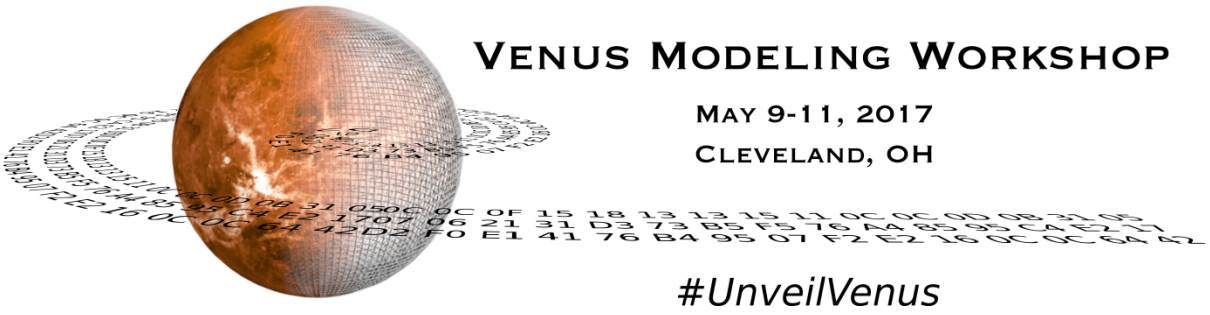

Workshop Report

May 9 – 11, 2017

Ohio Aerospace Institute
Cleveland, OH

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https://www.hou.usra.edu/meetings/venusmodeling2017/

I. Executive Summary

More than 60 scientists, engineers, and students, including several international attendees with ties and interests in Venus exploration met on May 9-11, 2017 at the Ohio Aerospace Institute, adjacent to the NASA Glenn Research Center to present, discuss and document the current state of modeling activities of the Venus interior, surface, atmosphere, and exosphere. The workshop was to communicate recent advances modeling capabilities which have been developed to support both mission-based and Earth-based observations of Venus, as well as the need for data from Venus and from the laboratory community to allow developments of better, more accurate, models of the Venus system. More than 45 oral and poster presentations were made in both plenary and break-out session formats. The program and abstracts for all papers are available at https://www.hou.usra.edu/meetings/venusmodeling2017. The program began with an update of the status of the Planetary Science Division programs given by Dr. Jonathan Rall from NASA Headquarters. The keynote science speaker at the workshop, Professor James Head from Brown University, also made a public presentation to a group of more than 80 attendees on Wednesday evening, May 10 at the Cleveland Museum for Natural History. The workshop concluded on Thursday May 11 with a plenary session to discuss findings and a summary for the workshop, followed by a tour of the NASA Glenn Research Center Extreme Environments Rig (NASA Glenn – GEER), which is the world's largest chamber capable of simulating Venus environmental conditions from high altitudes down to Venus surface conditions.

Thanks to the availability of the Ohio Aerospace Institute as a venue, and operational support from NASA Glenn Research Center and the Lunar and Planetary Institute (USRA/LPI), registration costs for the workshop were kept quite low (less than $150) and the nearby lodging costs were quite reasonable. Additionally, support from NASA Headquarters made possible the award of travel grants to six students attending the workshop.

The attendees expressed the strong opinion that the biggest need for improvement of models was the availability of in-situ data such as would be available from a lander/atmospheric descent vehicle. Furthermore, that high resolution topography is essential to advancing understanding of global, regional, and local geologic processes and thereby improving our understanding of Venus' evolution.

Key Points and Major Needs

- There is a strong need for a system science approach and coupling models (e.g. interior models coupled to surface models.) To do this, it may be necessary to host models in a centralized location and standardize model outputs/inputs,
- Researchers strongly want **in situ** data to constrain models (topography came up multiple times),
- Laboratory data (e.g. collision induced absorption, line lists) are needed for better modeling efforts,
- Modelers want to enable future missions, and
- The role of understanding Venus as a prototype for a large class of exoplanets can serve both the Venus and Exoplanet science communities.

