Venus Modeling Workshop

May 9-11, 2017

Cleveland, OH

#UnveilVenus

Program

Lunar and Planetary Institute

USRA

Venus Modeling Workshop

May 9–11, 2017 • Cleveland, Ohio

Organizer

Lunar and Planetary Institute

Universities Space Research Association

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Abstracts for this workshop are available via the workshop website at

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Guide to Sessions

Tuesday Morning, May 9, 9:00 a.m.

Lobby Registration

Tuesday Morning, May 9, 9:00 a.m.

Forum Room Plenary I: Past, Present, Future

Tuesday Afternoon, May 9, 1:00 p.m.

Forum Room Flash Talks and Introduction to Breakouts

Tuesday Afternoon, May 9, 2:00 p.m.

Forum Room Discipline Breakout: Orbital and Atmospheric I: Recent Advances

Industry Room A/B Discipline Breakout: Surface and Interiors I: Recent Advances

Tuesday Afternoon, May 9, 4:45 p.m.

Lobby Poster Session

Wednesday Morning, May 10, 8:30 a.m.

Forum Room Plenary II: Venus in Context: New Modeling Efforts, Cross-Disciplinary Themes, Mission Results, and Plans for the Future

Wednesday Afternoon, May 10, 1:00 p.m.

Forum Room Instructions to Breakout Sessions

Wednesday Afternoon, May 10, 1:30 p.m.

Forum Room Discipline Breakout: Orbital and Atmospheric II: Feed-Forward Modeling, Critical Needs, and Mission Direction

Industry Room A/B Discipline Breakout: Surface and Interiors II: Feed-Forward Modeling, Critical Needs, and Mission Direction

Thursday Morning, May 11, 9:00 a.m.

Forum Room Plenary III: Group Summary, Workshop Findings, and Plan for Report

Program

Tuesday, May 9, 2017
PLENARY I:
PAST, PRESENT, FUTURE
9:00 a.m.   Forum Room

9:00 a.m. Kremic T. * and Steffes P. G. *
Welcome, Logistics, and Plans

9:30 a.m. Green J. *
Headquarters Briefing

10:00 a.m. Head J. W. *
Venus Geological History: Current Perspectives, Unknowns, and Opportunities for the Modeling Community. **[#8030]**
The geological record yields multiple major modeling challenges: internal structure-evolution, mantle convection, thermal evolution, geodynamic, geochemical, petrogenetic, atmospheric origin-evolution, ionosphere, solar system formation-evolution.

10:45 a.m. Way M. J. * Del Genio A. D. Amundsen D. S.
Modeling Venus Through Time **[#8022]**
In a recent study we demonstrated that the long-term climatic history of Venus may have allowed for surface liquid water to exist for several billion years. We will discuss additional 3-D GCM studies that support our earlier conclusions.

11:15 a.m. Ghent R. *
Perspectives on Planetary Evolution

Early Career Luncheon
12:00 p.m.   Sunroom

Tuesday, May 9, 2017
FLASH TALKS AND INTRODUCTION TO BREAKOUTS
1:00 p.m. Forum Room

1:00 p.m. *Poster Flash Talks*

1:45 p.m. *Instructions and Directions for Breakout Themes and Discipline Groups*

Tuesday, May 9, 2017
DISCIPLINE BREAKOUT:
ORBITAL AND ATMOSPHERIC I: RECENT ADVANCES
2:00 p.m. Forum Room

Chairs: **Ludmila Zasova**
Glyn Collinson

2:00 p.m. Lebonnois S. * Garate-Lopez I. Gilli G. Guilbon S. Lefèvre F. Määttänen A. Navarro T. Stolzenbach A.
Status of the IPSL Venus Global Climate Model **[#8007]**
In this presentation, latest improvements of the IPSL Venus GCM will be presented, together with the latest results from the reference simulation. These include implementation of latitudinal structure of the cloud layer, with significant impact.

2:30 p.m. Brecht A. S. * Bougher S. W. Shields D. Liu H.
Incorporating Planetary-Scale Waves into the VTGCM: Understanding the Waves' Impact on the Upper Atmosphere of Venus **[#8032]**
The VTGCM will be utilized in understanding the impact planetary-scale waves have on the varying thermospheric structure. The inclusion of a moving lower boundary and Kelvin waves produces close to observed O_2 IR nightglow intensity variability.

2:45 p.m. Jacobson N. S. * Kulis M. J. Radoman-Shaw B. Harvey R. Myers D. Schaefer L. Fegley B. Jr.
Thermodynamic Modeling of the Lower Venusian Atmosphere **[#8012]**
The lower venusian atmosphere is the region from the surface to the cloud deck, which is approximately 0–50 km. We introduce an very small increasing oxygen gradient from the surface to the cloud layer to model some features with thermodynamics.

3:00 p.m. Woon D. E. * Maffucci D. M. Herbst E.
Quantum Chemical Studies of Reactions Involving Sulfur and Sulfur-Chlorine Compounds for Venus Atmospheric Modeling Networks **[#8016]**
We are characterizing reactions involving sulfur and sulfur-chlorine compounds thought to be relevant to Venus using high level quantum chemical theory and reaction rate theory in order to improve atmospheric modeling studies.

3:15 p.m. Lorenz R. D. *
Stochastic Models of Lightning and Lightning Detection on Venus **[#8017]**
Flash of Brilliance / Discrepant observations / Lightning is bursty.

3:30 p.m. *Discussion*

4:00 p.m. BREAK

4:15 p.m. *Return to Plenary: Discipline Group Summaries*

Tuesday, May 9, 2017
DISCIPLINE BREAKOUT:
SURFACE AND INTERIORS I: RECENT ADVANCES
2:00 p.m. Industry Room A/B

Chairs: **Thomas (Tommy) Thompson**
Martha Gilmore

2:00 p.m. O'Rourke J. G. *
New Perspectives on the Accretion and Internal Evolution of Venus from Geology and Magnetism **[#8042]**
Only certain scenarios elucidated by new numerical models of coupled atmosphere-interior dynamics may explain the prevalence of dark-floored craters, modern lack of a dynamo, and detection (or convincing non-detection) of crustal remnant magnetism.

2:30 p.m. King S. D. *
Is Evidence for Resurfacing on Venus Buried Deep Within the Interior? **[#8015]**
Venus surface past / Could it be catastrophic? / Secret lies within.

2:45 p.m. Balcerski J. A. *
Limits of Climate-Driven Wrinkle Ridge Formation on Venus **[#8027]**
Climate-driven thermal stresses acting upon the upper crust can potentiate pre-existing lithospheric stresses to allow for the creation of wrinkle ridges but are insufficient as the only driving sources of stress.

3:00 p.m. Flores L. A. * Rojo P. Valenzuela M.
Geological and Thermal Analysis of VIRTIS Images of Eastern part of Parga Chasma, Venus **[#8036]**
Using IDL this work show an emissivity map with information of the eastern part of Parga Chasma, reaffirming the possibility of possibly active volcanism, and calls into question the surface composition.

3:15 p.m. Moore W. B. * Kankanamge D. G. J.
Venus: No Breaks from an Extended Childhood **[#8039]**
High surface temperatures lead to lower heat flow and lower stress as planets transition out of the heat-pipe mode into subsolidus convection. This causes Venus to miss the window for plate tectonics due to an extended heat-pipe childhood.

3:30 p.m. *Discussion*

4:00 p.m. BREAK

4:15 p.m. *Return to Plenary: Discipline Group Summaries*

Tuesday, May 9, 2017
POSTER SESSION
4:45 p.m. Lobby

Lee G. Warwick S. Ross F. Sokol D.
Venus Atmospheric Maneuverable Platform (VAMP) — Pathfinder Concepts **[#8006]**
Northrop Grumman has been developing a versatile new class of vehicle that will serve as an atmospheric rover for exploration of planets and moons of the solar system. VAMP is a powered, long endurance, semi buoyant aircraft.

Grandidier J. Osowski M. L. Lee M. L. Atwater H. A.
Low Intensity High Temperature (LIHT) Solar Cells for Venus Exploration **[#8002]**
The goal is to develop and mature Low Intensity High Temperature (LIHT) photovoltaic technology that will enable Venus surface and aerial exploration with temperatures approaching 500°C or higher.

Rehnmark F. Cloninger E. Hyman C. Zacny K. Kriechbaum K. Hall J. Melko J. Bailey J. Wilcox B. Sherrill K.
VISAGE Rock Sampling Drill **[#8038]**
A rock sampling drill capable of operating in the high temperature and pressure environment found on the surface of Venus has been built and tested at JPL's Venus Materials Test Facility (VMTF).

Parish H. F. Mitchell J. L.
Modeling Venus' Atmosphere at Cloud Altitudes with a New Middle Atmosphere GCM **[#8013]**
We discuss simulations using a new Venus Middle atmosphere Model (VMM), which simulates the atmosphere from just below the cloud deck to around 100 km altitude, with the aim of focusing on the dynamics at cloud levels and above.

Akins A. B. Bellotti A. Steffes P. G.
Simulation of the Atmospheric Microwave and Millimeter Wave Emission from Venus Using a Radiative Transfer Model Based on Laboratory Measurements **[#8009]**
An overview of a lower atmosphere radiative transfer model for Venus, and the effects of uncertainties in the distributions of sulfur compounds on modeling results.

Mills F. P. Petrass J. B. Allen M. Jessup K. L. Sandor B. J. Yung Y. L.
Simulations of Vertical Profiles and Time-of-Day Variability in Vertical Profiles of SO and SO_2 on Venus **[#8024]**
This contribution explores potential chemical and dynamical mechanisms that may lead to the observed mesospheric inversion layer in the vertical profiles of SO and SO_2 and compares results from different types of 1-d photochemical calculations.

Wilson C. F. Ghail R. C. Widemann T.
EnVision, a Proposed ESA Venus Orbiter Mission **[#8028]**
The EnVision Venus orbiter proposal has been proposed to ESA. It will focus on establishing current and historical rates of geological activity on Venus. Supporting modelling work would be welcome.

Anderson K. R. McNamara C. Gatti A. Guererro J.
Optimized Supercritical Fluid Refrigeration Cycle for Venus Lander Payload Electronics Active Cooling **[#8003]**
This paper presents an active electronics thermal control system allowing for continuous operation of instruments for Venus lander missions. The thermal control system uses supercritical fluids cascaded and optimized for minimum compressor power.

Hazeli K. Kingstedt O. T.
Significance of Environmental Variables on Flight Electronics and Design Concerns for Extreme Environments **[#8011]**
It is critical to investigate the performance of electronic systems and their components under the environments experienced during proposed missions to improve spacecraft and robotic vehicle functionality and performance in extreme environments.

Helbert J.   Maturilli A.   Dyar M. D.   Ferrari S.   Mueller N.   Smrekar S.
Laboratory Venus Analog Spectra for all Atmospheric Windows **[#8023]**
For the first time, the community has access to spectra obtained in emission, covering the spectral range from 0.7 to 1.2 µm (and beyond) and obtained at typical Venus surface temperatures of 460°C.

Port S. T.   Chevrier V.
Experimental and Thermodynamic Study of the Stability of Pyrrhotite Under Simulated Venusian Surface Conditions **[#8035]**
The effects of CO_2, SO_2, and COS at different temperatures found on Venus on pyrrhotite (Fe_7S_8) through the use of experimental and thermodynamic modelling techniques.

Richardson J. A.   Glaze L. S.
Monitoring and Modeling Effusive Volcanism on Venus **[#8040]**
Current lava flow modeling and monitoring capabilities could be applied to Venus to test fundamental hypotheses about the geochemistry and production rates of volcanic terrains.

Kenda B.   Lognonné P.   Komjathy A.   Banerdt W. B.   Cutts J.   Jackson J.
Modeling the Airglow Response to Quakes on Venus **[#8005]**
We model the fluctuations of the nightglow induced by quakes on Venus, investigate the opportunity of detecting them through orbiting airglow cameras and discuss the significance for understanding the interior of the planet.

Maffucci D. M.   Woon D. E.   Herbst E.
A Kinetic Study of the Gas Phase Neutral-Neutral Reactions Between Sulfur- and Chlorine-Containing Molecules Present in the Atmosphere of Venus **[#8021]**
Using updated electronic structures, we employ a variety of kinetic theories to calculate the reaction rate constants for neutral-neutral chemical reactions between sulfur- and chlorine-containing molecules observed in the atmosphere of Venus.

