Techniques and Technologies for Investigating the Interior Structure of Venus

From the *Probing the Interior Structure of Venus* Study

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I. Technical Development List of Participants

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II. Executive Summary

The goal of our program is to develop innovative techniques and technologies for investigating the interior structure of Venus. The KISS Technical Development Program has enabled major progress towards this end. The infrasound technique for seismic investigation of Venus has been firmly established as a credible approach for studying the interior of Venus. The study has also fostered a number of productive interdisciplinary collaborations that would not have been possible otherwise, including the genuine collaboration of the JPL team members with mineral physicists at Caltech. The shared goal of understanding the interior of Venus is within reach.

Key areas of accomplishment:

- Demonstration of the feasibility of a balloon acoustic monitoring system by conducting a flight experiment on Earth. This flight experiment focused on using barometer instruments on a tethered helium-filled balloon in the vicinity of a known seismic source generated by a seismic hammer, using ground sensors to benchmark signals (e.g., Krishnamoorthy et al. 2018; Martire et al. 2018, submitted to GRL).

- Numerical modeling (finite difference simulations) of atmospheric acoustic and gravity waves created by seismic surface waves propagating in Venus interior is performed in a windy and attenuating atmosphere.
  New models of planetary boundary layer and atmosphere/surface interactions have been created to enhance the deep atmosphere dynamics and its interaction with surface topography (Lebonnois and Schubert, Nat. Geosci. 2017, Lebonnois et al. 2018, submitted)
- A complete study of a suite of candidate samples important for understanding Venus: silicate amorphous phases (glasses), hydrous sulfates, hydrous and anhydrous oxides, over a range of Earth-like and hypothesized Venus conditions (e.g., Finkelstein et al. 2017, Solomatova et al. 2017, Perez et al. 2017), with key findings that some phases retain their “water” under significantly high temperatures and pressures (Ohira et al. 2017) and others have volumetric collapse phase transitions at shallow and deep crustal conditions. These samples will be exposed to Venusian surface-atmospheric conditions at the GEER facility, as part of our follow-on activities.

III. Introduction

A major accomplishment of our KISS study was the recognition that Venus quakes will produce strong infrasonic signals that can be detected as pressure waves at altitudes in the Venus atmosphere where long duration observations are possible with existing technology.

Scientific motivation. The dense atmosphere of Venus, which efficiently couples seismic energy into the atmosphere as infrasonic waves, enables an alternative to conventional seismology: detection of infrasonic waves in the upper atmosphere using either high altitude balloons or orbiting spacecraft. Infrasonic techniques for probing the interior of Venus can be implemented without exposing sensors to the severe surface environments on Venus. This approach takes advantage of the fact that approximately sixty-times the energy from a seismic event on Venus is coupled into the atmosphere on Venus as would occur for a comparable event on Earth. The direct or epicentral wave propagates vertically above the event, and the indirect wave propagates through the planet as a Rayleigh wave and then couples to an infrasonic wave. Although there is abundant evidence of tectonic activity on Venus, questions remain as to whether the planet is still active and whether energy releases are seismic or aseismic.

Technical motivation. In recent years, seismologists have developed techniques for probing crustal and interior structure in parts of the Earth where there are very few quakes. We have begun an effort to determine if this is also possible for Venus. Just as seismic energy propagates more efficiently upward across the surface-atmosphere interface, equally acoustic energy originating in the atmosphere will propagate downwards more effectively. Measurements from a balloon platform in the atmosphere of Venus could assess the nature and spectral content of such sources, while having the ability to identify and discriminate signatures from volcanic events, storm activity, and meteor impacts.

We have ceased these opportunities by: 1) conducting a flight experiment on Earth that focused on using barometer instruments on a tethered helium-filled balloon in the vicinity of a known seismic source generated by a seismic hammer and an ultradense array of ground sensors, 2) modeling atmosphere-solid interaction, and 3) understanding how candidate minerals/glasses on Venus' surface and in its interior change with extreme environmental changes.

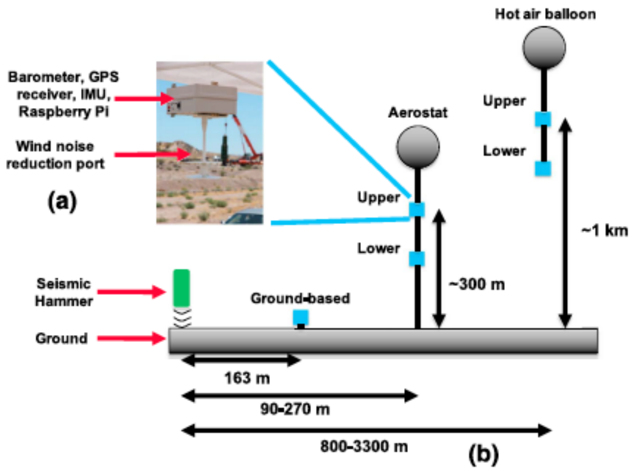

Figure 1. Barometer configuration utilized in the Pahrump experiment. (a) Description of each barometer package containing a pressure sensor, Global Positioning System (GPS) receiver, inertial measurement unit (IMU), a noise reduction port, and a Raspberry Pi computer (b) Deployment plan for the barometers: barometers were deployed in the lower troposphere as the first step toward deploying them on high-altitude balloons in the future.

IV. Outcomes of the technical development program

a. Results of the technical development program

1. Balloon-borne infrasonic measurements with ground sensors (Leads: Cutts, Komjathy, Krishnamoorthy, Pauken, Mimoun, Garcia, Jackson)

The mechanical coupling between solid planets and their atmospheres enables seismic waves to generate acoustic waves propagating from the ground to the upper atmosphere. We conducted an active seismic experiment in Pahrump, NV in June 2017, where artificial seismic signals were created using a seismic hammer, and the possibility of detecting them from their acoustic signature was examined (**Figure 1**). In this work, we analyze the pressure signals recorded by highly sensitive barometers deployed on the ground and on tethers suspended from balloons. Our signal processing results show that wind noise experienced by a barometer on a free-flying balloon is lower compared to one on a moored balloon. This has never been experimentally demonstrated in the lower troposphere.

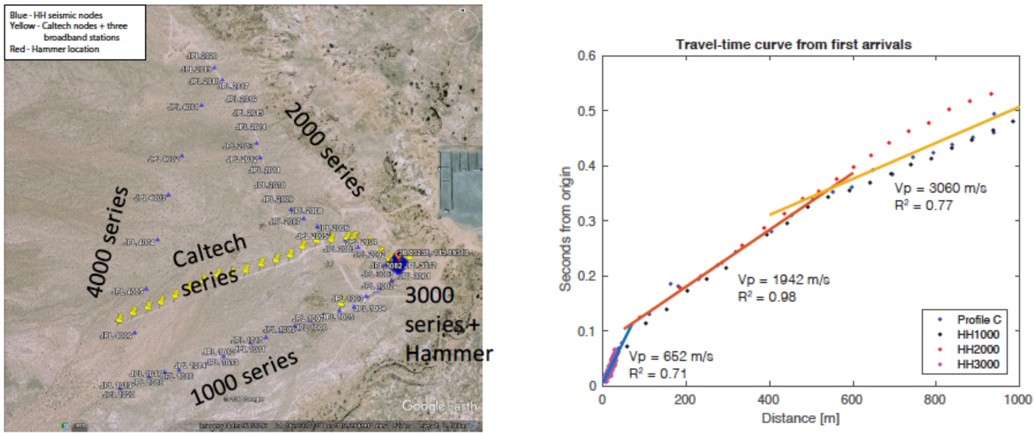

***Figure 2**.* (left) Ultradense network of ground sensors were deployed around the seismic hammer. This network consists of instruments from Caltech, ISAE, and the HH Seismic company. (right) Travel time curves to constrain the depth-dependent crustal velocity.

