astrobiology's conception of habitability has expanded significantly by studying extremophilic microbes in a wide variety of environments on Earth and provides justification for why the Venus cloud layer is a compelling target in the search for life. The discussion also yielded a good list of useful measurements that Venera-D or a similar mission could obtain.

Presenter: Tetyana Milojevic

Talk title: Metallophilic extreme thermoacidophiles: potential biosignatures in the Venusian clouds

Talk category: Experiment, theory

Notes from talk:

- Potential for metallophilic extreme thermoacidophiles on Venus
 - Based on elevated temperatures, acidity, availability of sulfur and iron species for redox biotransformations, and CO₂ abundance in the cloud layer
- Archaeal order *Sulfolobales*: metallophilic extreme thermoacidophiles on Earth
 - Currently cultivating these species and studying them in the lab
 - Studying metal-microbial interface in *Metallosphaera sedula* on terrestrial and extraterrestrial materials
 - Biological activity indicated by active iron oxidation on the cell surface
 - Would be helpful to synthesis Venusian simulants
- Studying metallophilic extreme thermoacidophiles would provide a guiding point for in situ measurements to analyze collected Venus aerosol samples
- Discussion
 - Lots of interest from the general astrobiology community in understanding Venus as a whole, not just the potential for life in its clouds
 - Chemistry of Venus materials very poorly known. Crystalline basalts are probably the way to go, but it's not clear how much of that material would make its way up to the atmosphere

Main Points: Milojevic's talk discusses the potential for metallophilic extreme thermoacidophiles on Venus. Laboratory-based experiments are investigating such terrestrial species, which can inform future interpretation of samples collected on Venus.

Presenter: Anastasia Kosenkova

Talk title: Venera-D: Spacecraft and Orbits

Talk category: Instrument

Notes from talk:

- Mission targets
 - Investigate Venus with remote and contact methods
 - Amplify the volume of the fundamental explorations made by previous spacecraft
- Orbiter targets
 - Transport the lander and the detachable payload up to desired points near Venus
 - Assure that the onboard payload could get the scientific information of required volume and expected quality
 - Transmit the scientific information to Earth from the onboard payload and to receive/retransmit the scientific information to Earth from the Lander and the other payload
 - Capture photo/video recordings of the selected regions of the Venus clouds/surface using the onboard payload
- Orbiter specifications
 - Can observe Venus from the orbit 500×72000km
 - Can communicate with the Lander, LLISSEs, aerial platforms, other detachable elements, CubeSats, subsatellites in L1/L2 and Earth using a bunch of antennas (not simultaneously!)
 - Life expectancy 3+ years
- Launch specifications
 - Angara-A5 rocket career with its upper stage (KVTK)
 - Rocket can accommodate augmentations
 - Target launch windows are in 2026, 2028, 2029 and 2031
 - Technical solutions for the Orbiter mostly depend on the onboard (regarding the accommodation) and detachable payload (regarding using robotic arms or something else and amount of it) needs.
- Discussion: no questions

Main Points: Kosenkova's talk outlines the Venera-D's mission targets and explains how its orbiter component's specific targets will help accomplish these goals. Orbiter specifications and launch logistics are communicated.

Day 4: Cloud Habitability Session 2: Origin and Survivability

Presenter: Anatoli Pavlov

Talk title: Permanent infection of the Venus upper atmosphere by transfer of terrestrial microorganisms through the ejected dust particles from Earth and Mars

Talk category: Theory

Notes from talk:

- Panspermia (hypothesized transfer of biological material between planets) may have transferred living things to Venus, planting the seeds for a Venusian biosphere
 - There may be a sustained process of microbe transfer via small dust grains from Earth to Venus via the impact process; some of this material is not sterilized during atmospheric entry.
- Hypothetical mechanisms for inoculating Venusian atmosphere
 - Large meteorite impact on Earth or Mars
 - Ejection of dust particles with microorganisms to space
 - Slow drift of micron-sized particles to Sun
 - Capture of dust particles by Venus without extremal heating at entry into upper atmosphere
 - After escape the dust particles move around the Sun on circled orbits; they have a slow drift to Sun due to the Poynting-Robertson effect.
- Survival of transferred microbes
 - Vacuum drying in space, cosmic and UV radiation, and heating from atmospheric entry pose substantial hazards to biota.
 - Survival of high temperature and vacuum conditions is possible, based on laboratory and space experiments. UV radiation is only a concern on the surface, as it is easily shielded by rock or dust.
 - Cosmic rays seem to be the limiting factor for microbial survival during interplanetary transfer.
 - Life could be in the cloud layer of the Venus atmosphere if terrestrial microorganisms are able to adapt to such environments.
- Discussion
 - Would be helpful to quantify expected flux of particle transfer is to Venus
 - Could look for traces of biological materials of terrestrial origin on the Moon.