Lefèvre M.   Spiga A.   Lebonnois S.
Mesoscale Modeling of the Atmosphere of Venus: Convection and Gravity Waves **[#8026]**
The impact of the cloud convective layer of the Venus atmosphere on the global circulation remains unclear. As the recently observed waves at cloud top are not resolved by GCMs we thus developed an unprecedented 3D LES model using WRF dynamical core.

Cutts J. A.   Matthies L. H.   Thompson T. W.
Venus Aerial Platform Modeling Needs **[#8014]**
The purpose of this paper is to define the models that are important for both engineering and scientific aspects of the design of Venus aerial platform missions and to discuss how they will be applied in assessing technology readiness.

Wednesday, May 10, 2017
PLENARY II:
VENUS IN CONTEXT: NEW MODELING EFFORTS, CROSS-DISCIPLINARY THEMES, MISSION RESULTS, AND PLANS FOR THE FUTURE
8:30 a.m. Forum Room

8:30 a.m. *Welcome Back: Summary of Day 1: Themes and Introduction to Day 2*

9:00 a.m. Lee, Y. J. *
Atmospheric Modeling and Updates on Venus Climate Orbiter

9:45 a.m. Collinson G. A. * Glocer A. Frahm R.
Atmospheric Escape at Venus **[#8041]**
We outline the current state of knowledge of atmospheric escape at Venus.

10:15 a.m. BREAK

10:30 a.m. Zasova L. * Senske D. Economou T. Eismont N. Esposito L. Gerasimov M. Ignatiev N. Ivanov M. Lea Jessup K. Khatuntsev I. Korablev O. Kremic T. Limaye S. Lomakin I. Martynov A. Ocampo O.
Venera-D — Mission for the Comprehensive Study of the Atmosphere, Surface and Plasma Environment of Venus **[#8019]**
The JSDT formulated concept of mission Venera-D consisting of baseline elements: orbiter and lander, and of additional elements: aerial platforms, long-lived stations on the surface and sub-satellite.

11:00 a.m. Limaye S. S. * Ansari A. H. Mogul R. Smith D. J. Vaishampayan P.
Ultraviolet Absorbers and Cloud Contrasts on Venus **[#8033]**
Origins of the ultraviolet absorption in the clouds of Venus and contrasts prominent at ultraviolet (day side) and at near infrared wavelengths (1.74–2.3 μm) are not well understood. Microorganisms could contribute to these contrasts.

11:30 a.m. Kane S. R. *
Comparative Planetology: Seeking the Twin of Earth's Twin **[#8029]**
In this talk I will present the latest results in the search for terrestrial-size exoplanets, the diversity of their sizes and orbital parameters, and the search for Venus analogs.

Wednesday, May 10, 2017
INSTRUCTION TO BREAKOUT SESSIONS
1:00 p.m.   Forum Room

1:00 p.m.   *Instructions and Directions for Breakout Themes and Discipline Groups*

Wednesday, May 10, 2017
DISCIPLINE BREAKOUT:
ORBITAL AND ATMOSPHERIC II:
FEED-FORWARD MODELING, CRITICAL NEEDS, AND MISSION DIRECTION
1:30 p.m. Forum Room

Chairs: **Giada Arney**
Sebastien Lebonnois

1:30 p.m. Arney G. N. * Meadows V. S. Lincowski A.
Lessons Learned from Radiative Transfer Simulations of the Venus Atmosphere **[#8020]**
We discuss the challenges of modeling the spectrum of the venusian lower atmosphere, which can be used for retrievals of lower atmosphere gas abundances. We also discuss applications of radiative transfer simulations to exo-Venuses.

2:00 p.m. Lincowski A. P. * Meadows V. S. Crisp D. Robinson T. D. Arney G. N.
Climates of Venus-Like Exoplanets **[#8037]**
We use a new generalized, 1D RCE climate model with H2SO4 condensate cycle to model Venus-like climates of newly discovered, likely-terrestrial exoplanets, such as TRAPPIST-1 b and c. This work outputs data used for exoplanet spectral analyses.

2:15 p.m. Bellan J. *
Fundamental Studies of High-Pressure Turbulent Multi-Species Mixing Relevant to the Venus Atmosphere **[#8004]**
Salient results from a theory of high-pressure multi-species turbulent mixing relevant to the Venus atmosphere are discussed. The influence of the insights obtained from these results on Venus exploration and planned future studies are addressed.

2:30 p.m. Justh H. L. * Dwyer Cianciolo A. M.
Venus Global Reference Atmospheric Model Status and Planned Updates **[#8043]**
Details the current status of Venus Global Reference Atmospheric Model (Venus-GRAM). Provides new sources of data and upgrades that need to be incorporated to maintain credibility and identifies options and features that could increase capability.

2:45 p.m. Navarro T. * Schubert G. Lebonnois S.
Data Assimilation of the Atmosphere of Venus **[#8010]**
Data assimilation is a technique used for weather forecast to reconstruct as accurately as possible the state of the atmosphere using both observations and a global climate model. The time has come to consider this technique to be applied for Venus.

3:00 p.m. *Discussion*

3:30 p.m. BREAK

3:45 p.m. *Return to Plenary: Discipline Group Summaries*

Wednesday, May 10, 2017
DISCIPLINE BREAKOUT:
SURFACE AND INTERIORS II:
FEED-FORWARD MODELING, CRITICAL NEEDS, AND MISSION DIRECTION
1:30 p.m. Industry Room A/B

Chairs: **Sue Smrekar**
Bob Grimm

1:30 p.m. Glaze L. S. * Baloga S. M.
Data Needs for Lava Flow Modeling on Venus **[#8008]**
Substantially improved imaging and topography data are critical in order to advance our understanding of lava flow emplacement processes on Venus.

2:00 p.m. Pandey S. P. *
Understanding Thermal Convection Effects of Venus Surface Atmosphere on the Design and Performance of Venus Mission Hardware **[#8025]**
Work focuses on transient effects of thermal convection in Venus surface atmosphere on exposed mission hardware. Review of accurate and efficient state equation options for CFD modeling is presented. Convective heat transfer experiment plan presented.

2:15 p.m. Radoman-Shaw B. G. * Harvey R. P. Costa G. C. C. Jacobson N. S. Avishai A. Nakley L. M.
The Stability of Minerals and Volcanic Glasses on the Surface of Venus **[#8031]**
We are currently conducting experiments that expose a variety of geologic material to simulated Venusian surface temperature, pressure and atmospheric chemistry conditions using the Glenn Extreme Environment Rig (GEER) at NASA Glenn Research Center.

2:30 p.m. DeCroix D. S. * Peterson C. G. Okhuysen B. S. Wiens R. C. Clegg S. M.
Modeling of LIBS Laser Propagation Through the Venus Atmosphere **[#8034]**
This paper describes a process to assess and demonstrates the viability of using Laser Induced Breakdown Spectroscopy (LIBS) to obtain quantitative chemical measurements on the surface of Venus.

2:45 p.m. Hensley S. * Tsang C. Arumugam D. Duan X. Smrekar S. Lundgren P.
Variations in Venus Atmosphere Variability and Implications for SAR Interferometry at X-Band **[#8018]**
High resolution radar imagery and topography are integral components to understanding how Venus evolved. The thick Venus atmosphere has implications for SAR missions. We examine atmospheric impacts to X-0band radar interferometry.

3:00 p.m. *Discussion*

3:30 p.m. BREAK

3:45 p.m. *Return to Plenary: Discipline Group Summaries*

Thursday, May 11, 2017
PLENARY III:
GROUP SUMMARY, WORKSHOP FINDINGS, AND PLAN FOR REPORT
9:00 a.m. Forum Room

9:00 a.m.	*Plan for Report*
9:30 a.m.	*Group Summaries and Findings*
10:30 a.m.	BREAK
10:45 a.m.	*Final Roundtable*
11:45 a.m.	*Adjourn*
12:00 p.m.	LUNCH
1:00 p.m.	*Glenn Extreme Environment Rig (GEER) Tour*
2:30 p.m.	*Committee, Chair, Student Data Collection and Report Coordination*

CONTENTS

Simulations of the Atmospheric Microwave and Millimeter Wave Emission from Venus using a Radiative Transfer Model based on Laboratory Measurements.

A. B. Akins[1], A. Bellotti[1], and P. G. Steffes[1], [1]Georgia Institute of Technology School of Electrical and Computer Engineering, Atlanta, Georgia

Introduction: The Georgia Tech Venus Radiative Transfer Model (VRTM) can be used to model the effects of the abundances of microwave and millimeter wave absorbing constituents on the emission from the Venus troposphere and mesosphere. The primary components of the Venus atmosphere are CO_2 and N_2, but variation in concentration of sulfur compounds, specifically gaseous H_2SO_4 and SO_2, result in continuum brightness temperature variations from the troposphere at microwave and millimeter wavelengths.

Sulfur compound opacity formalisms have been empirically verified through laboratory experiments that use cavity and open resonators to differentially measure the complex permittivity of gas mixtures at temperatures and pressures representative of Venus conditions [1]. Such experiments can be used to validate pressure-broadened lineshape models. In cases where such line-based models do not match measured data, continuum best fit models are developed. These opacity formalisms are combined with temperature/pressure profiles from previous Venus missions to form the radiative transfer model.

Estimates of microwave and millimeter wave emission derived from this model have many applications in Venus radio astronomy, such as the interpretation of observations from the Combined Array for Research in Millimeter-wave Astronomy (CARMA) [2] and the Atacama Large Millimeter Array (ALMA) [3]. This radiative transfer model will be of specific use to remote study of atmospheric abundances of sulfur dioxide and sulfuric acid in accordance with VEXAG Goals I.C and III.B [4].

Model Components: The VRTM consists of a set of inputs built around a ray tracing algorithm. Atmospheric emission at radio frequencies is modeled by calculating the path of an energized ray through discrete atmospheric layers. This ray path is modeled as energy traveling towards the planet as opposed to being emitted, as the integrated forward and return paths are isomorphic. In each layer, the ray signal is attenuated and refracted according the homogeneous atmospheric composition of the layer in local thermodynamic equilibrium. The ray path of the signal may reach the surface with minimal refraction if the receiving source is closer to nadir pointing, but the signal can follow a much longer path in the case of limb sounding and even trace a path around the planet. Ray tracing can be used to model passive emission from the surface, radio occultation experiments, or communications between a lander and an orbiter.

In addition to calculating emission along a single pencil-beam associated with the ray tracing model, the VRTM can also calculate the cumulative disk-averaged emission from the Venus disk. Additionally, specific antenna gain patterns can be introduced which allow computation of the emission measured by a specific beamshape.

The inputs to the ray tracing model include empirical data about the composition and structure of the Venus atmosphere derived from prior missions and observations, as well as estimations of the emissivity for a surface with a bulk dielectric permittivity between 4 and 4.5 [5]. The effects of the opacity for each atmospheric layer form an integrated weighting function. At frequencies close to 5 GHz, absorption occurs primarily near the surface, but as the frequency increases, absorption from higher points in the atmosphere dominate the weighting function, as shown in Figure 1. Evaluations of the VRTM with previously recorded Venus disk-averaged emissions show agreement from 1-86 GHz [6].

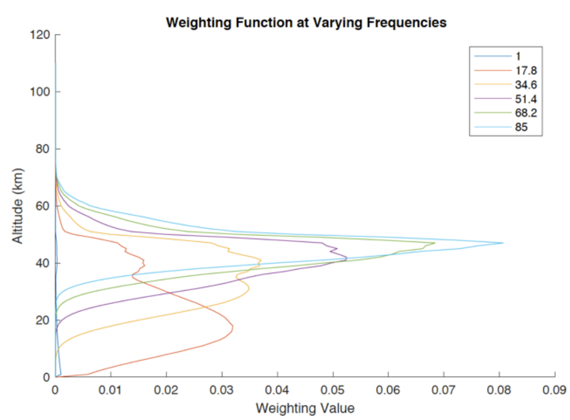

Figure 1: Frequency-Dependent Atmospheric Weighting Functions

Sources of Model Uncertainty: The VRTM uses temperature-pressure profiles derived from the Pioneer-Venus Sounder and North probes measured at the equator and at a latitude of 60° [7]. Recent temperature-pressure profiles for the mesosphere have been obtained through Venus Express observations [8]. Radio occultations from the VeRa instrument suggest a diurnal variation of 30-40K between 65 and 55 km near the equator [9]. Additionally, nightside variations in temperature at higher altitudes have been measured through submillimeter variations in CO [10]. The effects of temperature discrepancies in the model could result in variations in the derived atmospheric weighting function, particularly at submillimeter wavelengths.