We demonstrate the detection of seismoacoustic signals on our moored balloon platform. Our results have important implications for performing seismology in harsh surface environments such as Venus through atmospheric remote sensing. Ground-truthing of the balloon-borne signals was achieved by deploying an ultradense network of ground sensors were deployed around the seismic hammer. This network is shown in the left panel of **Figure 2**. This dense network also provided some constraints on the crustal velocity model for which the surface waves would be transmitted (**Figure 2, right panel**). With a repeatable seismic source, the infrasound traces for each shot were expected to be similar and could therefore be stacked (**Figure 3**).

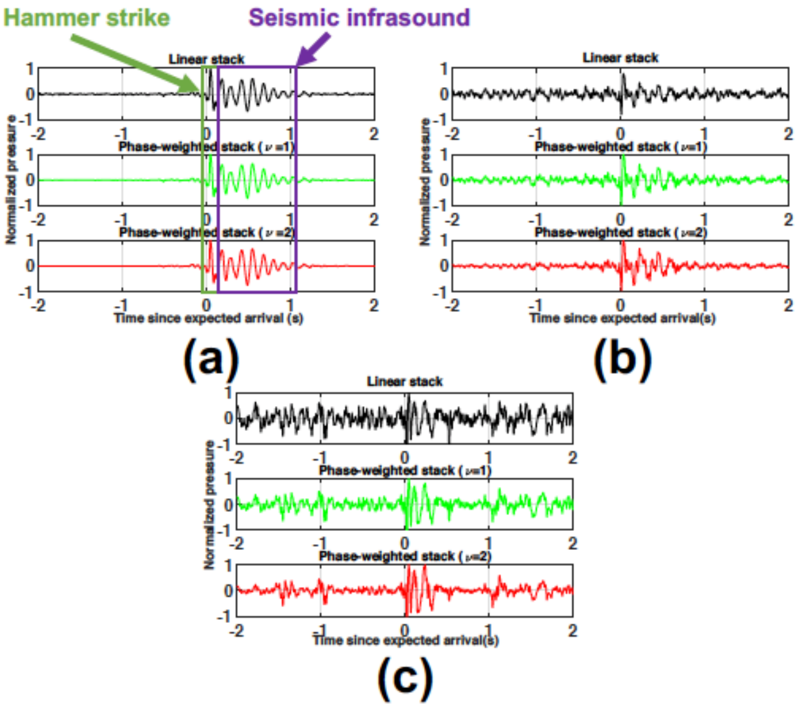

Figure 3. Results from linear and phase-weighted stacking (a) 108 shots for the ground-based barometer, (b) 31 shots each for the lower aerostat barometer, (c) 31 shots for the upper aerostat barometer.

Specifically, with the knowledge of the positions of the hammer shots and the barometers, the arriving pressure signals could be aligned and stacked using the expected arrival time as a reference. Pressure traces from the shots may be stacked by averaging individual instances after alignment using the expected arrival time. This strategy works well for the ground-based barometer, but does not produce a high signal-to-noise ratio for the aerostat barometers. Therefore, we also employed phase-weighted stacking (see Krishnamoorthy et al. 2018 for more details). Results from linear and phase-weighted stacking are shown in **Figure 3**.

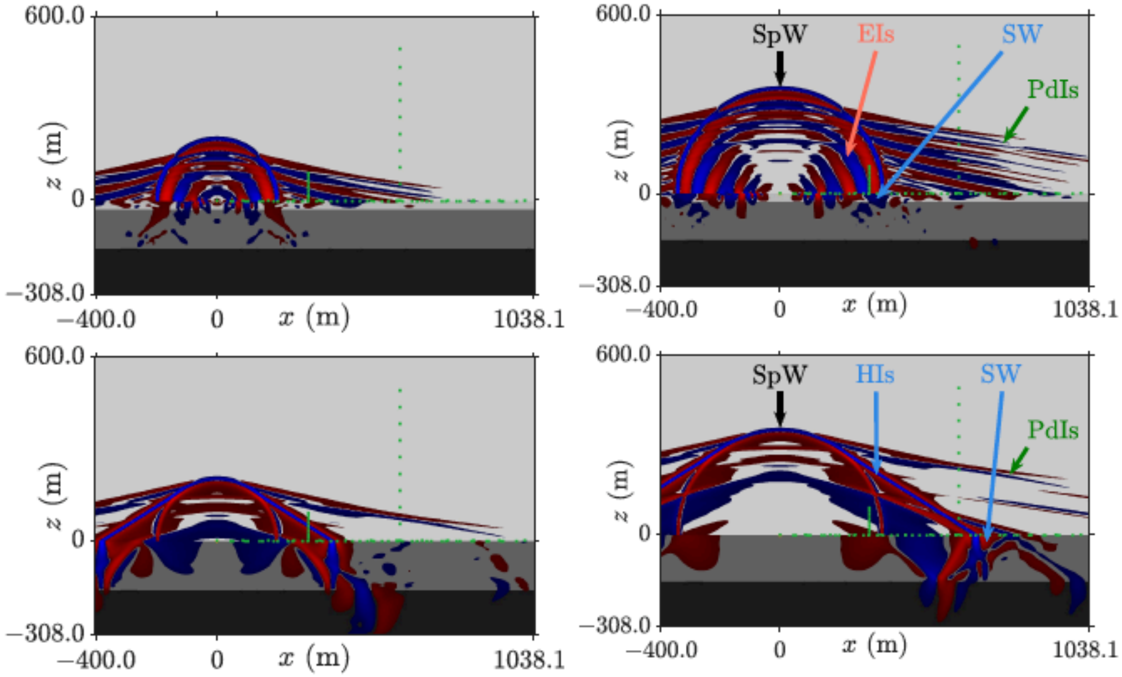

Figure 4. Snapshots of the active seismic experiment (seismic hammer) simulations, for soft (top) and hard (bottom) ground models. We represent the pressure perturbations in the atmosphere, and the vertical velocity in the ground. Color scale is saturated at 1% (red for positive values, blue for negative ones). Left column: t = 0:6 s, right column: t = 1:0 s. Labels: SpW = Spherical Wave, EIs = Epicenter infrasound, SW = Surface Waves, PdIs = P-diffracted waves infrasound. Comparison with measured data is shown in Figure 5 (Martire et al. 2018, submitted to GRL).

Modeling the mechanically coupled ground/atmosphere system. We model the mechanically coupled ground/atmosphere system using a 2D simulation tool relying on a continuous Spectral Element Method (SEM) in the elastic solid Earth, and on a discontinuous SEM to solve the fully compressible Navier-Stokes system in the atmosphere. Specifically, a new code fully coupling SPECFEM seismological tool with a realistic atmosphere is now available (Brissaud et al. 2017) and has been adapted to the specific attenuation of CO_2 atmospheres (Martire et al. 2018, submitted to GRL). We present the application for Active Seismic Experiments (ASE, i.e., Krishnamoorthy et al. 2018). We reproduce the results from this experiment numerically using a realistic underground model composed of unconsolidated materials. We remark that airborne receivers are able to monitor infrasound emitted close to the source where ground sensors typically saturate, and that surface waves generate an infrasonic plane head wave in the case of the rock-solid material. Snapshots of the active seismic experiment (seismic hammer) simulations, for soft and hard ground models, for the balloon-borne infrasonic measurements in Pahrump, NV are shown in **Figure 4**. In the near-surface, surface wave velocity V_s is less than c, the speed of sound in air, for ASE-soft (respectively $V_s > c$ for ASE-hard). Because of this, seismic surface waves will propagate slower (respectively faster) than any atmospheric signal. A comparison between simulated signals (synthetics) and the data from the seismic hammer shots is shown in **Figure 5**. Despite some limitations (source modelling and 2D geometry), the simulations underline how infrasound measurement on balloon platforms can help to constrain ground structure.