Summary of Presentations and Break-Out Sessions

Day1, Tuesday May 9, 2017:

The morning Plenary Session opened with a presentation by Jonathan Rall (NASA Headquarters) who discussed the FY18 NASA budget and future prospects for Venus missions in the New Frontiers call.) Jonathan noted that New Frontiers selection will be announced in November 2017 with the Phase B studies to begin in December 2017 and selected in mid-2018. Currently, there is no NASA/U.S. Mars mission identified beyond Mars 2020. The SLS launches will be needed for the Europa Lander. NASA is very interested in SmallSat/CubeSat missions with three Venus missions selected for further definition in NASA PSDS3 Program. A new NASA Planetary Advisory Committee will soon be in place to replace the Planetary Science Subcommittee in the NASA Advisory Council. Senior Reviews and Science/Technical Definition Teams will now have to adhere with Federal Advisory Committee Act (FACA) regulations. The NASA Advisory Committees (ACs), whose charters and terms of reference need to be updated, will be ad hoc. Jonathan concluded by noting that the current Decadal Mid-term Evaluation will report out in late 2017 or early 2018. The next (3rd) Decadal Survey for 2023 – 2032 will be underway by October 2019 with a Final Report in October 2022. In the Question and Answer session, it was noted that a Venus Flagship Mission Study will have to wait until the decisions regarding New Frontiers and Europa Clipper missions.

The keynote scientific presentation of the Plenary Session was given by James Head (Brown University) who spoke about Venus Geological history. A major theme of his talk (and of the conference in general) was **comparative planetology of terrestrial planets and a need for "Venus system science."** He made the point that Venus is difficult to explore due to its environment and therefore obtaining in situ information requires a non-traditional, non-linear path. He also discussed the distribution of craters on Venus, the mechanism for heat transfer on Venus, and the age of the Venus surface. He noted: "Venus conspires against us!" In particular,

"Given the lack of a Venus exploration program, it's clear modeling will really help focus our attention."

In the Question and Answer session, Bob Grimm commented that proposals with system science goals failed in a previous Discovery call and care must be taken on how to frame system science programmatically.

The second Plenary Session talk was by Michael Way (Goddard Institute for Space Studies) who spoke about "Modeling Venus Through Time." Using a global climate model, he predicts that a slow rotation rate generates thick subsolar clouds that can strongly cool Venus. **The exciting implication is that this mechanism could have kept Venus' surface temperature habitable for billions of years**. In the Question and Answer session, it was asked: "Is Venus more representative of terrestrial outcomes than Earth?" and also it was suggested that the

Venus community has “natural allies” in the exoplanet community. When asked about what the biggest need for in situ observations. Mike replied: “We want as much as we can get!”

The final Plenary Session talk for this first day was presented by Rebecca Ghent (Planetary Science Institute and the University of Toronto) who spoke on “Perspectives on Planetary Evolution”. She echoed previous speakers who expressed a need for **integrated models** and discussed the Venus cratering record and how the Venus resurfacing history has been variously interpreted by different members of the community. She noted a need for a **surface + Interior coupled model** and made the point that the geological history of Venus is not “settled science, and could benefit from significant improvements in topography measurements. She also reiterated the need for **“Venus system science.”**

Following lunch, a number of short “flash talks” were presented as previews of the poster presentations. The speakers discussed:

- Venus aerial platforms,
- Flight electronics designed for extreme environments,
- Kinetic studies of neutral-neutral reactions between S and Cl molecules,
- Sulfur chemistry in the Venus mesosphere,
- Modeling Venus clouds with a GCM,
- Effects of pyrrhotite under simulated Venus conditions,
- Low-intensity high-temperature solar cells for Venus exploration,
- Experimental and observational evidence for plume-induced Venusian subduction,
- Sulfur compounds’ roles in radiative transfer, and
- Adiabatic lapse rate calculated from gas mixture models.