The CO_2 and N_2 abundance in the the atmosphere is assumed to be constant at 96.5% and 3.5%, treating sulfur-bearing components as trace gases. Due to the low mixing ratio of sulfur molecules, the modeled refractivity is attributed to the primary gases [1]. Equatorial H_2SO_4 abundance profiles are included from Mariner 10 radio occultations at the equator and Magellan radio occultations at 67° North and 88° South [11]. Variations in the abundance from these probes highlight the problem of H_2SO_4 spatial variation in any modeling attempts.

SO_2 abundance is modeled as a continuous distribution from the surface to 48 km. Above this altitude, the gas abundance model decays with a scale height of 3.3 km due to photolysis [6]. At the equator, the uniform mixing ratio is chosen to be between 75 ppm and 150 ppm. However, latitudinal and temporal variations in the abundance of SO_2 can be inferred from the variability of measurements made at the cloud tops [12]. Recent results from the Venus Express SOIR instrument suggest an abundance of 3 ppm of SO_2 at 70 km for lower latitudes, continuing a trend of wide measurement variability [13, 14].

These abundance profiles are combined with the opacity characteristics of CO_2, N_2, and pressure-broadened absorption of SO_2 and H_2SO_4 to estimate optical depth. Millimeter wave CO_2 and N_2 absorption is collision induced and dependent on the square of the frequency [15]. The opacity of SO_2 follows the Van Vleck-Weisskopf formalism using the JPL spectral line catalog [16]. The opacity of gaseous H_2SO_4 is given as a series of best fit expressions based on laboratory measurements at centimeter wavelengths [1]. Since these measurements occurred at lower frequencies, there is a degree of uncertainty in attempting to extrapolate these best fit curves to radio observations in the millimeter and submillimeter regions. A comparison between the best fit extrapolated opacity for H_2SO_4 and that of a Van Vleck-Weisskopf or Gross lineshape is a factor of 10 as shown in Figure 2. This uncertainty has motivated a new series of laboratory measurements of gaseous H_2SO_4 opacity in the 2-4 mm and 7-9 mm bands.

Model Discussion: Direct examples of the discrepancies between the sulfuric acid opacity models and the resulting effects of the uncertainty on the atmospheric weighting function will be discussed. Initial measurements of the millimeter wave absorption will be presented to motivate discussion. Discussion will also cover latitudinal variations in the abundance profiles for SO_2 and H_2SO_4 and subsequent effects on the weighting functions. In addition to gaseous SO_2 and H_2SO_4, other atmospheric components such as H_2S, OCS, CO, H_2O, HDO, H_2SO_4 condensates are present in the upper troposphere and mesosphere. The absorption effects of these trace elements at millimeter wavelengths will be reassessed. Discrepancies between the temperature pressure profiles obtained with the SOIR/VeRa instruments and the Pioneer Venus probes in the upper troposphere region will be assessed. Suggestions will also be made for necessary model improvements.

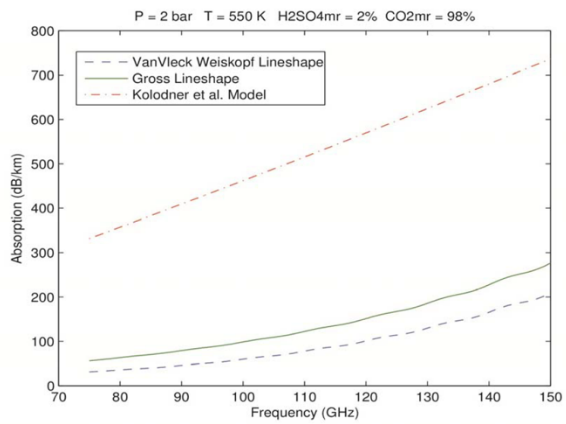

Figure 2: Variations in H_2SO_4 opacity

References: [1] Kolodner, M. A. and Steffes, P. G. (1998) *Icarus* [2] Bellotti, A. and Steffes, P. G. (2014) *Bulletin of the Amer. Astron. Soc.* [3] Encrenaz, T. et al. (2015) *Planetary and Space Science* [4] (2016) Goals, Objectives, and Investigations for Venus Exploration. [5] Pettengill, G. H. et al. (1992) *Jour. of Geophys. Res.* [6] Bellotti, A. (2015) *Master's Thesis* [7] Seiff, A. et al. (1980) *Jour. of Geophys. Res.: Space Phys.* [8] Parkinson, C. D. et al. (2015) *Planet. and Space Sci.* [9] Patzold, M. et al (2007) *Nature* [10] Clancy, R. T. et al. (2012) *Icarus* [11] Jenkins, J. M. et al. (2002) *Icarus* [12] Taylor, F. W. et al. (1997) *Venus II* [13] Belyaev, D. et al. (2008) *Jour. of Geophys. Res.* [14] Esposito, L. et al. (1997) *Venus II* [15] Ho W. et al. (1966) *Jour. of Geophys. Res* [16] Fahd, A. K. and Steffes, P. G. (1992) *Icarus*

OPTIMIZED SUPERCRITICAL FLUID REFRIGERATION CYCLE FOR VENUS LANDER PAYLOAD ELECTRONICS ACTIVE COOLING. K. R. Anderson[1], C.M. McNamara[2], A. Gatti[2], J. Guerrero[3], [1]California State Polytechnic University at Pomona, Department of Mechanical Engineering, (3801 West Temple Ave, Building 17-2353, Pomona, CA 91768 USA, kranderson1@cpp.edu), [2]Ingenium Technical Services, Inc. (10374 San Fernando Ave Cupertino, CA 95014, chris.m.mcnamara@gmail.com,ariel@ingeniumtsi.com), [3]Orbital ATK (2555 E. Colorado Blvd., Suite 204, Pasadena, CA 91107, jose.guerrero@orbitalatk.com).

Introduction:
Landing and operating on the surface of Venus has been a tremendous challenge that includes ten mission failures and only eight successes since 1962. Venus surface knowledge is limited due to the minimal operational time provided by past thermal system technology. The existing state-of-the-art established by previous Russian Venus landing missions included demonstrated survivability durations which serve as benchmarks for this effort. The Russian missions Venera 13 circa 1981 [1] and Venera 14 circa 1982 [2] are the longest lived mission lasting 127 minutes. A New Frontiers finalist for 2011 [3], Surface and Atmosphere Geochemical Explorer (SAGE) proposed a Venus surface design life of up to 3 hours. This timeline is ineffective to fully leverage the in-situ geochemistry and surface mineralogy tools and research for a Venus mission. Short-lived mission durations on the surface of Venus are due to extreme environments, where the temperature is 740 K (467 °C, 872 °F) with a pressure of 9.3 MPa (1348.8 psi). To this end, the current paper outlines an active instrument cooling payload concept utilizing a multi-cascaded refrigeration cycle application to Venus lander missions. The proposed state-of-the-art cascaded hybrid refrigeration system, if successful would enable future science instruments to survive this harsh environment for durations spanning days, weeks, and perhaps months to exercise the In-Situ geochemistry and mineralogy research of the Venus surface. This paper presents a novel refrigeration system that will allow future science instrument and electronics to survive the harsh surface environment with operational time measured in weeks instead of minutes. The current work is an extension of [4,5], wherein the concept of the multi-cascaded refrigeration cycle application to Venus lander missions was first proposed. The current paper presents results for a optimization of the input power to the cycle, preliminary compressor sizing for the topping cycle and overall heat transfer analysis of the system componentry. Figure 1 shows the concept of an active instrument cooled payload within the framework of a conceptual Venus lander. Figure 1 shows the lander with an upper Power Bay and a lower Volume Bay. The Power Bay is populated with Radioisotope Thermoelectric Generators (RTG), Fuel cells, or perhaps another Direct Energy Conversion technology such as Li-CO2 batteries. The power from the Power Bay is used to provide power to cool a Volume Bay were payload (seismic instruments, drills, etc.) may be housed. The cascaded refrigeration cycle discussed in this paper is housed in the Power Bay and is used to maintain the electronics in the Volume Bay at a prescribed temperature. Figure 2 shows the components of the proposed active cascaded refrigeration system which are housed on the bench of the Power Bay of Figure 1.

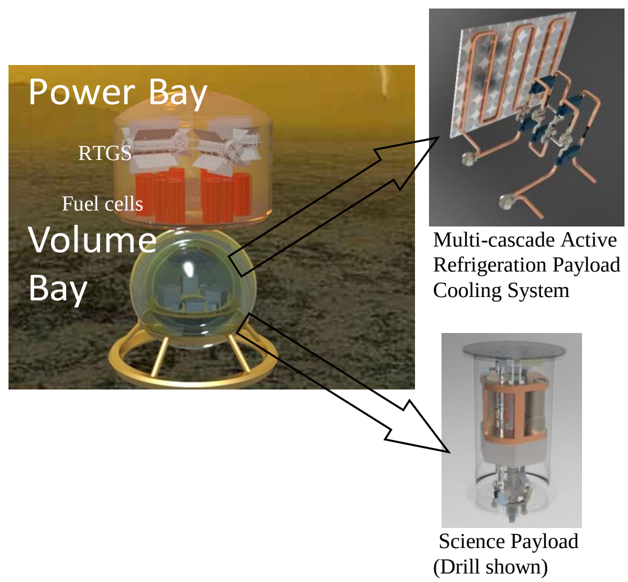

Figure 1. Proposed Venus Lander Configuration (background adapted from [6])