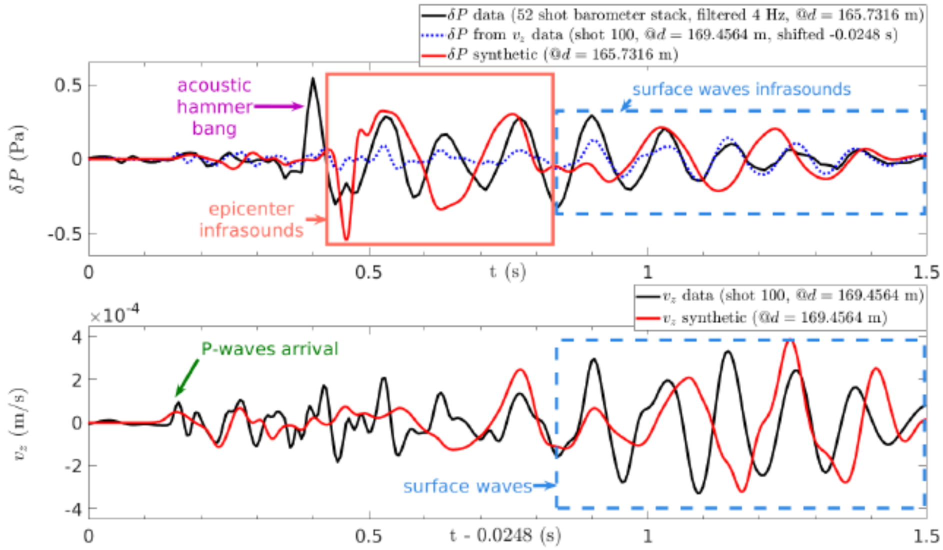

Figure 5. Comparison between simulated signals (synthetics) and hammer shots' data. Top is for pressure perturbation; bottom is for vertical ground movement (Martire et al. 2018, submitted to GRL). Differences can be explained in part by 1) a stratified sub-surface is an over simplification, 2) our source time function is modeled as a simple mono-frequency Gaussian, and the high frequency sound of the hammer against the metal plate is visible in the data but not in the synthetics.

We are also examining the feasibility of sending Cubesats or Smallsats to Venus to perform such scientific missions (**Figure 6**). Activities have included: modeling the wave propagation, understanding the background noise, and preliminary terrestrial balloon experiment instrument design. Specifically, we have investigated the concept "Venus Airglow Measurements and Orbiter for Seismicity (VAMOS)" that would enable a small spacecraft in Venus orbit to detect and characterize the perturbations of the neutral atmosphere and ionosphere induced by seismic waves. Venus is surrounded by the brightest naturally occurring airglow layer known in the Solar System. Airglow is a result of various atoms, molecules, and ions that get photoionized by ultraviolet radiation from the Sun and then release energy as visible and infrared light when they recombine and return to their normal state. Perturbations in the neutral atmosphere caused by seismicity on Venus leave an imprint in this airglow layer, which spans altitudes from 90-110 km. We use remote optical observations of this layer to study these perturbations, allowing us to infer the currently unknown seismicity and crustal structure of the solid planet below.

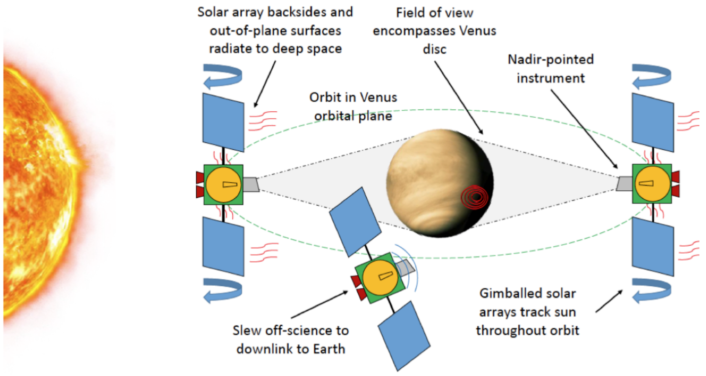

Figure 6. Infrared monitoring of Venus with Smallsat. Study of Venus Airglow Measurement Orbiter for Seismicity (VAMOS). This concept was funded by JPL internal funds and led to a 2017 proposal for Planetary Science Deep Space SmallSat Studies that was one of the four Venus proposals funded.

Equipped with an instrument of modest size and mass, the baseline VAMOS spacecraft would be designed to fit within a SmallSat form factor and travel to Venus predominantly under its own power. As shown in **Figure 6**, VAMOS would enter into an orbit uniquely suited for the long-duration, full-disk staring observations required for seismic readings. VAMOS' journey would be enabled by modern solar electric propulsion technology and SmallSat avionics, which allow the spacecraft to reach the planet and autonomously filter observation data on board to detect Venus-quake events. Trade studies are conducted to determine mission architecture robustness to launch and rideshare opportunities. Key spacecraft challenges for VAMOS, just as with many SmallSat-based mission concepts, include thermal and power management, onboard processing capabilities, telecommunications throughput, and propulsion technology.

Our mission concept VAMOS will measure atmospheric perturbations from an orbiting platform that could provide a breakthrough in detecting seismicity on Venus and in the monitoring of seismic wave propagation (Komjathy et al. 2018).

2. Theoretical investigation of the role of the Venus atmosphere and atmosphere-surface interaction on seismic studies of the interior of Venus (Leads: Schubert, Lebonnois, Garcia)

Progress towards this end includes the numerical modeling (finite difference simulations) of atmospheric acoustic and gravity waves created by seismic surface waves propagating in Venus interior is performed in a windy and attenuating atmosphere model provided by latest Global Climate Modeling (GCM) simulations of S. Lebonnois. The atmosphere is forced from below by the Venus surface with dispersive surface waves propagating at 4 km/s. Our study focuses on the effects of the strong winds present in Venus atmosphere on the acoustic wavefront. Recent finite differences simulations computed air density and temperatures variations in order to prepare computations of variations of CO_2 non-local thermodynamic equilibrium (4.3

μm) emissions by Miguel Lopez Valverde at Instituto de Astrofisica de Andalucia, in Spain (**Figure 7**).

We further investigate the conditions present in the deep atmosphere of Venus, as they may affect the simulations for the propagation of waves. The temperature profile measured by the VeGa-2 probe in 1985 leads us to the possibility of a vertical gradient in the N_2 mixing ratio in a layer 7-km thick above the surface. We are investigating this hypothesis, and consequences for the waves are currently being studied (Lebonnois & Schubert 2107; Lebonnois et al. 2018, submitted). Lebonnois et al. 2018 (submitted) discusses the nature of the planetary boundary layer, its thickness, thermal structure and variability during a solar day, its association with topography and location on the planet, and the role of slope winds in affecting the boundary layer. The results, based on the output of a numerical global circulation model, represent the first in depth study of the Venus boundary layer. Considering the lack of observations of this region of the atmosphere, the analysis in the paper is an important contribution to our understanding of the near surface atmosphere. It also provides crucial "data" for planning future missions to the surface and the lower atmosphere.