Main Points: Pavlov's talk discusses the potential for panspermic transfer of microbes from Earth to Venus, resulting in the establishment of a Venusian biosphere. Microbes would encounter many severe environmental conditions during transfer, but it is possible that some could survive the journey and adapt to a niche on Venus.

Presenter: Margarita Kruchkova

Talk title: High stability of mycobiota from desert soils to the impact of ionizing radiation (100 kGy) at low temperature and pressure

Talk category: Experiment

Notes from talk:

- Experiment to study the effect of gamma-radiation under low temperature and low-pressure conditions on desert fungi
 - Soil microbiota samples were exposed to an extreme irradiation (100 kGy), temperature (-50°C), and pressure (1 Torr) regimes consistent with Venus cloud conditions.
 - Survivorship was assayed with fluorescence microscopy.
 - Prokaryotes showed high resistance to these conditions.
 - Fungal communities were actually more stable than normal in response to these conditions.
 - Particle association was important for survivorship. Likewise, living microorganisms in the Venus atmosphere may be associated with mineral particles.
- Discussion
 - Studies were done with low temperatures and aerobic conditions; further studies should be done with more Venus-like conditions
 - Fungal spores are found in clouds on Earth.

Main Points: Kruchkova's talk describes an experiment investigating microbial (prokaryotic and fungal) survivorship in Venus-like conditions. It was found that prokaryotic species exhibited resistance to these conditions, while fungal species actually exhibited more stability in stressful conditions. Results from this study indicate that living organisms could survive the environmental conditions of the Venus cloud layer.

Presenter: Grzegorz Słowik

Talk title: Observation of the life cycle of extremophilic bacteria of the genus *Acidophilus* under the conditions of the reconstituted Venus atmosphere

Talk category: Experiment

Notes from talk:

- Many questions are still unanswered about Venus
 - We do know that it may have been water-rich in the past, potentially making it a hospitable climate for life
- *Acidophilus* might be able to survive in the conditions of the middle Venus atmosphere (47.5–50.5 km, which is ~1 atm, pH <3, and 60°C)
 - Assimilates carbon dioxide to obtain carbon necessary for the biosynthesis of cellular material
 - On Venus, nutrients could be coming up from the ground through sand storms
 - UV spectra of *Acidithiobacillus ferrooxidans* correlate highly with the spectra recorded for the Venus atmosphere in the same wavelength range λ of electromagnetic radiation.
- Proposing H₂SO₄ as a biomarker for chemoautotrophic metabolism by an *Acidophilus*-like bacterium living in the Venus cloud layer
- Discussion
 - It is important to consider microbial viability in aerosol conditions, as many of these studies take place in liquid culture
 - *A. ferrooxidans* has been studied in aerosols, but only in lab conditions. It has never been observed in the Earth's atmosphere.
 - This microbe may not be able to withstand the temperatures of a Venusian habitat
 - Community dynamics with other bacterial species could confer beneficiary relationships
 - Venus's atmosphere is highly anaerobic, but some oxidation may occur via photochemistry (e.g. photolyzing of CO₂ to generate (some) free oxygen; whether microbes could use that oxygen is another question.

Main Points: Słowik's talk discusses the *Acidophilus* genus of bacteria, which may be able to survive the conditions of the Venus cloud layer and can be sustained by ferrous iron and pyrite oxidation. This talk proposes H₂SO₄ as a biomarker that can be used to detect these bacteria in the Venusian clouds.

Presenter: Mark Bullock

Talk title: Venus atmospheric chemistry and possible metabolic pathways for microbial organisms

Talk category: Theory, instrument

Notes from talk:

- Can study potential Venus biology without requiring too many additional measurements (by characterizing gas and aerosol chemistry, particularly of sulfur cycles)
 - Atmosphere is in a state of chemical disequilibrium, which could foster life
- Plausible archaea and bacterial metabolisms could reduce sulfur and sulfate
- Cloud microbe model
 - This model calculates growth and loss of microbes that reduce available SO_4^{2-} to S_n and H_2S
 - Possible to develop a continuity equation for microbes in aerosols
 - This model requires both microbial colonies and endospores (to seed other aerosols)
 - Compatibility of Venus aerosol lifetimes with life
 - Particles remain aloft for 2-300 days
 - Microbes could persist if lifetime is greater than 14 days
- In situ exploration is critical
 - Potential platforms include balloon, descent probe, fixed-wing aircraft, aerobots, or rotorcraft
 - Preferred mission characteristics
 - Long-duration (30+ days) in ~6 locations around Venus
 - A capable payload (aerosol analyzer, microscopy, IR and Raman spectroscopy, and gas and aerosol collection)
 - Ability to navigate vehicle in 3D, to take advantage of downdrafts, gravity waves, etc. to visit regions with the unknown absorber
- Discussion
 - Sporulation took a long time for bacteria to evolve, is only present in a small subset of species, and takes a lot of energy
 - Proposed payload would be 100kg
 - Aerosol fallout speed would be substantially changed by updrafts
 - Unknown how much sulfate/sulfur and sunlight bacteria would need in this environment

Main Points: Bullock's talk discusses the need to further characterize Venus's gas and aerosol chemistry, arguing that a great deal of Venusian astrobiology work could be done by understanding these characteristics. This talk also outlines a potential strategy for in situ exploration of the Venus cloud layer.

Presenter: Mary Voytek

Talk title: NASA strategy for the search for life

Talk category: Theory

Notes from talk:

- NASA's strategy for searching for life beyond Earth
 - Understand space environments
 - Understand the evolution of the Earth's biosphere and organisms
- Life requires (in decreasing order of uncertainty):
 - Thermodynamic disequilibrium
 - Environment supportive of covalent bonds
 - Extremophilic life reflects "record holders," but most environments are frequently more restrictive
 - Liquid solvent
 - Doesn't have to be water, but must support covalent synthesis and non-covalent interactions
 - Water activity <0.6 on Earth
 - System supportive of Darwinian evolution
 - CHNOPS, transition metals for enzymes
 - Alternatives must be evaluated on their ability to support the requisite covalent and non-covalent chemistry and in reference to the properties, reactivity, and phase stability of the solvent
 - Only certain forms of P and Fe are biologically available
 - Redfield ratio – ecological stoichiometry, relatively consistent ratio of measurements in biomass samples, doesn't include chemical energy
 - Ratios of CHONPS in the universe overall are not equal to their ratios in biological systems
 - 106 C: 16N :1 P 0.1-0.001Fe
- Unknown factors affecting habitability
 - Origin of potential biota in Venus clouds
 - Organism survivability and ability to reproduce
 - Sources, sinks, and concentrations of bio-essential elements
 - Necessary conditions for aerosolized bacteria to acquire nutrients and reproduce
 - How to evaluate polyextremophily, and how it would limit microbial candidates and biomass
- Considerations for life detection
 - Reliable, unambiguous, resilient, and detectable biosignatures
 - Minimum cell density needed to explain the absorber, and what other spectral features would be necessary to confirm a biotic source
 - What is required to measure life directly (sampling, processing, detection)
 - Costs to a mission (mass, power)

- Best practices that the Venus community can learn from other communities (e.g. exoplanets)
- Discussion
 - Might not be too much UV in the lower/middle cloud layer, having been absorbed by the absorber in the upper cloud layer
 - Unknown how long life could survive above the cloud layer. Is there any upward transport of the unknown absorber?

Main Points: Voytek's talk outlines NASA's astrobiology strategy, defining the environmental requirements for known life, knowledge gaps in assessing the habitability of the Venus cloud layer, and important considerations for any potential life detection missions.

Presenter: David J. Smith

Talk title: Methods for sampling bioaerosols in Earth's troposphere and stratosphere

Talk category: Experiment

Notes from talk:

- Very difficult to study cloud life on Earth; in situ microbial detection almost impossible
 - Current aerobiological methods use aerial platforms, aircraft, balloons
 - More work obtaining in situ terrestrial cloud measurements is needed
 - Technology for applications on Venus could be available in 10-15 years with sustained investment and work
- Aerobiology studies
 - Microbes in Earth's clouds are transient, frequently being lofted from the ground to fall down or be rained out
 - Bioaerosols commonly associated with SO₄, organic carbon, dust, black carbon, and sea salt
 - Need to collect a bioaerosol sample in order to make measurements
 - Need to concentrate a huge volume of air to make measurements
 - NASA Ames Aerobiology Lab platform: C-20A aircraft flies for ~5 hours at ~12km, samples are analyzed in the lab
 - There may be 10²⁴ bioaerosols in the stratosphere (40% of all bioaerosols).
 - Bioaerosols can be collected and identified, but their metabolic activity is more difficult to pin down.
- Bioaerosol detection methods
 - Fluorescence spectroscopy
 - Bioaerosol sensors
 - Mass spectrometers
 - Resource effective bioidentification system (REBS)
 - Molecular tracer techniques
 - Proposing microscopy as a component of life detection, in addition to genetic and molecular measurements
- Discussion
 - It is currently unknown how reproducible microbial signals are in the atmosphere; more flights are needed.
 - Contaminants are distinguished from true bioaerosols via controls and blanks.
 - Optical microscopy has a high risk for false positives. Fluorescence microscopy coupled with another life detection method could be employed.