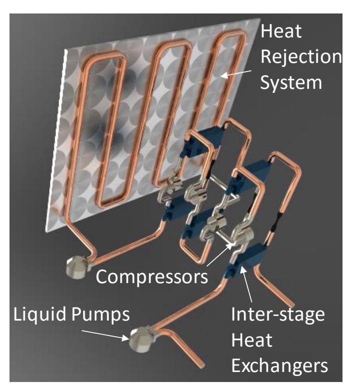

Figure 2. Multi-cascade Active Refrigeration Payload Cooling System

Figure 2 shows the various components of the multi-cascade active refrigeration cooling system including the liquid feed pumps, the interstage heat exchangers, the refrigerant compressors, and the heat rejection system. The technology goals of the current paper are vital to the development of a significantly increased science payload life for an in-situ Venus mission. The expectation to have long duration surface investigations on Venus depends on the ability to protect instruments and electronics from the external 740 K temperature. The proposed refrigeration system can extend life cycle of lower or high temperature electronics. To date, technology advancements in high temperature electronic components have been made. But, with the addition of our proposed active cooling, these components can operate for extended periods of time on the surface of Venus. The paper will extend the development of a hybrid, cascade refrigeration system of [4]. The system is cascaded into four stages, with the working fluids 1) NH3, 2) Transcritical CO2, 3) Supercritical CO2 (SCO2), and 4) Methyl Linoleate (MLL) Fatty Acid Methyl Ester (FAME). The system can be regarded as state-of-the-art in the arena of active electronics thermal control since the refrigeration system employs two supercritical fluids, namely the SCO2 and the MLL FAME. The SCO2 fluid is a supercritical fluid, which has found recent resurgence in applications in the renewable energy sector. The MLL FAME working fluid is a biofuel usually obtained from rape seed oil and presently uncharacterized for this application. The MLL FAME will be used in the topping cycle and will experience the highest temperature at 773K (500°C,932°F). The system is expected to lift 100W of thermal energy (dissipated by electronics driving instruments) while maintaining a payload environmental temperature of 150°C. The use of a refrigeration system still requires that electronic components operate at elevated temperatures but not at 740 K (467 °C, 872 °F). The current concept employs Commercial Off The Shelf (COTS) hardware (compressors and heat exchangers) with Technology Readiness Level (TRL) for the NH3 cycle is $6<TRL<9$, and $6<TRL<7.5$ for the CO2 cycles. The MML FAME hardware (compressor, seals, heat exchangers, throttling valve) has $1 < TRL < 3$ since most of the MML FAME hardware needs to be developed from the ground up. The current paper will focus on the following aspects of the proposed thermal control system: (i) optimization of the cascade refrigeration cycle for input power (ii) development of a compressor for the MML FAME working fluid topping cycle (iii) heat transfer analysis of heat exchangers for the cascade refrigeration system. For (i), the MATLAB Genetic Algorithm toolbox has been exercised in order to minimize the power input the various compressors for the cascaded system. The preliminary findings are as follows: NH3 compressor power = 42 W, Transcritical CO2 compressor power = 38 W, SCO2 compressor power = 21 W, and MLL FAME compressor power = 2 W. Thus a total of 103 W is required to power the cycle. The cycle has an overall Coefficient of Performance= Lift/Work = 0.984, thus the system can lift = 0.984*103 = 101 W of electronics dissipated energy. The details of the optimization of compressor power in each stage of the cascaded cycle will be presented in the paper. Regarding (ii) the novelty of this present work lies in the development of a compressor which can handle the FAME MML fluid at the high temperatures and high pressures of the Venus environment. A reciprocating compressor with flow rate of 6 kg/hr of MML FAME, volumetric displacement of 0.002 cubic meters/sec, compression ratio of 1.875, and volumetric efficiency of 86%, is currently being developed. The preliminary analysis results indicate that the use of a liquid / gas separator and/or superheating will be required in conjunction with the MML FAME compressor. Selection and specification of the appropriate seals and seal material candidates for the MML FAME compressor will also be discussed in this paper. Regarding iii) heat transfer thermal performance analysis of the various hardware components (heat exchangers, compressors, expansion valves) will be presented in the paper and results for overall thermal control system architecture based on temperature and pressure set-points will be presented. Future work will encompass the life cycle testing of the MML FAME working fluid and the various hardware components of the cascaded cycle.

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Lessons Learned from Radiative Transfer Simulations of the Venus Atmosphere. G. Arney[1,2], V. S. Meadows[2,3], A. Lincowski[2,3] [1]NASA Goddard Space Flight Center, [2]NASA Astrobiology Institute Virtual Planetary Laboratory, [3]University of Washington (giada.n.arney@nasa.gov)

Introduction: The Venus atmosphere is extremely complex, and because of this the spectrum of Earth's sister planet is likewise intricate and a challenge to model accurately. However, accurate modeling of Venus' spectrum opens up multiple opportunities to better understand the planet next door, and even for understanding Venus-like planets beyond our solar system.

Near-infrared (1-2.5 um, NIR) spectral windows observable on the Venus nigthside present the opportunity to probe beneath the Venusian cloud deck and measure thermal emission from the surface and lower atmosphere remotely from Earth or from orbit. These nigthside spectral windows were discovered by Allen and Crawford (1984) [1] and have since been used measure trace gas abundances in the Venus lower atmosphere (< 45 km), map surface emissivity varisions, and measure properties of the lower cloud deck [e.g. 2,3,4]. These windows sample radiation from below the cloud base at roughly 45 km, and pressures in this region range from roughly Earthlike (~1 bar) up to 90 bars at the surface. Temperatures in this region are high: they range from about 400 K at the base of the cloud deck up to about 740 K at the surface. This high temperature and pressure presents several challenges to modelers attempting radiative transfer simulations of this region of the atmosphere, which we will review.

Venus is also important to spectrally model to predict the remote observables of Venus-like exoplanets in anticipation of data from future observatories. Venus-like planets are likely one of the most common types of terrestrial planets [5] and so simulations of them are valuable for planning observatory and detector properties of future telescopes being designed, as well as predicting the types of observations required to characterize them.

Methods: We have modeled the spectrum of Venus using the Spectral Mapping Atmospheric Radiative Transfer Model (SMART), a 1-D line-by-line fully multiple scattering radiative transfer model to characterize its lower atmosphere based on observations and to predict the spectral remote observables of exo-Venus planets.

Challlenges of Modeling the Venus Lower Atmosphere: Due to high temperature and pressure, unusual lineshapes are required to model CO_2 and H_2O in the sub-cloud atmosphere: the far wings of H_2O lines are modeled with super-Lorentzian profiles, while the CO_2 band far winds are modeled as sub-Lorentzian. In order to fit the shapes of the spectral windows near 1.73 μm and 2.3 μm, it is necessary to include an additional CO_2 continuum absorption (α) providing extra opacity in these regions. From nightside spectra of Venus, we have measured $\alpha = (2.5 \pm 0.5) 10^{-8}$ cm^{-1} $amagat^{-2}$ for the 2.3 μm window, and $\alpha = (6.0 \pm 0.9) 10^{-9}$ cm^{-1} $amagat^{-2}$ for the 1.74 μm window, both of which are broadly consistent with previous constraints. It is not possible to adequately model the lower atmosphere spectrum without these extra continuum opacities.

Limitations of existing CO_2 linelists present additional challenges for modeling Venus' spectrum. The HITEMP 2010 linelist fits the spectral region between 2.2 and 2.3 μm poorly even when the additional CO_2 continuum opacity is included. HITEMP 2010 also significantly under-estimates the CO_2 opacity between the 1.1 μm and 1.18 μm spectral windows. These windows sense radiation from < 16 km, and this spectral region is important to model accurately because the short-wavelength side of the 1.18 μm spectral window is used to retrieve water vapor abundance in the lowest atmospheric scale height. Fortunately, newer CO_2 linelists such as that of Huang et al. (2014) [6] include temperature-dependent pressure broadening parameters (unlike HITEMP that includes broadening parameters at only one temperature), and we will show how this newer linelist addresses these issues in the Venus spectrum.

The Venus cloud deck presents additional challenges for spectral modeling. Because the optical properties of the Venus clouds vary with wavelength, it is vital to model the cloud deck carefully in order to remove its wavelength-dependent spectral effects from trace gas retrievals. Otherwise, spurious corrlations between the cloud deck opacity and trace gas abundances can be inferred, a phenomenon we call "cloud ghosting" because the cloud patterns can produce "ghostly" illusionary imprints of themselves on trace gas maps. Cloud ghosting has the greatest potential to be problematic in the 2.29-2.45 μm spectral region where the cloud particles have the largest extinction coefficient. To remove cloud effects, it is most critical to account for variations in cloud optical depth, but second order variability caused by differences in the refractive indices of the cloud particles from variable H_2SO_4/H_2O fractions are more difficult to account for. Unfortunately, laboratory measurements of H_2SO_4/H_2O solution refractive indices only exist at 75%, 84.5%, and 95.6% H_2SO_4 at Venus-like temperatures [7], and therefore more finely graded measurements of the lower cloud acid percentage are very difficult to perform. New measurements at additional H_2SO_4/H_2O concentrations are therefore needed for these types of studies.

The Spectrum of Exo-Venuses: A different, yet equally important application of radiative transfer modeling of Venus concerns what we may be able to learn about exo-Venus analogs. JWST may be able to observe exo-Venus analogs transiting their host stars. Venuslike exoplanets orbit their stars at closer orbital distances than Earthlike exoplanets, making them more detectable targets owing to their more frequent transits and higher transit probability. We have modeled the transit transmission spectrum of Venus and found that sulfuric acid produces spectral features in the near-infrared at 2.7, 6, 8.5, 9.7, and 11.5 μm that may be detectable on an exo-Venus planet. Such features may allow remote characterization of exo-Venus cloud decks. CO_2 features are also present, with strongest features near 4.5 and 15 μm.

The planets orbiting TRAPPIST-1 [8] are among the best known targets for JWST to observe because the large ratio of the planet sizes relative to the small star makes for deeper transit features. TRAPPIST-1 is an M8V dwarf, and M dwarfs experience a long super-luminous pre-main sequence phase (pre-MS) while the young star is contracting [9]. Even the planets currently in the TRAPPPIST-1 habitable zone would have experienced enough stellar irradiation over a period of 10s or 100s of millions of years during the pre-MS to drive them into a desiccated, post-runaway greenhouse state if they did not experience post-pre main sequence water delivery or late migration into the habitable zone. Therefore, Venus represents a plausible analog for many of the TRAPPIST-1 planets, and Venuslike spectra re interesting to consider for what the remote observables of these worlds may be like. We have modeled the spectrum of Venus-like TRAPPIST-1 planets and anticipate that spectral features with strengths of 10s of ppm are possible.

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LIMITS OF CLIMATE-DRIVEN WRINKLE RIDGE FORMATION ON VENUS. J. A. Balcerski[1], [1]NASA Glenn Research Center, Cleveland, OH. (jeffrey.balcerski@nasa.gov)

Introduction: Wrinkle ridges, small-scale tectonic fabric formed during compressive failure of brittle surface rock, cover between 70% of Venus' surface [1]. These regular bands of hundreds of kilometers in length and up to 200 meters in height have been observed be generally aligned with regional stress fields associated with large-scale topographic features [2]. However, their nearly ubiquitous presence upon the relatively young volcanic lowland plains suggests that they may have been formed by some global process active during Venus' recent history rather than planetary contraction which likely ceased well before the plains formation [3]. Given the apparent youth of the lowland plains it has been suggested that the planet experienced one or more episodes of massive volcanic activity in association with the production of basalt floods [e.g. 1]. This activity would have released a tremendous volume of volatiles such as CO_2, SO_2, and water vapor into the atmosphere, thereby causing rapid enhancement of the greenhouse effect and substantial elevation of surface temperatures [4]. Geochemical models of interactions between the lower atmosphere and materials likely present at the surface of the planet suggest that buffering reactions may determine the rate at which the volatile content of the atmosphere is able to return to equilibrium [e.g. 4, 5]. It has been suggested that a ~100 Myr excursion of surface temperatures above their present day average would have been sufficient to generate at least some amount of brittle failure of surface rock due to thermal stresses [3, 6]. Analytic elastoplastic models indicate that strains due to compressive stresses (resulting from thermal expansion during heating of the surface) might be consistent with wrinkle ridge formation, with magnitudes limited to at most a few percent [3]. However, numerical models that include nonlinear viscous creep rheologies result in unrecoverable strains of < 0.1%, manifested in extension rather than compression [6]. This deformation is likely too small (and of the wrong sign) to generate the observed features. More recently, structural modeling of re-activation of pre-existing faults provides a mechanism for thermally-driven stresses to be localized and expressed as surface strain [7].

Previous models of surface-atmosphere tectonic interaction were based upon the buffering reactions of a carbonate system [4]. However, more recent chemical modeling indicates that that a carbonate system is unstable and unable to buffer the excessive SO_2 that would have been present after widespread volcanism, without a catastrophic conversion of surface carbonates into atmospheric CO_2 [5]. One alternative, a pyrite-buffered system, can result in much more rapid increase in near-surface atmospheric temperatures but with a shorter overall duration of surface temperature excursion [5].

Approach: The commercial finite element software package MSC.Marc was used to model the response of representative dry basalt rheology [8] to prescribed surface temperature fluctuations. These thermal perturbations were set to rapidly increase from 800 K to 900 K and in the second case, 1000 K, over 1 million years, followed by a hold for 100 million years and a gradual return to baseline over 10 million years. In order to include effects of initial (seeded) topography, the 1-D finite element elastoviscoplastic model described by Dombard (2000) is extended to a 2-D plane strain formulation.

Results: The increased magnitude of thermal perturbation resulted in unrecoverable plastic strain in compression, consistent in sign with formation of wrinkle ridges. However, the magnitude of this strain was at most 0.15%, which is not substantially higher than previous results [3,6]. This plastic strain was not significantly affected by varying ramp rates or hold times, which simply thinned the depth of crust capable of supporting brittle deformation. It is therefore unlikely that stresses on the upper crust due to climate-induced thermal perturbations are, in isolation, sufficient to create the thrust faults necessary for wrinkle ridge formation. However, the apparent widespread and relatively recent appearance of these ridges on Venus' volcanic plains still implicates a global event. In the absence of evidence for recent changes in global lithospheric stresses, and simultaneously, evidence for ongoing fluctuations in volcanic gases in Venus' atmosphere, it is likely that climate-related perturbations acted upon pre-existing lithospheric stresses.