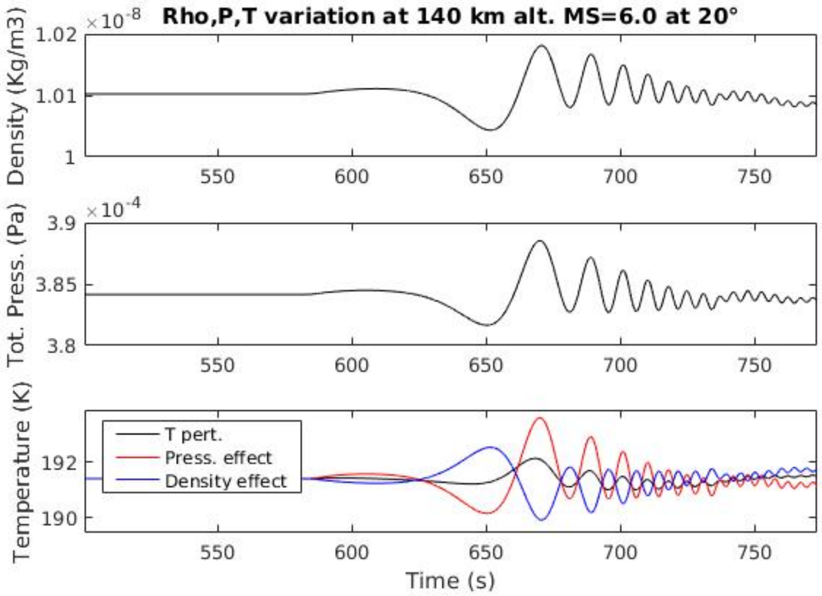

Figure 7. From top to bottom, air density, pressure and temperature variations at midday local time and 140 km altitude in Venus atmosphere from a simulated infrasonic wave front generated by seismic Rayleigh waves. Bottom panel shows explicit pressure and density effects on temperature variations.

3. Venus mineralogy and geophysical properties (Leads: Jackson, Zhan)

Future missions to the surface and lower atmosphere of Venus also require knowledge of the interaction between the atmosphere and interior mineralogy. However, these interactions are not well constrained. In this KISS technical development, experimental constraints have been placed on phase transformations, wave velocities, and ferric/ferrous concentrations of candidate Venus crustal materials (hydrous and anhydrous) under Earth-based and hypothetical Venus conditions. Specifically, these properties are: (1) oxidation and magnetic state changes in iron that may help understand volatile cycling in the crust and interior (**Figures 8-10**), and (2) volumetric collapse that could trigger phase transformational faulting, thus triggering a Venusian quake (**Figure 11**). Specifically, we have observed transitions in a hydrated iron sulfate composition at elevated pressures and silicate glasses. This research involves an interdisciplinary group of Postdoctoral scholars Gregory Finkelstein (Mineral Physics) and Justin Ko (Seismology) with graduate students Voon Hui Lai (seismology), Olivia Pardo and Natalia Solomatova (Mineral Physics) and undergraduate Tyler Perez (Planetary Science, Caltech). The next steps forward are subjecting these samples to Venus surface conditions at GEER (see Future Work, Section V).

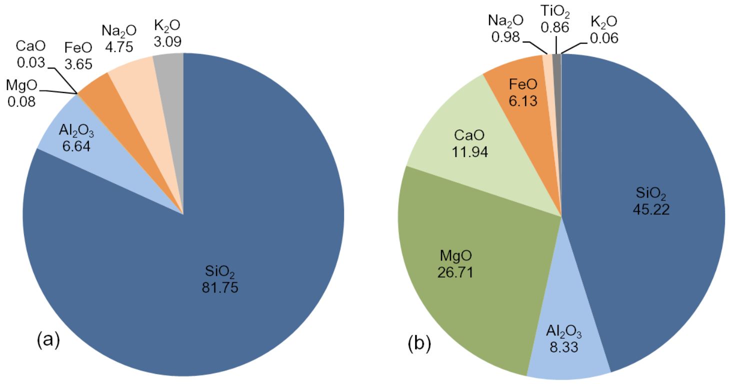

Figure 8. Composition in oxide mole percents for (a) rhyolitic glass and (b) basaltic glass. The rhyolitic and basaltic glasses contain about 0.1-0.2 mol% and 0.03-0.05 mol% of OH^-, respectively (*Solomatova et al. 2017).*

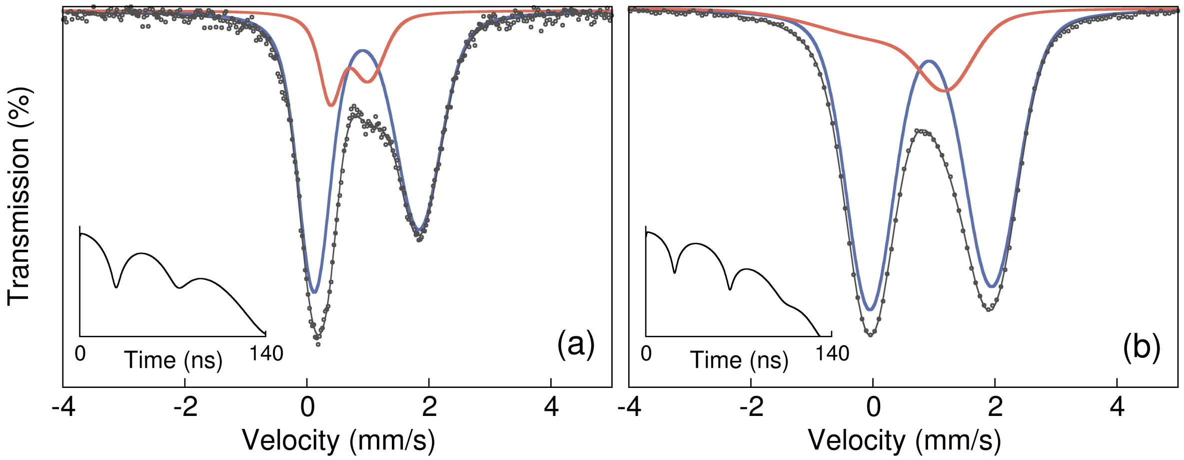

Figure 9. *Conventional Mössbauer spectra for synthetic (a) rhyolitic glass and (b) basaltic glass at room pressure and temperature, and the corresponding best fits using the software CONUSS (www.nrixs.com). Blue and red lines correspond to ferrous iron sites 1 and site 2, respectively. Insets show modeled time-domain spectra. More detailed spectral analysis of these data and those from high-pressure experiments are presented in Solomatova et al. (2017).*

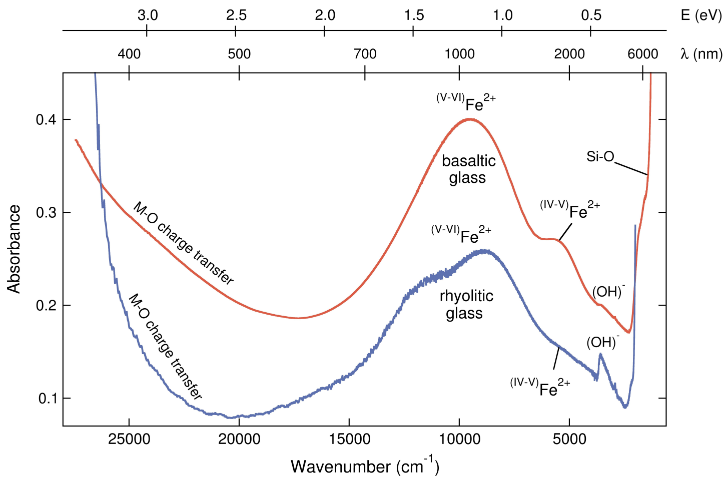

Figure 10. UV/VIS/NIR absorption spectra of rhyolitic glass (blue) and basaltic glass (red). The samples were polished to a thickness of 95 and 300 µm, respectively. The spectra are plotted for an equivalent iron concentration, and offset for clarity. Collectively, data shown in Figures 9&10 rule out ferric iron (*Solomatova et al. 2017)*.