To complete the first day, the attendees split into two breakout groups: 1) Orbital and Atmospheric, 2) Surface and Interiors. Both groups addressed “Recent Advances.”

Orbital and Atmospheric Breakout Group

Major themes and modeling needs that emerged were:

- Need for observations below the Venus clouds, cloud properties, haze below the clouds, gravity waves, solar heating rates,
- GCMs incorporate many physical phenomena but they require observational constraints and better fluid dynamics modeling of atmosphere-surface feature interaction,
- A strong need for better kinetics data,
- A need for better spectroscopic data to identify opportunities for constituent detection (as one can’t go looking for things you don’t have good spectroscopic data for),
- Challenges to detecting lightning on Venus (as Venus lightning is expected to be bursty),
- Measurements of constituent distributions are a way to check that combinations of chemistry and dynamics are simulated correctly, but such distributions hard to measure remotely,
- Chlorine chemistry that is proposed in models yet not studied in the lab.

In the Question and Answer session, it was noted that measurements of compositional distributions are a great way to test dynamics in models and that dynamics are hard to measure remotely.

Surface and Interiors Breakout Group

Major themes and modeling needs that emerged were: (1) Evidence for volcanism on Venus, and approaches for further study, and (2) understanding the nature of the Venusian lithosphere and why plate tectonics do not exist. Terrestrial planets all undergo a heat pipe phase, but the high surface temperature on Venus means that the planet experienced a long heat pipe period. (i.e. Venus never had plate tectonics?)

Day 2, Wednesday, May 10, 2017:

The morning Plenary Session opened with **Yeon Joo Lee** (JAXA) speaking about "radiative energy calculations in the Venus atmosphere from the troposphere to the mesosphere" illustrated with recent interesting observations taken with Akatsuki. Modeling needs that she discussed were: A) a need to use the most recent gaseous absorption data when modeling the Venus spectrum, B) the fact that H_2O/CO_2 collision-induced absorption may not be well known at high temperatures and pressures, and C) **we must understand the clouds better to understand the nature of the unknown UV absorber.**

The second Plenary Session talk on "UV Absorbers and Cloud Contrasts on Venus" was presented by **Sanjay Limaye** (University of Wisconsin) who discussed the provocative hypothesis that the unknown UV absorber could be bacteria living in the Venusian clouds, where atmospheric conditions are Earth-like. He argued that the nature of the unknown UV absorber is still unknown, and we should acquire more data and develop models to address this.

The third Plenary Session by **David Senske** was a report on the work of the Venera-D Joint Science Definition Team. The Venera-D baseline concept is a Polar Orbiter with a lifetime of > 3 years, plus a lander with 2+ hours on the surface, launching in mid 2020's. The Orbiter will study the dynamics and nature of super-rotation; radiative balance; characterize thermal structure, winds, tides, measure composition of atmosphere, cloud structure, investigate the upper atmosphere. The Lander will: conduct chemical analysis of surface materials; study the surface and atmosphere interactions; study structure and chemical composition of the atmosphere down to the surface including abundances and isotopic ratios of noble gases; perform direct chemical analysis of cloud aerosols; characterize geology of local landforms at different scales; search for volcanic and seismic activity and lightning. Most importantly, the lab work needed to support this mission was identified as: measurements of IR spectral line profiles under higher pressure and temperature, emissivity experiments at 1 μm, and mid-IR optical fiber technology.