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FUNDAMENTAL STUDIES OF HIGH-PRESSURE TURBULENT MULTI-SPECIES MIXING RELEVANT TO THE VENUS ATMOSPHERE. J. Bellan, Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, MS. 125/109, Pasadena CA 91109 and Mechanical and Civil Engineering Department, California Institute of Technology, Pasadena, CA 91125, Josette.Bellan@jpl.nasa.gov

Introduction: The thermodynamic conditions in the Venus atmosphere, nominally at a pressure of 92 atm, a temperature of 750 K and having a global nominal composition of 96.5% CO2 and 3.5% N2 imply that heat and mass exchange processes in the atmosphere occur under supercritical conditions. In contrast to well-known heat and mass exchange processes at 1 bar, 298 K and Earth atmosphere composition, those on Venus must be described using real-gas thermodynamics, generalized species-mass and heat fluxes based on the formulation of dissipation-fluctuation theory [1] and consistent high-pressure transport properties utilizing high-pressure valid mixing rules [2]. The presence of minor (i.e tracer) species in the Venus atmospherre – 150 ppm SO2, 70 ppm Ar, 20 ppm H2O and 17 ppm CO --- may though introduce some aspects, such as metastable states, that have not been considered so far.

A comprehensive theory of high-pressure multi-species mixing [3] is presented and salient results pertinent to the Venus atmosphere are discussed. Further, using this theory, simulations of CO2 and N2 mixing at high pressure and temperature are discussed and analyzed [4]. The influence of the insights obtained from these results on Venus exploration and planned future studies are addressed.

Model and results: Following a description of the general theory and simulations used to understand high-pressure and high-temperature mixing, an application to a Venus-relevant situation is described and discussed.

Turbulent high-pressure multi-species mixing theory. The model equations relevant to simulations of high-pressure and high-temperature multi-species mixing are the differential conservation equations for mass, species partial density, momentum and total energy coupled to a real-gas equation of state for the mixture. The theory includes the complete form of the species mass- and heat-fluxes consistent with fluctuatin-dissipation theory which is valid for non-equilibrium thermodynamic processes. Thus, the species-mass flux is the sum of three terms: the Soret effect which accounts for temperature gradients, the barodiffusion which accounts for pressure gradients and a mass-diffusion term accounting for the species mass-fraction gradients. Each of these terms contains molecular-diffusion coefficients which are computed based on high-pressure binary diffusion coefficients which enter high-pressure mixing rules to compute the pair-wise diffusion coefficients. The heat flux contains the Fourier effect and the enthalpy transported by the species; in the Fourier term the thermal conductivity is computed using high-pressure mixing rules. The equations are solved using the Direct Numerical Simulation (DNS) methodology wherein all scales overwhelmingly responsible for the dissipation are resolved. For ease of interpretation of results, the equations are solved in a mixing layer configuration which is pertinent to the Planetary Boundary Layer (PBL). The initial Reynolds number is based on a reference viscosity and all other transport properties are scaled by the ratio of the reference viscosity to the physical viscosity to ensure that the Schmidt number, the Prandtl number and the Lewis number have physical values. A database is created by varying the initial Reynolds number, the free-stream pressure (60 atm, 70 atm and 80 atm) and the initial composition of the two streams of the mixing layer. In each case, the mixing of five species is simulated: three major species and two minor species. In each simulation, the computation is conducted until a transitional time which is defined as that the flow exhibits turbulence characteristics. The results show development of regions where the magnitude of the density gradient becomes very large as illustrated in Fig. 1 in a streamwise/spanwise plane at the transitional time. These density gradients are similar to experimental observations obtained at much larger Reynolds number values than achievable in DNS. The trace species can undergo uphill diffusion which may lead to species and/or phase separation. Modeled species-specific effective Schmidt numbers exhibit values exceeding unity in many regions of the flow field as shown in Fig. 2 (the STP value is 0.7), and the modeled effective Prandtl number (STP value of 0.7) reaches values similar to those of refrigerants (i.e., 4-5) and even liquid water (i.e., 7) as shown in Fig. 3. The negative values of the Prandtl number are due to uphill diffusion of the minor species.

Turbulent mixing of CO2 and N2. To evaluate the model, spatial, rather than temporal simulations were performed of a N2 jet at 750 K injected into a chamber pressurized to 60 atm and containing CO2 at 450 K. This configuration represented an experimental configuration used at the University of Southern California (USC). While the experimental data is still forthcoming, the DNS computations revealed that the high density gradients observed in the five-species mixing are still present and are of order 10^4 kg/m^4 as shown in Fig. 4 where the mass fraction of N2 is also plotted showing the mixing with CO2 further downstream and furthermore depicted is the second invariant of the rate of deformation tensor which is indicative of vortical structures in the flow displaying the vortex rings near the inlet and the breakdown of the flow into small turbulent features downstream. Time-averaged results (not shown) reveal a potential core near the inlet downstream of which the density increases due to the mixing of N2 with the heavier CO2.

Summary and conclusions: The studies described above show the intricacies of multi-species mixing under high-pressure high-temperature turbulent conditions. The model can be used to study the time evolution of a three-dimensional vertical slice of the Venus PBL with a domain having non-reflecting boundary conditions (i.e. domain size influence minimized). Since the near-ground Venus atmosphere composition is not known with certainty, additional to CO2/N2, other compositions, i.e. including minor species, can be simulated to determine whether the Venus atmosphere could be in a metastable state in which micro-drops are suspended into a fluid; then the interpretation of signals from probes moving vertically through the Venus atmopshere would require special interpretation, i.e. accounting from scattering from the micro-drops. The near-ground unstable temperature gradient may also be explained by such findings.

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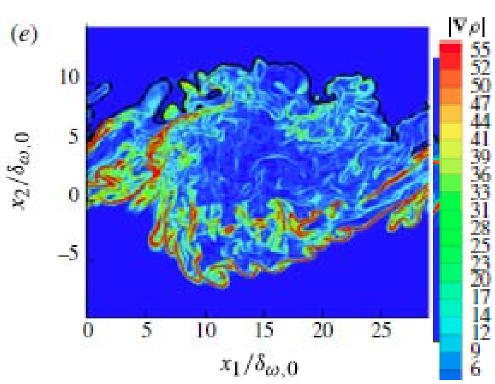

Figure 1 Instantaneous density gradient magnitude in a streamwise/crosstream plane of a temporal mixing layer developed from mixing at 80 atm of five species, two of which are CO2 and N2. Units are 10^3 kg/m^4. $\delta_{\omega,0}$ is the initial momentum thickness of the layer.

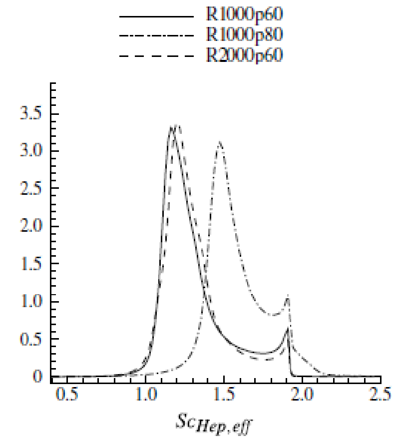

Figure 2 Probability density function over the three-dimensional domain at the transitional time of the Schmidt number for one of the species undergoing regular diffusion. "R" denotes the initial Reynolds number and "p" denotes the free-stream pressure in atm.

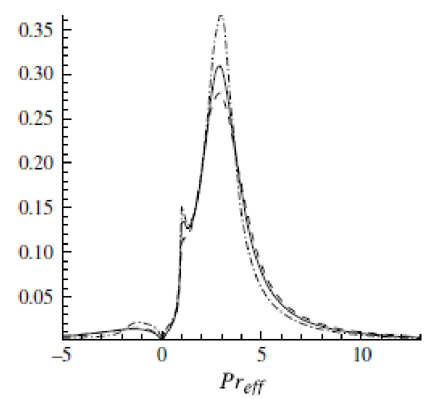

Figure 3 Probability density function over the three-dimensional domain at the transitional time of the Prandtl number. Same legend as Fig. 2.

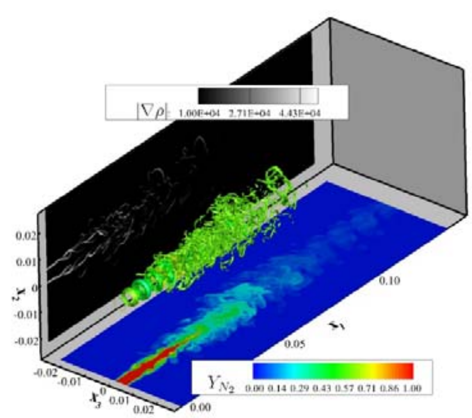

Figure 4 N2 jet (at 750 K) injection into a CO2-filled chamber at 60 atm (and 450 K). Instantaneous snapshot of the vortical jet features, the density gradient magnitude in kg/m^4 and the mass fraction of N2.

INCORPORATING PLANETARY-SCALE WAVES INTO THE VTGCM: UNDERSTANDING THE WAVES' IMPACT ON THE UPPER ATMOSPHERE OF VENUS. A. S. Brecht[1], S. W. Bougher[2], D. Shields[3], H. Liu[4], [1]NASA Ames Research Center, M/S 245-3, Moffett Field, CA, 94035, USA (Amanda.S.Brecht@nasa.gov), [2]CLaSP, 2418C Space Research Building, University of Michigan, Ann Arbor, MI, 48109, USA, [3]NCAR/HAO, Boulder, CO, 80301, USA.

Introduction: Venus has proven to have a very dynamic upper atmosphere. The upper atmosphere of Venus has been observed for many decades by multiple means of observation (e.g. ground-based, orbiters, probes, fly-by missions going to other planets). As of late, the European Space Agency Venus Express (VEX) orbiter has been a main observer of the Venusian atmosphere. Specifically, observations of Venus' O_2 IR nightglow emission have been presented to show its variability (e.g. [1], [2], [3], [4]). Nightglow emission is directly connected to Venus' circulation and is utilized as a tracer for the atmospheric global wind system. More recent observations are adding and augmenting temperature and density (e.g. CO, CO2, SO_2) datasets (e.g. [5], [6], [7], [8]). These additional datasets provide a means to begin analyzing the variability and study the potential drivers of the variability. A commonly discussed driver of variability is wave deposition. Evidence of waves has been observed, but these waves have not been completely analyzed to understand how and where they are important. A way to interpret the observations and test potential drivers is by utilizing numerical models.

Results and Discussion: For the presented work, the 3-D Venus Thermospheric General Circulation Model (VTGCM) will be utilized in understanding the impact implementing planetary-scale waves at the VTGCM lower boundary (near the top of the cloud deck) will have on the thermospheric structure and variability (~70 – 200 km). Currently, the VTGCM utilizes Rayleigh friction (RF) to help simulate mean thermospheric conditions observed by VEX. Two RF scenarios are utilized: one is symmetric to provide a constant deceleration to the winds (RF-sym) and the second is asymmetric to simulate the retrograde superrotation zonal wind (RSZ) [9]. The purpose of RF is to obtain a 1st order approximation of the necessary wave deposition to reproduce observations. Therefore, the RF provides guidelines for the implementation and adjustment of wave momentum deposition schemes.

Kelvin waves have been incorporated within the VTGCM, but most importantly the Kelvin wave implementation has also been tested with a self-consistent moving lower boundary (winds are not equal to zero and temperature is not constant). The moving lower boundary is composed of non-uniform zonally averaged temperature, zonal wind, meridional wind, and geopotential height at the lower boundary of the VTGCM as provided by the Oxford Venus GCM [10], [11].

Figure 1 represents initial tests with Kelvin waves within the VTGCM and its impact on the O_2 IR nightglow peak integrated intensity with respect to time (days) of simulation. The last 8 days of a 51 day simulation are shown. There are four cases shown: (1)[KW] this is a simulation with RF-sym and Kelvin waves, (2) [NoKW] is a simulation with only RF-sym, (3) [KW+OXVGCM] is a simulation with RF-sym, Kelvin waves, and moving lower boundary, (4) [NoKW+OXVGCM] is a simulation with RF-sym and the moving lower boundary. It can be concluded that the Kelvin waves do provided a small amount of variability, about 0.3 MR. However, the combination of the moving lower boundary and Kelvin waves induces an intensity range from 1.4 MR to 2.8 MR. Moreover, of those four cases, the combination of the moving lower boundary and Kelvin wave is the only case to provide temporal shifts for the nightglow peak local time; 23:00 to 1:00 local time (figure not shown).