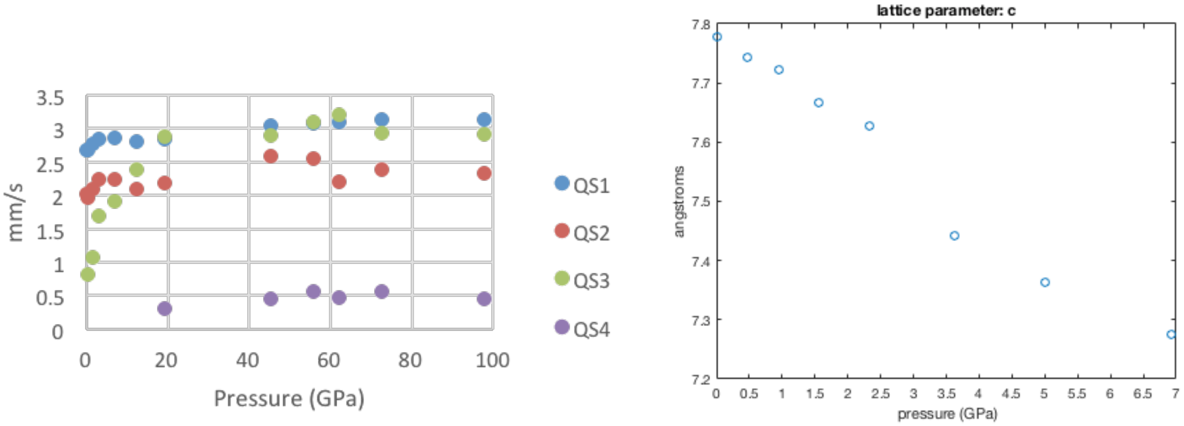

Figure 11. *(right) Analysis of the quadrupole splitting of four distinct iron sites (QS1-4) in szomolnokite, a hydrated iron sulfate mineral, up to pressures of Earth's (Venus') lower mantle (Perez et al. AGU 2017). Note that there is a steep gradient in quadrupole splitting below 10 GPa (crustal and shallow upper mantle conditions). (left) X-ray diffraction studies in this low-pressure range suggest that this region corresponds to a transition occurring between 1 and 1.5 GPa and between 2.5 and 3.5 GPa, indicated by discontinuous changes in the c-lattice parameter.*

b. Dissemination of results from technical development program

Book Chapter

Komjathy, A. and J.A. Cutts co-authored a book chapter "Geoacoustic Observations on Drifting Balloon-Borne Sensors" in "Infrasound Monitoring for Atmospheric Studies" by Springer Verlag" (2019, in press). https://www.springer.com/us/book/9783319751382

PhD thesis

Solomatova, N.V. (2017), Iron-bearing oxides, silicate glasses and carbonates at lower mantle pressures. California Institute of Technology.

Papers (reverse chronological order)

Martire, L., Q. Brissaud, V.H. Lai, R.F. Garcia, R. Martin, S. Krishnamoorthy, A. Komjathy, A. Cadu, J.A. Cutts, J.M. Jackson, D. Mimoun, M.T. Pauken, A. Sournac, (2018): Numerical simulation of the atmospheric signature of artificial and natural seismic events, Geophysical Research Letters, submitted.

Lebonnois, S., G. Schubert, F. Forget, and A. Spiga (2018): Planetary boundary layer and slope winds on Venus, *Icarus*, submitted.

Krishnamoorthy, S., A. Komjathy, M.T. Pauken, J.A. Cutts, R.F. Garcia, D. Mimoun, A. Cadu, A. Sournac, J.M. Jackson, V.H. Lai, D.C. Bowman (2018): Detection of artificial Earthquakes from balloon-borne infrasound sensors, Geophysical Research Letters, 45. https://doi.org/10.1002/2018GL077481.

Didion, D., A. Komjathy, B. Sutin, et al., (2018): Remote Sensing of Venusian Seismic Activity with a Small Spacecraft, the VAMOS Mission Concept. Accepted in IEEE Aerospace Conference, Big Sky, MT, March 3-10.

Solomatova, N. V., J.M. Jackson, W. Sturhahn, G.R. Rossman, and M. Roskosz (2017): The electronic environment of ferrous iron in rhyolitic and basaltic glasses at high pressure, Journal of Geophysical Research: Solid Earth,122 (8), 6306-6322.

Brissaud, Q., R. Martin, R.F. Garcia, D. Komatitsch (2017): Hybrid Galerkin numerical modeling of elastodynamics and compressible Navier-Stokes couplings: applications to seismo-gravito acoustic waves, Geophysical Journal International, 210 (2), 1047-1069.

Finkelstein, G.J., J. M. Jackson, W. Sturhahn, D. Zhang, E. E. Alp, and T. S. Toellner (2017): Single-crystal equations of state of magnesiowüstite at high pressures, American Mineralogist, 102, 1709-1717. *Editors pick as a Notable Paper.*

Lebonnois S. and G. Schubert (2017): The deep atmosphere of Venus and the possible role of density-driven separation of CO_2 and N_2. Nature Geoscience, 10:473-477. 10.1038/ngeo2971

Brissaud Q., R. Martin, R.F. Garcia, D. Komatitsch (2016): Finite-difference numerical modelling of gravito-acoustic wave propagation in a windy and attenuating atmosphere, Geophysical Journal International, doi: 10.1093/gji/ggw121.

Garcia, R.F., Q. Brissaud, L. Rolland, R.Martin, D. Komatitsch, A. Spiga, P. Lognonné, B. Banerdt (2016): Finite-Difference Modeling of Acoustic and Gravity Wave Propagation in Mars Atmosphere: Application to Infrasounds Emitted by Meteor Impacts, Space Science Reviews, doi:10.1007/s11214-016-0324-6.

Technical Reports

Komjathy, A. et al. (2018). Venus Airglow Measurement Orbiter for Seismicity. Planetary Science Deep Space SmallSat Study (PSDS3 Study) Final Report. JPL Internal Technical Document.

Conference Abstracts / Presentations (reverse chronological order)

2018

Lebonnois S., Schubert G., Forget F., Garate-Lopez I., LeSaux A., Navarro T., Spiga A. (2018): Investigations below the clouds of Venus with the IPSL Venus GCM, International Venus Conference. Niseko, Hokkaido, Japan, September 11-14.

Sutin B, James Cutts, Alan M. Didion, Mélanie Drilleau, Matthew Grawe, Jörn Helbert, Ashley Karp, Balthasar Kenda, Attila Komjathy, Siddharth Krishnamoorthy, Gregory Lantoine, Philippe Lognonné, Jonathan J. Makela, Barry Nakazono, Mayer Rud, Mark Wallace (2018): VAMOS: A SmallSat Mission Concept for Remote Sensing of Venusian Seismic Activity from Orbit. SPIE, Submitted to the Journal of International Society for Optics and Photonics.

Krishnamoorthy S. Komjathy A. Cutts J. A. Pauken M. T. Martrire L. et al. (2018): Seismic Infrasound as a Geophysical Probe for Venus. Presented at the 49th LPSC Meeting, The Woodlands, TX, March 19-23.

Komjathy A., Didion A., Sutin B., Nakazono B., Karp A., et al. (2018): Remote Sensing of Seismic Activity on Venus Using a Small Spacecraft: Initial Modeling Results. Presented at the 49th LPSC Meeting, The Woodlands, TX, March 19-23.

Kenda B., Lognonné P., Komjathy A. Banerdt B. Cutts J. et al. (2018): Modeling Airglow Disturbances Induced by Quakes on Venus: Perspectives for Future Observations. Presented at the 49th LPSC Meeting, The Woodlands, TX, March 19-23.