The fourth Plenary Session talk by **Glyn Collinsion** (Goddard Space Flight Center) addressed "Atmospheric escape at Venus." He noted that an "electric wind" surrounding Venus is able to strip away heavy ions, including oxygen ions. This in turn may explain where the oxygen went, if and when Venus underwent a runaway greenhouse characterized by massive water vapor photolysis and loss. However, "accurately running back the clock" on Venus requires knowing "how the clock works." **Better in situ measurements of the electric field are needed, plus more modeling work.**

The fifth and final Plenary Session talk by **Steven Kane** (San Francisco State University) presented "The Venus Zone: Seeking the Twin of Earth's Twin." One of his major points was that **the exoplanet community needs to be informed by the planetary science community**. For instance, the planetary science community can inform that community of the most interesting and useful things to measure in the atmospheres of planets orbiting other stars. In the Question and Answer session it was noted: "The atmosphere of the planet is the campfire we can all gather around and tell our stories about what it all means."

To complete this second day, the attendees again split into two breakout rooms: 1) Orbital and Atmospheric, 2) Surface and Interiors, and the overarching theme this time was "Feed forward modeling, critical needs, and mission direction."

Orbital and Atmospheric

Major themes and modeling needs that emerged from the atmospheres session were:

- Better measurements of H_2SO_4 refractive indices are needed to model the clouds.
- Better line lists are needed for radiative transfer modeling.
- Venus modeling studies can inform exoplanet studies.
- High pressure fluids can behave in unexpected ways, including chemical species unmixing and spontaneous segregation.
- The team at NASA Marshall SFC developing Venus-GRAM wants the Venus community to let them know what things to include in the model that would be helpful, and they want to help maximize contributions for mission planning phases of proposals.
- There is a plan to host a virtual workshop to update all GRAMs (including Venus). VIRA is also in need of updating.
- The amount of data now accessible and the maturity of GCMs have advanced enough so as to incorporate data assimilation, a significant step in filling gaps in the datasets, while pointing out the potential biases of the models.

Surfaces and Interiors

In the surfaces & interiors session, major points included:

- There is much yet to be learned about volcanism on Venus (e.g. intensity, length of time, lava viscosity). The spatial resolution of Magellan is not enough and new data is needed. **(i.e., Better topography is needed!)**
- "Lava flow knowledge" right now is "stuck" and awaiting new data (topography).
- Thermal convection's impact on probes and landers is being studied.
- Current experiments in the NASA Glenn Venus Simulator (GEER) show that sulfates grow instead of breaking down under Venus conditions.
- Modeling tested whether Venus' atmosphere would affect X band radar interferometry. Atmospheric variations in SO_2 may have some moderate impact on phase measurements.
- Resources needed to advance modeling capability are: heat transfer validation, collision induced absorption, species interactions.
- Need Computational Fluid Dynamical models of the atmosphere near the surface, and temporal variations should be used to construct statistical time varying atmospheric models.

Day 3, Thursday, May 11, 2017:

The final day of the Workshop was focused on identifying Workshop findings, obtaining feedback from the audience, and establishing a reference for the needs of the community. **Giada Arney** opened the session with some polls of the audience**. The attendees expressed the strong opinion that the biggest need for improvement of models was the availability of in-situ data such as would be available from a lander/atmospheric descent vehicle.** It was clear that that modelers want a mission to Venus and they want to enable future Venus missions.

Desires of the community that emerged and major discussion points/questions were:

- A **listserv** for the Venus community is needed, possibly a monthly newsletter (Recent publications are currently included on the VEXAG website.)
- **An index of computational tools** is also desired.
- **Lab data is still needed to support modeling.**
- **Systems integration should occur across models.**
- **There are existing technologies which can now go to Venus;** no need to wait.
- **An index or framework for integration of modeling**, possibly a set of interfaces.
- **Astrobiologists need to be included in the discussion of Venus.**
- Current work on preparing a **modeling Wiki** should continue.
- The Venus community does not typically post to **arXiv**. Maybe it's time to get on board that train
- What can we do now in absence of a mission?
- How do we get onboard new researchers in Venus studies without a mission?
- Mission and instrument requirements are desired.

- Is Venus so complex and hostile that the technology availability needs to drive the science?
- Collaboration across the Venus community and across disciplines remains an avenue to learn new things with current data.
- We need to be general enough in defining our needs so as to allow a diverse set of missions to be proposed, but be specific enough to constrain our requirements.