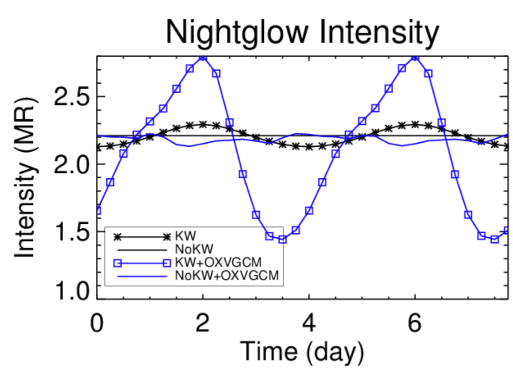

Figure 1: O_2 IR nightglow peak integrated intensity with respect to time of simulation. MR = Mega-Rayleigh (10^{12} photons cm^{-2} s^{-1} in 4π sr). The time is the last 8 days of a 51 day simulation. The four cases shown are: (1)[KW] a simulation with RF-sym and Kelvin waves, (2) [NoKW] a simulation with only RF-sym, (3) [KW+OXVGCM] a simulation with RF-sym, Kelvin waves, and moving lower boundary, (4) [NoKW+OXVGCM] a simulation with RF-sym and the moving lower boundary.

For an initial comparison, [12] employed a simple Venus GCM and implemented Kelvin waves. Their GCM has RF-sym and a non-moving lower boundary. With Kelvin waves the O_2 IR nightglow peak integrated intensity varies from 1.11 MR to 1.32 MR. The local time variation is 23:50 to 00:20. The VTGCM produces similar intensity variations when Kelvin waves are employed without the moving lower boundary. The VTGCM local time variation is comparable too, with just Kelvin waves.

Both model results can be compared to the 3-D statistical map of the O_2 IR nightglow from VEX VIRTIS limb and nadir observations in [4]. The statistical peak intensity is 1.58 MR. However, it can range from ~0.79 MR to 1.58 MR and in local time it ranges from 22:30 to 1:30. The VTGCM intensity variation (Kelvin wave with the moving lower boundary) is too large, while [12] intensity variation is too small compared to the observations. However, the VTGCM does a better job capturing the local time variation (Kelvin wave with the moving lower boundary) compared to the [12] results with respect to the observations.

Conclusion: In conclusion, it has been shown that Kelvin waves can contribute to the variability to O_2 IR nightglow. However, the work to be presented will be to show more sensitivity tests with the Kelvin waves, implementation of Rossby waves, Rossby wave sensitivity tests, and the impacts these waves have on the upper atmosphere of Venus.

The characterization of waves (e.g. planetary-scale and gravity waves) with observations (current and future) and models is important in understanding the variability within Venus' upper atmosphere. The current parameter space for modeling waves (e.g. wavelengths, amplitudes) is very wide and largely uses Earth parameters. Furthermore, testing the boundary conditions (lower and upper) of the VTGCM will be important due to the impact it has on propagating waves through the thermosphere. Lastly, these wave studies are imperative to knowing if they contribute to RF within Venus' upper atmosphere.

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Atmospheric Escape at Venus.
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Introduction: Until recently it has been thought that, with no magnetic field, atmospheric escape from Venus is dominated by loss processes resulting from the Solar Wind impacting the unshielded ionosphere. However, tantalizing new results from Venus and Mars may challenge this paradigm. We present an overview of what is known, and what is unknown about atmospheric escape at Venus, and what challenges remain to constrain the atmospheric evolution of Earth's closest sibling.

Venus Aerial Platform Modeling Needs , J. A. Cutts[1], L. H. Matthies[1] and T.W. Thompson[1], [1]Jet Propulsion Laboratory, California Institute of Technology, MS 321-B41, 4800 Oak Grove Drive, Pasadena, CA 91109, **James.A.Cutts@jpl.nasa.gov**.

Introduction: NASA's Planetary Science Division is performing an assessment of the state of technology in aerial platforms for exploration of Venus. A key factor in the design of aerial platforms is knowledge of the Venus environment. Modeling the Venus environment, which is the subject of this workshop, is needed for the design of robust aerial platforms that can carry out their missions successfully. The purpose of this paper is to define the models that are important for both engineering and scientific aspects of the design of an aerial platform mission. We anticipate that information presented at this Venus Modeling Workshop will be folded into the technology assessment that will be conducted during the remainder of this year.

Aerial Platforms at Venus: The first and only aerial platform missions to have been carried out at Venus were the VeGA balloons deployed by the Soviet Union in 1985 [1]. Each of them floated in the the superrotating atmosphere for approximately two days at a near constant altitude of 55 km altitude and were successfully tracked from Earth. VeGA was an important proof of principal and has led to concepts for more ambitious missions to follow

Constant altitude balloon: One direction that has been pursued involves scaling up the VeGa concept, enabling larger payloads and missions of longer duration but still at a constant altitude. The technology needed here is still the superpressure type of balloon used for VeGa but with stronger material and greater protection against the sulfuric acid environment. These vehicles can also be used to deploy and relay data from descent probes as in the Venus Climate Mission endorsed by the Planetary Science Decadal Survey in 2011 [2].

Altitude controlled balloon: A more ambitious capability is a vehicle which can change altitude in a controlled fashion enabling atmospheric sampling over a broad range of altitudes. Concepts for implementing this over an altitude range from 70 to 30 km have been explored [3].

Hybrid airship concepts: Concepts have also been devised with some degree of horizontal control. The Venus Atmospheric Maneuverable Platform (VAMP) would use a combination of flotation and lift to rise to 65 km on the dayside of Venus but sink to 50km on the nightside when no solar power is available [4].

Solar powered airplane: Solar power near the cloud tops on Venus is adequate for powered flight. Heavier-than-Atmosphere (HTA) vehicles can remain in continuous sunlight by flying in the opposite direction to the superrotating flow [5]. However, cloud opacity and temperature will limit how deeply a solar airplane can penetrate into the cloud layers.

Deep atmosphere platforms: Concepts for buoyant vehicles that would operate near the surface of Venus have also been explored. These include concepts for lifting samples up to the more clement parts of the atmosphere for analysis since lifetimes of vehicles at the surface are limited to a few hours. A similar vehicle can also serve as the first stage in a Venus Surface Sample Return system. After arriving in low density regions of the atmosphere, the sample would be launched into orbit [6]. This type of vehicle has also been contemplated for a Venus Mobile Explorer studied by the Planetary Science Decadal Survey [7].

Environmental Modeling Needs: Knowledge of the Venus environment captured in models is vital for the design of atmospheric platforms and the missions they will implement.

Atmospheric circulation models: For balloon missions, it is necessary to know where the platform will travel in order to assess the likely duration of the mission. Current expectations are that superpressure balloons deployed at 55 km will drift towards the pole, but the rate at which this occurs is uncertain. For platforms with altitude control, it will be important to know if there is any variation in this meridional component of velocity; if it were to reverse, it might enable some degree of control of latitude. For hybrid airpships, the meridional component will determine how much control authority the vehicle will need to avoid drifting to pole.

Solar and thermal radiation models: Knowledge of the variation of solar radiation with depth in the cloud layer is needed for the design of many types of buoyant vehicle where heating of the envelope by the sun impacts performance. The solar flux is also a factor in the design of any long duration aerial platform mission dependent on solar power. Hybrid and HTA vehicles are most dependent on it because clearly their need for power for propulsion will limit how deep into the cloud deck the vehicles can descend. Altitude controlled balloon missions will be much less sensitive because they do not require power for propulsion. However, it will be important to know how deep in the atmosphere it will be practical to operate a solar power system. Performance is impacted by 1) the fall in the intensity of solar flux deeper in the clouds, 2) the selective loss of short wavelength radiation, and 3) the increase int temperature which selectively degrades the performance of photovoltaic converters of longer wave radiation. Models [8] used in recent balloon design [2] should now be updated based on the Venus Express and Akatsuki data.

Cloud characteristics: The nature of the aerosols in the cloud layer and their size distribution will be important to aerial platform design. Balloon missions planned to date are very conservatively designed to tolerate immersion in sulfuric acid. However, if models indicate that sulfuric acid exists only as a very finely dispersed mist, this requirement might be relaxed. There may be other implications for balloon emissivity and thermal control, the surfaces of optical instrument, and for the entry ports of gas analysers.

Physical properties and chemistry of the deep atmosphere: As explained in a companion paper (Bellam), the behavior of mixtures of gases under high pressures and temperatures can introduce some counter intuitive behavior. It is possible that the anomalous lapse rates observed near the surface of Venus result from these unusual processes [9].

Scientific Modeling Needs: In addition to the need for models that can ensure that the aerial vehicle can survive, generate power, and access the parts of the atmosphere needed to execute its mission, models will also be needed to carry out scientific experiments. There will be many different types of models needed for this purpose but we include here a discussion of some that have been the subject of recent work by the senior author and his collaborators.

Infrasound generation and propagation: Seismic disturvances on Venus couple very efficiently into the atmosphere because of the density of the Venus atmosphere. Models have been developed to characterize the propagation into the atmosphere, which indicate that Rayleigh waveforms are accurately replicated as an acoustic signal according to work by Garcia [10]. However, models focusing on the epicentral wave that have been developed for the Earth still need to be adapted to Venus.

Infrasound background generation: To confirm the feasibility of detecting quake-related infrasound signatures, it is important to understand other sources of infrasound on Venus. Building on general circulation models, efforts are underway to understand the size of signals generated in the boundary layer [11]. If Venus has very levels of seismic activity, they may prove to be a source of excitation that can be used for probing the internal structure of the planet.

Engineering Modeling Needs: Models are also required to describe how engineering systems for aerial platforms interact with the environment. Some examples of these are described below:

Entry models: Modeling of concepts with rigid entry systems is well developed for Venus, although in need of refinement. Modeling for concepts where the vehicles enter the atmosphere in an inflated state are required.

Balloon and airship thermal models: Solar heating of the envelopes of balloons and airships elevates the temperature of the enclosed gas, increasing its pressure and exerting stress on the envelope. Improved models integrating the environmental effects are needed to characterize these effects.

Solar power generation models; Solar power is the most practical source of power. Models are needed to optimize the design of multijunction cells to account for the changing intensity, spectral content and temperature with depth in the atmosphere.

Navigation models: Localization of the vehicles is important to the science they can accomplish. Terrain relative navigation (TRN) requires viewing the surface at high resolution and is only possible within 10 km of the surface, and even there is degraded. Models characterizing surface visibility building on the pioneering work of Moroz [12] will be required.

Summary: The development of high fidelity models is vital for the further exploration of Venus and particularly for the operation and scientific utilization of aerial platforms. Environmental models are needed to characterize the environment in which the vehicles operate so they can be designed to effectively carry out their mission. Engineering models are needed to characterize the response of the vehicles to their environment so they survive entry, diurnal changes and acquire sufficient power for operation. Finally, purely scientific models are needed so that diagnostic signatures of the phenomena being investigated can be understood.

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MODELING OF LIBS LASER PROPAGATION THROUGH THE VENUS ATMOSPHERE. D.S. DeCroix, C.G. Peterson, R.T. Newell, B.S. Okhuysen, R.C. Wiens, and S.M. Clegg, Los Alamos National Laboratory, PO Box 1663, MS B224, Los Alamos, NM, 87545. ddecroix@lanl.gov, sclegg@lanl.gov.

Introduction: Very limited information about the surface can be obtained from orbit and surface missions are required for quantitative chemical and mineralogical investigations. The Venus surface consists of 9.2MPa of supercritical CO_2 at ~733K. Under these extreme surface conditions, very rapid measurements are required as the landers will only survive for a couple hours. Remote measurements made from within the safety of the lander are ideal and avoid the risks, sampling limitations, and extended amount of time required to collect a sample that can be delivered to instruments inside the lander.