Main Points: Smith's talk discusses current methods in bioaerosol collection and characterization in the Earth's troposphere and stratosphere. It is currently difficult to study life in the Earth's clouds, and all analyses rely on sample return to the lab. With

sustained investment and development, in situ aerobiology techniques could be ready for implementation on Venus in 10-15 years.

Presenter: Diana Gentry

Talk title: Bioaerosol sampling considerations for in situ analysis

Talk category: Observation planning

Notes from talk:

- Habitability and life detection considerations
 - Habitability constraints: solvent and energy availability, radiation, temperature, particle size, residence time, CHNOPS presence
 - Life detection methods: optical, chemical, and agnostic biosignatures
 - Venus analogs for energy source, temperature, radiation, particle size, and residence time have been defined on Earth
 - Water availability's impact on habitability goes beyond molarity, pH, or salinity
 - Also involves gravitational potential, internal/external physical pressures, partial molar water volume, matric effects, and osmotic balance
 - Osmotic and matric effects dominate on microbial scales
 - Venus's aerosols are similar to dry deserts on Earth in terms of water availability
 - Any Venusian life would likely be a "desert bloom" scenario
 - Activity dependent on sporadic influx of distant water/nutrients
 - Very low biomass during typical dry stage
 - Ability to store/harvest energy for repair, growth, and metabolism
- In situ targets
 - Compare aerosol regions with upwelling or mixing to isolated regions
 - Spectral irradiance constrains available photochemical energy
 - Measure water activity (and/or major factors affecting it)
- Benchtop work
 - Water activity in aerosol analogs
 - Energy and kinetics of potential metabolic pathways
 - Adaptation of relevant sensors to Venusian temperature and pH
- Lessons from terrestrial analogs: Earth's troposphere and stratosphere
 - Stratosphere probably a better analog (isolated, stratified, dry, sulfate layer)
 - Need to concentrate a lot of air (both temporally and spatially) to get a signal
 - Sample starts changing immediately after capture

- Vast majority of bioaerosols are dead or dormant, resulting in different signatures
- Bioaerosols sparse and unevenly distributed
- Need very good baseline for spectrum
- Balloons and other passive platforms may miss hotspots
- Possible approaches include isotopic or elemental fractionation, chiral excess, molecular size/complexity
 - Mass spec and optical approaches unlikely to be conclusive alone
- Discussion
 - Variable altitude balloons would permit sampling of specific, targeted sites
 - Mechanism for microbial adherence to aerosols is complicated. Some express surface proteins, some dry onto particles, and some stick by electrostatic charge.

Main Points: Gentry's talk discusses outlines habitability analysis and life detection considerations for applications on a putative Venus astrobiology mission. Lessons from terrestrial analogs (notably, the Earth's stratosphere) are expanded upon, implications for Venus exploration are detailed, and recommendations are made for life detection strategies.

Presenter: Satoshi Sasaki

Talk title: Life-signature detection microscope for cloud layer particles

Talk category: Instrument

Notes from talk:

- Descending inertial impactor sampler for bioaerosols
 - Used on the JAXA Biopause Project
 - Sampler descends through the stratosphere, and atmospheric aerosol particles are collected on the impactor plates
 - Carried by a balloon
 - Ring-shaped “satellite structure” around impacted particles allows for distinguishing true bioaerosols from contaminants
- Fluorescence microscopy for bioaerosol analysis
 - Can distinguish living from dead cells
 - Can image cells, proteins, proteinoids, polycyclic aromatic hydrocarbons
 - Black dye can reduce false positives caused by background fluorescence
- This sampling device could be turned into an instrument to be flown on Venus by hybrid airplane or balloon
 - Life Detection Microscope (LDM)
- Resolution
 - Viking TVGCMS detected 10^7 cells/gram of sand
 - There are only 10^4 cells/gram of sand in Atacama
 - Lower limit of fluorescence microscopy detection is $<10^4\text{g/cm}^3$
 - Can also can detect biomolecules (e.g. DNA)
- Future plans
 - Design of turret impactor sampler to fit the microscope
 - Miniaturize microscope ($<100\text{g}$) for space application
 - Identify effective fluorescent dyes
 - Identify model microbe(s)
- Discussion
 - Takes about 1 hour to collect samples, use dye, and take image
 - Microscope could be used in clouds, not on surface (too hot)
 - Not all dyes can work in the presence of H_2SO_4