The conference ended with an engaging and interesting tour of the GEER lab at NASA Glenn Research Center where cutting-edge Venusian laboratory work is being pursued.

Summary of Major Findings

The workshop organizing committee encouraged presentations and discussions that addressed current and future needs of the Venus modeling community. Some of these needs are common to all of planetary science, so addressing them in the context of Venus will yield benefit to many other objects of study. Other needs, however, are particular to studies of Venus and require specific investment and development in technology, policy, and scientific approach.

- *New mission data*
  Recent data from Venus Express and Akatsuki are continuing to reveal more about Venus' atmosphere and space environment, but topography and in situ chemical and physical data (from Magellan, Pioneer Venus, Venera, Vega) are now several decades old. Modeling and laboratory work over the past several decades have produced many testable and predictive hypotheses for how the planet operates, and in many case these can only be confirmed or refuted by new mission data.

- *System science modeling*
  The dynamics and states of Venus' atmosphere, surface and interior are intricately linked. Generally, modeling addresses a particular aspect of a planetary environment. General circulation (or global climate) models are beginning to break that paradigm by incorporating drivers from many different aspects of a planetary body. This integrative trend must extend to more modeling endeavors to enable a true understanding of Venus as a system, rather than simply a collection of processes. It was recognized that a standardized way is needed for exchanging data, variables, constraints, and results between models, in order to couple dynamical systems.

- *Accessibility of science results, approaches, data, and tools*
  Venus science results are often published behind paywalls and therefore limit accessibility to a diverse community of potential researchers. Options exist for publishing pre-submission manuscripts that would encourage collaboration. Data discovery remains a challenge for all planetary scientists, due to different archiving requirements and the low level processing knowledge often required to make use of mission data. With regard to modeling tools, many computational approaches remain proprietary and efforts are often duplicated in the reproduction of toolchains. The

planetary community would be well served by developing a maintained repository of software, tutorials, benchmark problems, and links to relevant data sets. Comparisons between models of similar phenomena can help identify key gaps in input data.

- *Feed-forward guidance for mission design*
  Though encouraged as a topic of discussion, few presenters offered specific requirements for future mission data. Some participants stated that this is specific to the unique constraints of each mission proposal and also represents proprietary information for competed proposals. Furthermore, it was argued that the VEXAG Goals and Objective, and Exploration Roadmap already contain the necessary scientific targets and justification for future mission design.

- *Laboratory data (e.g. collision induced absorption, line lists) are needed for better modeling efforts.*

- *The role of understanding Venus as a prototype for a large class of exoplanets can serve both the Venus and Exoplanet science communities.*

- *Habitability*
  The longevity of liquid water on the surface of Venus, the mechanisms by which that water was lost, and the potential for evolutionary pathways for extinct and/or extant microbial life were topics of great interest to both the workshop and to the general public and media. Participants agreed that the Venus community should conservatively explore the topic of metabolic viability in the extreme environment of Venus' clouds.

Actions

- The workshop organizing committee has committed to producing: A) a workshop report which summarizes the salient points of presentations and discussion (this document); and B) a maintained wiki page that will serve as a living reference for references for modeling work (https://www.lpi.usra.edu/wiki/vexag/Venus_modeling_workshop_2017). The wiki will initially be populated by volunteer maintainers, shall be publicly viewable, with further editing permissions extended to known members of the Venus research community, at the discretion of the VEXAG Executive Council.

- The Venus Global Reference Atmospheric Model (GRAM) is being updated by maintainers at Marshall Space Flight Center. The maintainers have requested contributions, collaboration, and review by others in the Venus research community.

- The VEXAG Executive Council recognizes that the guidance documents (Goals and Objectives, and Exploration Roadmap) require updates, in light of recent findings from Venus Express and Akatsuki, and with consideration to new technology developments. Work on this will be announced at a future date.