A remote Raman and Laser-Induced Breakdown Spectrometer (LIBS) instrument similar to the SuperCam instrument selected for the Mars 2020 rover is capable of probing many disparate locations around the lander representing thousands of measurements. Raman and LIBS are highly synergistic analytical techniques. Raman is fundamentally sensitive to the molecular vibrations from which the definitive mineralogy is determined and chemistry is inferred. LIBS is an elemental analysis technique capable of quantitative chemical analysis from which mineralogy can be inferred. Compared to the 1-2 measurements that could be made bringing samples into the lander, several thousand spectra would provide an unprecedented description of the Venus chemical and mineralogical heterogeneity.

Raman and LIBS spectroscopy (RLS) requires directing 532 and 1064 nm laser beams through up to 2 m of the Venus atmosphere. This paper describes how the thermal gradients on the optical window could affect the ability propagate the laser through the atmosphere. We have conclusively demonstrated that the Venus atmos-phere has no impact on the Raman mineralogical measurements [1] and therefore these analyses specifi-cally address focusing the 1064 nm laser to create the LIBS plasma at the target. After traveling through space and descending to the planet surface, the interior of the lander is colder than the ambient surface temperature, thus the sapphire window that the laser propagates through is cold relative to the atmosphere. Fluid adjacent to the window will be colder than the ambient atmosphere and this temperature difference causes changes in the density of the fluid, and thus changes the index of refraction. In addition to density variations due to buoyancy, the presence of a surface wind will drive fluctuations due to the shedding of turbulent eddies off the lander and window. The spatial and temporal density variations need to be understood in the context of the laser beam propagation.

Analysis Methods: A computational fluid dynamics model has been created of the hypothetical lander body, including an optical port (window) approximately 87mm in diameter. The port is cylindrical, angled downward at 45 degrees, and points toward the surface. A three-dimensional unstructured tetrahedral mesh was created around the lander body, with high mesh resolution in the vicinity of the optical port, approximately 1 mm minimum cell resolution. A large-eddy simulation (LES) technique was used in order to accurately simulate the spatial and temporal evolution of the flow. LES explicitly simulates structures in the turbulent flow the size of the grid mesh, and larger; scales of motion smaller than the grid size are modeled using a Smagornisky turbulence closure method.

Using the LES technique, we simulated the flow of the Venusian atmosphere around a hypothetical lander body, with an optical port/window protruding into the ambient Venusian atmosphere. The nominal surface conditions are in the supercritical fluid regime with 96.5 %mol CO_2, 3.5%mol N_2, a 1 m/s wind speed, a static temperature of 733K, a static pressure of 9.2MPa, and a gravitational acceleration of 8.85 m/s^2. In addition to the surface conditions, the wind direction with respect to the lander needed to be specified. It is expected that the lander will not have a mechanism to control this angle, thus we have analyzed several possible wind directions that represent bounding conditions. We have simulated and analyzed the flows of both real and ideal gas simulations, with the figure of merit being the relative difference in energy density and profile at the target, and an assessment of whether a plasma can be created. The results demonstrate that assuming an ideal gas is the worst case and is used for the data presented here.

We simulated a 1 m/s mean wind speed and four different wind directions with respect to the window: 1) the wind direction is oriented directly toward the window (0º); 2) a direction 180º from condition 1, placing the window in the wake of the lander; 3) a direction that places the window 45º to the incident wind, and 4) a no-wind condition, representing free convection. As the wind flows around the lander, a vortex sheds off the edge of the port, which "traps" the cold fluid adjacent to the window and causes a fluctuation of the den-sity gradient near the window. This causes fluctuations in the index of refraction the laser beam propagates through, and causes insignificant beam profile distortions from a nominal Gaussian shape. The density gradients of the atmosphere on the optical window are shown in Figure 1. This figure shows a single "snapshot" in time and the pattern shown varies as the vortex sheds and the flow separates from the window. We have simulated 10 seconds of flow around the window, at a 20 samples per second, to perform the laser beam propa-gation analysis. This represents 2-3 vortex shedding events and provides a reasonable ensemble of flow conditions.

Zemax is an optical design program used to design and analyze optical systems. For this work we employ the Physical Optics Propagation toolset, which represents a multi-mode Gaussian beam as an array of discretely sampled points. The array is propagated through the modeled Venus atmosphere according to accumulated optical phase shifts using a transfer function calculation. This method is superior to geometric ray tracing in cases like ours, in which high-order beams are perturbed by arbitrary phase shifts. Zemax calculates the peak irradiance, and radius of a circle containing 86% of the beam energy at focus. These values are used as the figures of merit to gener-ate a LIBS plasma. For each configuration, the zero-phase condition, the condition where no atmosphere induced change in the index of refraction, is also calculated to directly compare to the perturbed cases.

Discussion: Figure 2 summarizes the propogated laser bean diameter (top) and beam irradiance (bottom) of these theoretical experiments. We compare 2 different beam profiles, Beams 1 and 2, and a single-mode Gaussian beam, Beam 3. The top plot in Figure 2 shows the perturbed spot diameter versus the zerophase spot diameter, or more simply; output diameter versus input diameter. Each of the 4 wind conditions are shown as symbols, and the line through the points represents the average. Notice that all three beams track the Y=X line well, but the higher beam quality results in an offset from the Y=X line. Also note that for the lower quality beams 1&2, there is little difference between the 0.25 and 0.5m focal lengths because minimum spot size is acheived. The bottom plot in Figure 2 also shows that for each beam the peak irradiance is about the same at any given focal length, even though the perturbed spot sizes are different. This change in laser spot size is smaller than the instrumentally limited 250 μm spot size required for a Venus lander instrument. Consequently, the peak irradiance will also decrease due to this observed change in spot size but this will still be driven by the instrument rather than the atmosphere. The results of these analyses demonstrate that a LIBS instrument similar to ChemCam and SuperCam will generate useful laser induced plasmas on every laser shot under Venus surface conditions. These slight changes in irradiance are not enough to degrade the accuracy and precision of compositions determined by a LIBS instrument on Venus.

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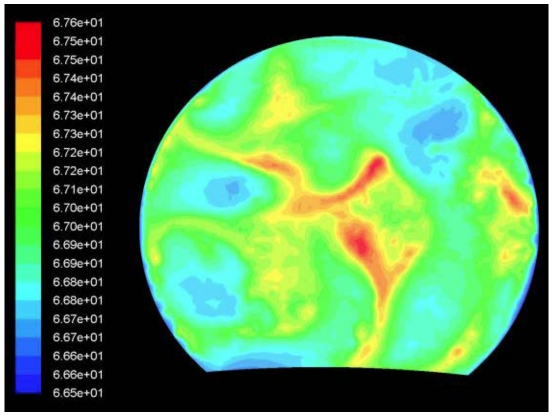

Figure 1 Contours of fluid density on the window. These contours represent a 1.6% change in density.

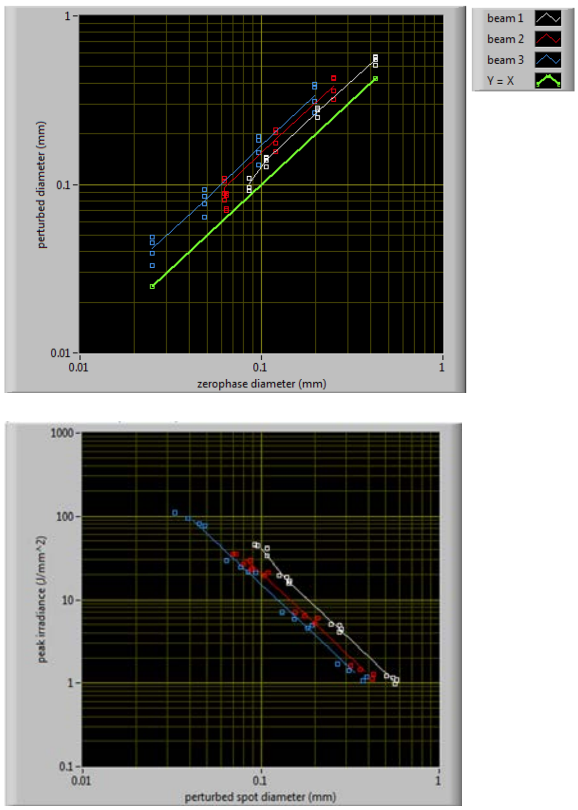

Figure 2 Changes in the spot size diameter (top) and peak irradiance (bottom) produced under Venus surface conditions.

Geological and thermal analysis of VIRTIS images of eastern part of Parga Chasma, Venus.

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Introduction: Venus plays a fundamental role in understanding the evolution of the terrestrial planets [1], and after the Earth, it is one of the best characterized planets, but geological evolution and volcanic activity are poorly understood, yet[2].

The study of these subjects is the principal motivation for the European Space Agency (ESA), and was the main objective of Venus Express mission [2], which specific goals included the measurement of surface emissivity, given that this parameter is key for the understanding of volcanism on Venus and the improving of the acquisition of images in some areas poorly observed by the Magellan mission using the Visual InfraRed Spectral and Thermal Spectrometer (VIRTIS) on board of Venus Express, thus achieving the correlation between the altimetry and the variation in surface brightness [3].

The Magellan images and altimetry data show that the surface of Venus is dominated by a mosaic of obviously volcanic plains that cover about 70-80% of the surface [4]. In addition to this, and thanks to the discovery of atmospheric windows, is possible to measure the surface radiation, with a low atmospheric intervention, using VIRTIS data base.

Working with VIRTIS: The respository contain 95.359 file [5], but just few part of this and available to processes due to the resolution, for this reason, is necessary filter case-by-case the data and use the data of nominal missions.
The file are stored in a structure named data cube (3-dimension matrix) and stored in radiation units [5]. The processes of reading and calibrating the data requires the use of the library created in IDL by ESA.

Parga Chasma: For understand the evolution of Venus is necessary to study one of the most attractive geological zones is the region Parga Chasma, for it extension and large numbers of coronaes. It is a long fracture system in the southern hemisphere of Venus [6]. This is one of the principal branches of the BAT (Beta-Atlas-Themis regions) zone that have been interpreted to be hot spots.

Using IDL library and based on previous work [3][7], but with significant differences that allow the construction of a map of emissivity with information of the eastern part of Parga Chasma, next to Themis Regio.

Taking into account that studies based on VIRTIS, show possible volcanic activity in Themis Regio[8], this work reaffirms that hypothesis and extends the area where there may possibly be active volcanism. and calls into question the surface composition.

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DATA NEEDS FOR LAVA FLOW MODELING ON VENUS. L. S. Glaze[1] and S. M. Baloga[2], [1]NASA Goddard Space Flight Center (Code 690, 8800 Greenbelt Road, Greenbelt, MD 20771; Lori.S.Glaze@nasa.gov), [2]Universities Space Research Associatoin (sbaloga1@starpower.net).

Introduction: Tremendous progress has been made over the last 15 years in modeling lava flows on Mars [1-6]. Much of this progress is directly attributable to high spatial resolution, geodcticaly referenced topography enabled by the Mars Orbiter Laser Altimeter [7, 8]. While much of this work has been focused on levee-forming lava flows, increased sptial resolution imaging combined with topography has also motivated new lava flow modeling studies that explore the fundamentally different emplacement of inflated pahoehoe lova flows [9, 10]. However, improved models such as these require much finer resolution imaging and orders of magnitude improvements in topography over what Magellan currently offers for Venus.

Modeling Requirements: The primary objective of lava flow modeling studies for Mars [1-6, 8-10] has been to place constraints on the lava viscosity as well as the emplacement conditions (volume flow rates, emplacement times, etc.). Typical models, based on the conservation of volume, require detailed estimates of how the dimensions of a control volume (width x thickness) change as a function of distance along the flow (Figure 1).

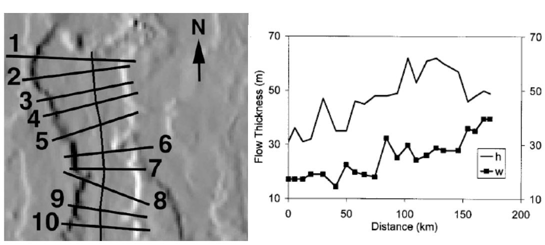

Figure 1. (left) Distal extent of a leveed lava flow north of Pavonis Mons. Numbered transects indicate topographic profiles used to reconstruct the flow width and thickness as a function of distance (right).