Komjathy, A., P. Lognonné, A. Didion, B. Sutin, M. Wallace, J. Cutts, J. Makela, M. Grawe, S. Bougher, B. Kenda, B. Nakazono, A. Karp, G. Lantoine, S. Krishnamoorthy, M. Rud, M. Drilleau and Jörn Helbert (2018): Venus Airglow Measurements and Orbiter for Seismicity (VAMOS). Presented at the Planetary Science Deep Space SmallSat Mission Concepts Meeting (LPSC). The Woodlands, TX, March 18.

2017

Brissaud, Q., A. Komjathy, R.F. Garcia, J.A. Cutts, M.T. Pauken, S. Krishnamoorthy, D. Mimoun, J.M. Jackson, V.H. Lai, S. Kedar, and E. Levillain (2017): Numerical modeling of the 2017 active seismic infrasound balloon experiment. NH51B-0132 in poster session Natural Hazards. Fall AGU, New Orleans, LA.

Krishnamoorthy, S., A. Komjathy, M.T. Pauken, J.A. Cutts, R.F. Garcia, D. Mimoun, A. Cadu, A. Sournac, J.M. Jackson, V.H. Lai, and D.C. Bowman (2017): Detecting Seismic Infrasound Signals on Balloon Platforms, Abstract: 230145, S44A in Oral Session Geophysical Acoustics. Fall AGU, New Orleans, LA.

Morrison, R.A., J.M. Jackson, W. Sturhahn, D. Zhang, and E. Greenberg (2017): Equations of state and anisotropy of Fe-Ni-Si alloys. Abstract: 291314, DI33B-0423, in Poster Session New Insights into the Earth's Core. Fall AGU, New Orleans, LA.

Solomatova, N. V., J.M. Jackson, P.D. Asimow, W. Sturhahn, G.R. Rossman, and M. Roskosz (2017): Computational and experimental studies of iron-bearing carbonates and silicate glasses at lower mantle pressures. DI11B-04 in Oral

Session Consequences of Mantle Phase Transitions. Fall AGU, New Orleans, LA. Invited.

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Zhang, B., S. Ni, D. Sun, Z. Shen, J. M. Jackson, and W. Wu (2017): Constraints on Small-scale Heterogeneity in the Lowermost Mantle from Observations of Near Podal PcP Precursors. DI31A-0383 in Poster Session Multiscale Heterogeneity in Earths Deep Interior: Constraints from Imaging, Modeling, and Experiments. Fall AGU, New Orleans, LA.

Krishnamoorthy, Siddharth, Attila Komjathy, James A. Cutts, Michael T. Pauken, Raphael F. Garcia, David Mimoun, Jennifer M. Jackson, Sharon Kedar, Suzanne E. Smrekar, Jeffery L. Hall (2017): Development of Venus Balloon Seismology Missions through Earth Analog Experiments. VEXAG Meeting, APL, Lauren MD, Nov 14-16.

Lebonnois S., Schubert G., Forget F., Spiga A. (2017): Characteristics of the Venus Boundary Layer, as modeled by the IPSL Venus GCM, European Planetary Science Congress, Riga, Latvia, September 18-22, 2017.

Lebonnois S., Schubert G., Forget F., Spiga A. (2017): Characteristics of the Venus Boundary Layer, as modeled by the IPSL Venus GCM" Venera-D Modeling Workshop, Moscow, Russia, October 5-7, 2017.

Ohira, I., S. kamada, J.M. Jackson, W. Sturhahn, G.J. Finkelstein, T. Kawazoe, F. Maeda, N. Hirao, S. Nakano, E. Ohtani, A. Suzuki (2017): Compressional behavior of δ-(Al,Fe)OOH to lower mantle pressures. 9th High-Pressure Mineral Physics Symposium (HPMPS-9), St. Malo, France.

Solomatova, N. V., J.M. Jackson, P.D. Asimow, W. Sturhahn, G.R. Rossman, and M. Roskosz (2017): Computational and experimental studies of iron-bearing carbonates and silicate glasses at lower mantle pressures. 9th High-Pressure Mineral Physics Symposium (HPMPS-9), St. Malo, France. Invited.

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Krishnamoorthy, Siddharth, Attila Komjathy, James A. Cutts, Michael T. Pauken, Raphael F. Garcia, David Mimoun, Jennifer M. Jackson, Sharon Kedar, Suzanne E. Smrekar, Jeffery L. Hall (2017): Infrasound Detection From Balloons – Perspectives from Simulations and Experiments. Presented at the Venera-D Modeling Workshop, Oct 5-7, 2017.

Komjathy, Attila, James Cutts, Michael Pauken, Sharon Kedar, Suzanne Smrekar, Dr. Jeff Hall, Alan Didion, Balthasar Kenda, Jennifer Jackson, David Mimoun, Raphael Garcia, Philippe Lognonne (2017): Advances in planetary seismology using infrasound and airglow signatures on Venus, Presented at the LCPM-12 2017 Meeting in Pasadena, CA, Aug 15-17.

Komjathy, Attila, James Cutts, Michael Pauken, Sharon Kedar, Suzanne Smrekar, Jeff Hall, Alan Didion, Balthasar Kenda, Xing Meng, Olga Verkhoglyadova, Jennifer Jackson, David Mimoun, Raphael Garcia and Philippe Lognonné (2017): Planetary Seismology Using Infrasound and Airglow Signatures on Venus.”Presented at the IAG-IASPEI Meeting, July 30 to Aug 4. Kobe, Japan.

Komjathy A., S. Krishnamoorthy, J. Cutts, M. Pauken, S. Smrekar, J. Hall, A. Didion, B. Kenda, J. Jackson, D. Mimoun, R. Garcia, and P. Lognonne (2017): Advances in Planetary Seismology Using Infrasound and Airglow Signatures on Venus. Presented at the LCPM-12 Meeting, Pasadena, California, on August 15-17, 2017.

Kenda, B., P. Lognonné, A. Komjathy, B. Banerdt, J. Cutts, L. Soret, and J. Jackson (2017): Investigating the Concept of Using Airglow Measurements to Detect Seismicity on Venus. Session SM5.5/PS1.5 Extraterrestrial seismology – Advances in instrumentation and methodology, European Geosciences Union, Vienna, Austria.

Mimoun, D., R. Garcia, A. Cadu, J. Cutts, A. Komjathy, M. Pauken, S. Kedar, J. Jackson, and D. Stevenson (2017): Exploring Venus interior structure with infrasonic techniques. Session SM5.5/PS1.5 Extraterrestrial seismology – Advances in instrumentation and methodology, European Geosciences Union, Vienna, Austria.

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2016

Finkelstein, G.J., J. M. Jackson, W. Sturhahn, D. Zhang, E. E. Alp, and T. S. Toellner (2016): Defect structures of Magnesiowüstite and Wüstite from Hybrid-Mode Synchrotron Mössbauer Spectroscopy. Fall AGU Meeting in San Francisco, California.

Jackson, J.M., James A. Cutts, Michael Pauken, Attila Komjathy, Suzanne Smrekar, Sharon Kedar, David Mimoun, Raphael Garcia, Gerald Schubert, Sebastien Lebonnois, David J. Stevenson, Philippe Lognonné, Zhonwen Zhan, Justin Ko, and Victor Tsai (2016): Exploring the interior of Venus with seismic and infrasonic techniques. Ionospheric and Atmospheric Monitoring of Natural Hazards: Existing Terrestrial and Potential Planetary Applications II, Fall AGU Meeting in San Francisco, California (NH53D-06: 122988). Invited.