Main Points: Sasaki’s talk discusses a new bioaerosol sampling and imaging methodology, which is currently being developed towards a Life Detection Microscope for potential use on Venus. By collecting bioaerosols on an impactor plate and imaging them with fluorescence microscopy, life can be detected at a concentration less than 10^4g/cm^3 .

Presenter: Kevin Baines

Talk title: An aerosol instrument package for characterizing the Venus cloud habitability zone

Talk category: Instrument

Notes from talk:

- Understanding Venusian aerosols
 - H₂SO₄ aerosols are the key to Venus's clouds, radiative balance, meteorology, and circulation
 - More data needed on Venusian particle interiors; particle size, distribution, and concentration; and particle type
- Quadrupole Ion Trap Mass Spectrometer (QITMS) instrument
 - Aerodynamic lens system separates aerosols from atmospheric gases
 - Components
 - Spectrometer (mass spectrometer to determine composition)
 - Nephelometer (particle size, distribution, type)
 - Goal of measuring HCl/H₂SO₄ abundances at 2ppm measured to 10% accuracy in 300s at 55km with H₂SO₄ mass density of 20mg/m³
 - Work ongoing to make the instrument <9 kg, <40 W peak power (30 W nominal); adding noble and reactive gases adds 2 kg
- Overview of desired measurements from cloud layer
 - Carbon, hydrogen, oxygen, nitrogen, and sulfur have been detected in the Venusian atmosphere. Is phosphorus also present?
 - If present in the cloud layer it is most likely present in the aerosols. Phosphine (PH₃), unstable in the Venus atmosphere, is the only likely volatile phosphorus compound.
 - Confirming the presence of phosphorus in aerosols of the Venus cloud habitability layer would provide critical information on the potential for supporting life.
 - Bulk cloud properties, cloud dynamics, cloud particle trace species composition, and composition of attendant cloud gases, etc.
 - Looking for astrobiology experts to fill out and expand upon the chart
- Discussion: no questions

Main Points: Baines's talk provides an overview of the Quadrupole Ion Trap Mass Spectrometer (QITMS), which is an instrument that could characterize the aerosols and gases of the Venus cloud layer. This talk also contains an overview of desired measurements to be taken in the cloud layer, providing a method of organizing desired data for the workshop participants.

Presenter: Jason Rabinovitch

Talk title: Aerobots to explore Venusian clouds

Talk category: Instrument

Notes from talk:

- Aerobots are robotic balloon-based aerial vehicles
 - Have some control on trajectory and altitude
 - Could explore Venusian clouds for weeks to months
 - Can carry out atmospheric and geophysical measurements
 - Can deploy drop probes to the surface
- Several different types of balloon
 - Pumped Helium (change the buoyancy by pumping He between the balloons)
 - Air Ballast (change the weight by pumping the air into the balloon)
 - More difficult to pump Venusian atmosphere (sulfuric acid)
 - Mechanical Compression (change the volume by squeezing)
- Key metrics
 - Mass of 100kg under balloon
 - Energy consumption to change altitude
 - Achievable altitude range of 52 – 60km for -10 – 60°C
 - Aerobot would circumnavigate in 5-6 days
 - Each has different design complexities and power and mass requirements
- Recommend either a pumped helium or mechanical compression balloon for a long-lived Venus aerobot
 - All considered platforms have flown on Earth; more work needed for Venus
 - Need for advanced simulation tools for balloon dynamics and thermodynamics
- Discussion
 - Vega balloons experienced up- and downdrafts of a few meters per second, straight up and down.
 - Topography might control up- and down-drafting.
 - A stable platform would be needed for downward-looking instruments
 - Altitude stability is not always good, it may be better to move with air currents in order to understand the circulations in Venus' clouds.

Main Points: Rabinovitch's talk proposes aerobots (robotic balloon-based aerial vehicles) for atmospheric studies on Venus. Several types of balloon were considered, with pumped helium or mechanical compression balloons being recommended.