Ko, Y.-T. (Justin) and Z. Zhan (2016): A two-step full waveform inversion technique based on the WKM method, Fall AGU Meeting in San Francisco, California (DI23A-2601), San Francisco, CA

Solomatova, N.V., J. M. Jackson, W. Sturhahn, and M. Roskosz (2016): The electronic structure of iron in rhyolitic glass at high pressure. Fall AGU Meeting in San Francisco, California (DI52A-08).

Komjathy, A., J. Cutts, M. Pauken, S. Kedar, S. Smrekar, J. Hall, A Didion, B. Kenda, J. Jackson, D. Mimoun, R. Garcia and P. Lognonné (2016): Infrasound as a Geophysical Probe Using Earth as a Venus Analog, Presented at the 2016 AGU Meeting, San Francisco, CA, Dec 12-16.

Cutts, J., A. Didion, A. Komjathy, C. Sotin and M. Wallace (2016): Venus Smallsat and Cuvesat Mission, Presented at the 14th VEXAG Meeting, Nov 29 to Dec 1.

Komjathy, A., Cutts, J., M. Pauken, S. Kedar, J. Jackson J, S. Smrekar, D. Mimoun and R. Garcia (2016): Infrasound as a Geophysical Probe Using Earth as a Venus Analog, Presented at the DPS 48/ EPSC 11 Meeting of the American Astronomical Society, Pasadena, CA, Oct 16-21.

Lebonnois S. and G. Schubert (2016): A density-driven separation of CO2 and N2 in the deep atmosphere of Venus. Presented at the DPS 48/EPSC 11 Meeting of the American Astronomical Society, Pasadena, CA, Oct 16-21.

Cutts, J., M. Pauken, J. Jackson, D, Mimoun, R. Garcia, D. Bowman, A. Komjathy, S. Kedar and members of the KISS Venus Interior Study Team (2016): Venus Exploration with Infrasound Techniques, Presented at the 13th International Planetary Probe Workshop, Presented at JHUAPL, June 13-17.

Garcia, R.F., D. Mimoun, S. Lebonnois, Q. Brissaud, G. Poler (2016): Infrasounds from Venus quakes: Numerical modeling and balloon observation project. Presented at International Venus Conference 2016 at Oxford, April 4-8.

Cutts, J.A., M. Pauken, J. M. Jackson, D. Mimoun, and Members of the Keck Institute for Space Studies Study and Development Teams (2016): Venus: Exploring its interior with seismic and infrasonic techniques. Presented at International Venus Conference 2016 at Oxford, April 4-8.

c. External funding proposed/received

Materials Under Extreme Conditions and Hydrodynamics Graduate Fellowship. Awarded by the Department of Energy National Nuclear Security Administration's Stewardship Science Graduate Fellowship Program. PI: O. Pardo, PhD student. Four year graduate fellowship at Caltech.

Melting of compressed iron-alloys by monitoring atomic dynamics. Awarded by the National Science Foundation (1727020). PI: Jackson.

CSEDI: Integrated seismic, geodynamic, and mineral physics studies of the deepest lower mantle. Awarded by the National Science Foundation (1600956). PI: Jackson, Co-Is: M. Gurnis, D. Helmberger, Z. Zhan (Clatech).

Institut Supérieur de l'Aéronautique et de l'Espace (PIs: D. Mimoun, R. Garcia, and A. Cadu) has leveraged funding for travel and parts.

Venus Airglow Measurement Orbiter for Seismicity (VAMOS). Study of concept funded by JPL internal funds. Led to proposal for Planetary Science Deep Space SmallSat Studies (PSDS3) which was one of four Venus proposals funded.

Elucidating surface-atmosphere interactions on Venus through simulations and experiments. Submitted to the Presidents Director’s Fund (JPL/Caltech). PIs: J.M. Jackson (Caltech) and J. Bellan (JPL), Co-I’s: O. Pardo (PhD student, Caltech), James Cutts (JPL), and J. Izraelevitz (JPL).

Collaborative Research: Physical Mechanism of Deep Earthquakes Initiation. Submitted to the National Science Foundation EAR Geophysics. PIs Z. Zhan (Caltech) and Z. Peng (Georgia Institute of Technology).

Infrasound as a Geophysical Probe Using Earth as a Venus Analog. Submitted to ROSES PSTAR 2017. While we received excellent reviews on the scientific part of the proposal, it was not selected at this time owing to operational deficiencies. We plan on re-submitting the PSTAR proposal in FY19.

V. Future Work

a. Strategic planning

The infrasound approach is now making an impact on future mission concepts. In April 2018, a concept for a program of low cost missions to Venus called Venus Bridge was briefed to the Associate Administrator Dr. Thomas Zurbuchen which included coupled infrasound experiments in orbit (VAMOS) and on a small balloon. NASA is continuing to study strategic missions to Venus including Venera D jointly with Russia and Venus Flagship (U.S. led) and the use of infrasound for seismic detection is firmly established. A Venus Aerial Platform study is near completion in which infrasound experiments are explicitly included on the payload. A NASA program of Venus Aerial Platform development is being advocated.

b. Proposal opportunities

The most immediate opportunity following the PSDS3 study of a $100M class mission is the 2018 Small Innovative Missions for Planetary Exploration (SIMPLEX) call for a mission with a $55M cost target. The VAMOS team has examined many possibilities but has not been able to devise a way of getting into Venus orbit for this cost target. Given the conservative technology posture for the Discovery program, it will be necessary to carry out the Earth demonstration of natural quakes for a credible proposal. However, there are excellent cases for proposals to NASA's PICASSO and MATISSE programs.

c. Moving forward

The second phase of the Active Seismic Experiment (ASE) development is planned for late 2018 and early 2019 with tests using large underground chemical explosives at the Nevada National Security Site (NNSS). The balloon infrasound measurement program will heavily leverage the DOE funded experiment and involves a collaboration with Sandia laboratories. This is funded in FY19 by JPL R&TD funds. The subsequent Passive Seismic Experiment (PSE) planned for Oklahoma is not currently funded but has received an outstanding scientific rating by the PSTAR program and various funding options are now being explored. In addition, to experiments in which Earth is used as an analog for Venus, we are also exploring applications where innovative Earth science is the objective.

GEER experiments (surface-atmospheric coupling): An experiment at the GEER facility at Glenn Research Center is being planned to investigate mechanisms for a hypothesized N_2 gradient in the Venus boundary layer (July 30 - August 11, 2018). A numerical simulation investigation has also been initiated at JPL under the leadership of Dr. Josette Bellan. The interaction of Venus' near surface atmosphere with the solid surface will be investigated by graduate student Olivia Pardo and Prof. Jennifer Jackson (Caltech), where the interpretations will be informed via collaborations with Drs. Josette Bellan and James Cutts (JPL). Experiments are being scheduled for Fall 2018.

VI. Conclusions

This Technical Development activity has more than met its initial objectives. The infrasound technique for seismic investigation of Venus has been firmly established as a credible approach for studying the interior of Venus and the only viable near to mid-term approach that is feasible. The study has also fostered a number of productive interdisciplinary collaborations that would not have been possible otherwise, including the genuine collaboration of the JPL team members with mineral physicists at Caltech. The shared goal of understanding the interior of Venus is now achievable. A number of alternative pathways are now being pursued towards application on a mission including both orbital and balloon based concepts. Continued work using Earth as a Venus analog is needed and this work is opening up new fields of Earth science using the infrasound probe.

VII. Acknowledgments

We acknowledge matching support from the JPL R&TD program and for guidance and support from both Dr. Satish Khanna and Dr. Christophe Sotin.

Appendix A: Pictures (appended as a separate document)

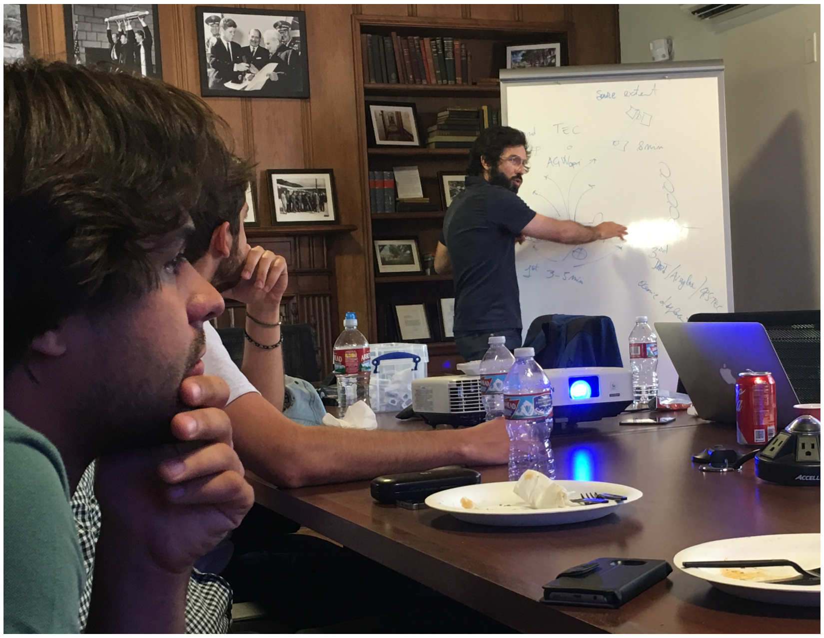
Appendix A: Pictures

Infrasound Instrument field test team members with the Seismic Hammer (HH Seismic), near Pahrump, Nevada: June 26-28, 2017. Left to Right: unidentified (HH), Jennifer Jackson (Caltech), John Hampshire (HH), Kirk Barrow (JPL: 5020), Rob Hensley (HH), James Cutts (JPL: 4300), Michael Pauken (JPL: 353K), Giorgio Savastano (JPL: 335G), Gerry Walsh (JPL: 333C), Attila Komjathy (JPL: 335G). Not pictured: D. Mimoun, A. Cadu, A. Sournac (ISAE).

Installing seismometers at the hammer site for infrasound experiments near Pahrump, Nevada: June 26-28, 2017. From Left to Right: Giorgio Savastano (JPL: 335G), Michael Pauken (JPL: 353K), James Cutts (JPL: 4300), Jennifer Jackson (Caltech).

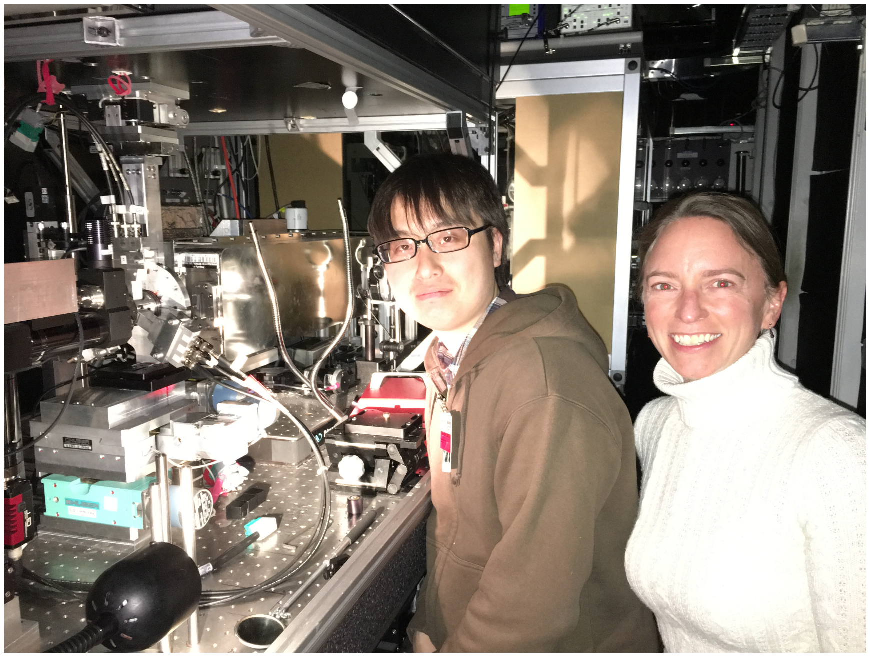
Deploying the moored balloon with infrasound instruments on-board, at the hammer site near Pahrump, Nevada: June 26-28, 2017.

KISS-Venus Team Meeting: March 15, 2017. Black Hole Conference Room, Keck Institute for Space Studies. From Left to Right: James Cutts, Georgio Sevastano, Panagiotis Vergados, Balthasar Kenda, Jennifer Jackson, Giovanni Occhipinti, Attila Komjathy, and Tibor Durgonics.

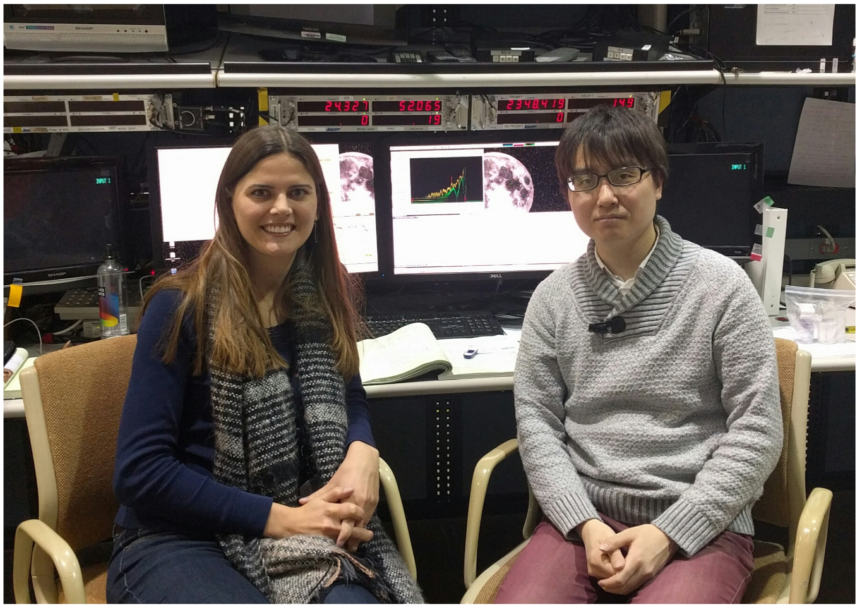


KISS-Venus Team Meeting: March 15, 2017 Black Hole Conference Room, Keck Institute for Space Studies.

KISS-Venus Team Meeting: March 15, 2017 Black Hole Conference Room, Keck Institute for Space Studies.



KISS-Venus student (Itaru Ohira, visiting student from Tohoku University, Japan) and Prof. Jennifer Jackson (Caltech) inside the experimental hutch, preparing nuclear resonant scattering experiments on hydrous phases and silicate glasses at Sector 3 of the Advanced Photon Source, Chicago area, IL.



KISS-Venus graduate students (Natalia Solmatova, Caltech) and Itaru Ohira (Itaru Ohira, visiting student from Tohoku Universtiy, Japan) conducting nuclear resonant scattering experiments hydrous phases and silicate glasses at Sector 3 of the Advanced Photon Source, Chicago area, IL.

Networking at the 2015 Space Connection, sponsored by JPL and Caltech. Left to Right: Prof. Jennifer Jackson (Caltech) and Dr. Jessica Watkins (Postdoctoral Fellow in the GPS Division at Caltech; AGEP Fellow; NASA Astronaut Candidate, class 2017).