Most importantly, the way in which the thickness increases with distance from the vent is directly related to the increase in bulk viscosity and can provide insights into the lava rheology. Other key data required for modeling includes the local slopes and how changes in slope affect dynamics [6].

Analogous modeling of lava flows on Venus is not even conceivable with the currently available data (Figure 2). The first issue is fundamental to the complications of radar images, where individual flow units will appear as a single unit if their radar properties are the same. Thus, it is challenging to even determine the lateral extent of individual flow units. Even if one could determine the widths of individual flow units, the data are restricted to two dimensions. The Magellan radar altimetry data had footprints that >10 kilometers wide (across-track). In the best cases, the along track spacing of the altimeter was ~2 km, but worse in many cases. Because of this extremely large footprint, small features such as lava flows with typical widths of a few to a few tens of km, are smeared and any topographic measurement is unreliable. To further complicate things, the effective range resolution of the Magellan altimeter was ~100 m, making it impossible to identify flows with thickness of a few tens of meters.

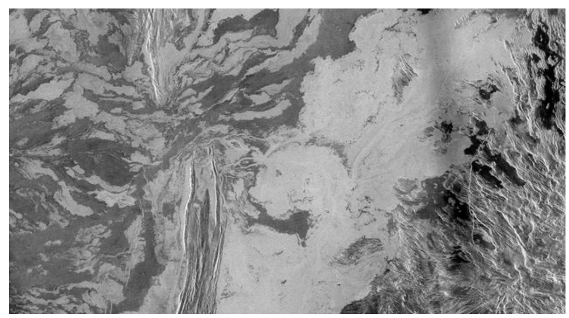

Figure 2. Magellan mosaic of lava flows in the Lada region.

Conclusion: Substantially improved imaging and topography are critical in order to advance our understanding of lava flow emplacement processes on Venus.

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LOW INTENSITY HIGH TEMPERATURE (LIHT) SOLAR CELLS FOR VENUS EXPLORATION.

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Current solar cells do not function effectively in Venus aerial and surface environments, and are not suitable for long-duration Venus aerial missions. In anticipation of objectives in the next decadal survey, the Venus Exploration Analysis Group (VEXAG) has recommended to NASA to develop the required critical spacecraft systems, subsystems and payload instruments that can survive and operate in Venus harsh aerial and surface environments for long duration. Therefore, we have proposed to develop Low Intensity High Temperature (LIHT) solar cells that can function and operate effectively in Venus atmospheric conditions at various altitudes, and survive on the surface of Venus, where the temperature reaches 450-500°C. [1] The projected performance advantages of the proposed LIHT solar cells are that they: a) operate efficiently (> 16%) at high temperatures (i.e., 300°C), b) operate effectively at the low solar intensities characteristic of Venus environments, c) survive and operate in Venus corrosive environments, d) provide long operational capability (> six months) at 25km Venus altitude where temperature is 300°C, and e) survive at Venus surface temperature for more than a month.

The goal is to develop and mature LIHT photovoltaic (PV) technology that will enable and significantly enhance performance, and reduce technical risk, for in situ mission concepts that would explore high-temperature environments with temperatures approaching 500°C or higher. This technology development would expand the range of science that can be achieved at Venus. The high-temperature solar cells developed here would also benefit solar concentrator photovoltaic power systems in terrestrial applications.

We are developing a dual-junction high-temperature GaAs/GaInP solar cell. A detailed schematic of the two-junction solar cell structure is shown in Fig. 1. The novel features of the proposed cell include: a) high bandgap semiconductor materials (GaAs/GaInP), that are optimized to capture solar irradiance efficiently at Venus, b) high-temperature tunnel junctions, c) high-temperature solar cell contacts, d) anti-reflection coatings, and e) Al_2O_3 corrosion protection coatings. This advanced LIHT cell would capture the red-shifted peak of the Venus spectrum in the GaInP layer and the remaining longer wavelengths in the GaAs layer. Layers will be current matched by simple layer thickness modifications to optimally capture the full Venus solar spectrum. This cell will also demonstrate more robust, high temperature electrical contacts that have eluded previous designs. [2] This type of solar cell employs the high-band-gap semiconductor materials similar to state-of-the-art triple junction solar cells. However, this cell does not contain the Ge bottom sub-junction of the current state-of-the-art triple junction solar cells. This modification improves high-temperature performance of the cells.

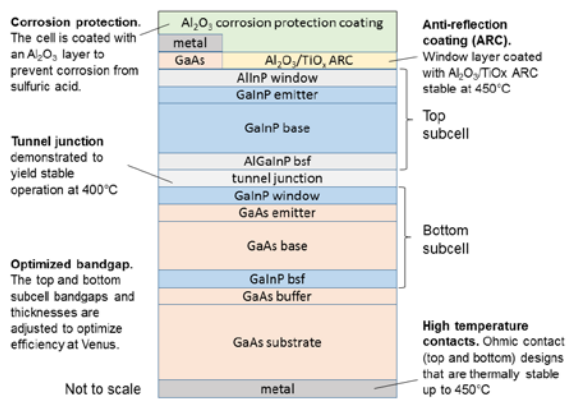

Figure 1: Low Intensity High Temperature (LIHT) Solar Cell designed to survive and provide optimal power in a Venus environment

References:

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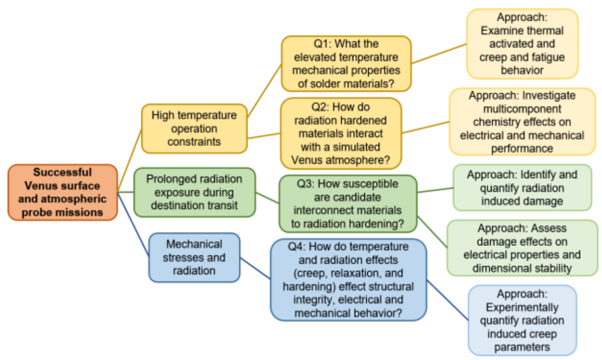
SIGNIFICANCE OF ENVIRONMENTAL VARIABLES ON FLIGHT ELECTRONICS AND DESIGN CONCERNS FOR EXTREME ENVIRONMENTS K. Hazeli[1] and O. Kingstedt[2]. [1]Mechanical & Aerospace Egineering Department, University of Alabama in Huntsville, 301 Sparkman Drive, Huntsville, AL 35899. Email: kavan.hazeli@uah.edu. [2]Department of Mechanical Engineering, University of Utah, 1495 E 100 S, Salt Lake City, UT 84112. Email: o.kingstedt@utah.edu.

Introduction: With high interest levels to send spacecraft and robotic vehicles into extreme environments, such as the surface of Venus and Mercury, or the deep atmospheres of Gas Giants, it is necessary to investigate the performance of electronic systems and their components under the environments experienced during these proposed missions to improve spacecraft and robotic vehicle functionality and predictibility. Extreme environments experienced during a mission tend to be coupled consisting of one or more of the following: high-temperatures, prolonged irradiation, corrosive conditions or high pressures. These conditions give rise to the following questions:

a) What effect does prolonged thermal fatigue have on the mechanical and physical properties such as yield strength, hardness and electrical resistivity of candidate electronic materials?
b) What correlations can be made between radiation exposure doses, dimensional stability and mechanical and physical properties?

Present State of Knowledge: A range of work has been conduct to improve the compatibility of electrical systems with high-temperatures and radiation environments. Semi-conductors such as silicon carbide (SiC) and gallium nitride (GaN) have been identified as potential electronic materials for extreme temperature conditions. A recent demonstration showed successful operation of a SiC transistor at 500ºC for 1000 hrs of operation [1]. Progress has also been made in the development of electronic devices, resistors and capacitors on high-temperature tolerant substrates [1]. Significant effort has also gone into the development of radiation tolerant components. Currently, components capable of sustaining 300 krads total integrated dose (TID) and some up to 1 Mrad TID are readily available [2]. However, a remaining challenge, to be discussed here, is the identification of optimized electronics microstructure for operation at combined high temperature, radiation and corrosive environments.

Knowledge gaps for electronic materials intended for use in extreme environments: Figure 1 summarizes a sequence of conditions that a spacecraft may encounter during a mission to locations targeted in the most recent decadal survey, and emphasizes knowledge gaps associated with the performance of electrical components in those environments. For optimal tolerant material design to be accomplished, the accumulation of effects imposed by individual and combined environmental variables must be thoroughly considered. Markedly absent in literature, are studies that address the combined effects of the environmental conditions (temperature, radiation, high-pressure, corrosive environment) on the mechanical and electrical properties of the materials used in flight electronics.



Summary: This presentation discusses a systematic experimental and modeling framework that will permit the investigation of microstructural defects and processes associated with mechanical and electrical degradation of aerospace electronic materials under conditions that mimic those experienced during operation in extreme environments encountered in terrestrial and space exploration. Specific environments to be explored in this study simulate the surface of Venus and Mercury, and gas-giant atmospheric entry. The primary focus is to investigate high temperature electronic materials under elevated temperature aging, thermal fatigue, energetic particle radiation, and corrosive environments. For each condition the origins of defect formation and evolution will be monitored to quantify the density, morphology and distribution of the defects with respect to thermal stresses, applied voltage, temperature, and radiation doses.

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VENUS GEOLOGICAL HISTORY: CURRENT PERSPECTIVES, UNKNOWNS, AND OPPORTUNITIES FOR THE MODELING COMMUNITY. James W. Head, Department of Earth, Environmental and Planetary Sciences, Brown University, Providence, RI 02912 USA (james_head@brown.edu)

Introduction: Acquisition of Earth-based radar image observations, followed by regional image coverage (Venera 15/16) and finally global image coverage by Magellan, together with global altimetry, have provided the data necessary to analyze stratigraphic relationships and produce a global geological map of Venus [1]. The resulting stratigraphic column provides an outline of the major themes in the geological evolution of Venus in terms of fundamental processes such as tectonism [2] and volcanism [3]. The paucity of superposed and embayed impact craters and the impression that they are randomly distributed precluded the traditional counting of superposed craters on individual geological units to derive an impact crater size frequency distribution-based absolute chronology. The recent utilization of techniques of buffered crater counting and related methods has recently provided a basis for linking the sequence of events in the geology/stratigraphy to an absolute chronology [4]. We now have an interpretative framework for the geologic history of Venus that can be used as a basis for identifying outstanding questions and applying a wide range of modeling techniques to address these questions.

The geological history of Venus can be characterized by three basic consecutive phases (Fig. 1): **Phase I** represents the period prior to the formation age of the geomorphological/geological units on the surface (the pre-Fortunian Period) and occupies the majority of the history of Venus. Although some rocks comprising the oldest observed preserved unit, the tessera, could date from this era, the observed geologic record starts with Phase II. **Phase II** is comprised of two regimes, an initial *global tectonic regime* which begins with the intense tectonic deformation (the Fortunian Period) interpreted to have formed the globally distributed tesserae highlands of thickened crust that comprise about 7.3% of the planet, followed by many tectonic structures in the surrounding highly deformed plains, including ridge belts, groove belts and coronae. The second regime in Phase 2, the *global volcanic regime*, starts with the emplacement of volcanic plains dotted with thousands of small shield volcanoes, and is immediately followed by regional plains interpreted to have been emplaced as flood basalts in lows between the tesserae highlands, and then deformed by wrinkle ridges. The shield and regional plains comprise 61.3% of the surface of Venus. Thus, the vast majority of the observed surface geologic units on Venus (80.7%) formed over a relatively short period of time (the Fortunian and Guineverian Periods), estimated to have lasted less than several hundreds of millions of years. **Phase III** represents a distinctive change in style, an extended period of global network rifting (the Atlian Period), with rift zones often radiating from topographic rises; volcanism continues (perhaps to today [5]), but is primarily characterized by lobate lava flows associated with the rifts (the *network rifting-volcanism regime*). In summary, the geological record consists of the majority of history that leaves no geological/geomorphological record (Phase I), followed by Phase II, a period of intense global tectonic deformation followed immediately by global shield plains and regional plains volcanically resurfacing over 60% of the planet, followed by Phase III, relative quiescence and development of a global rifting system linking several broad rises. The last two phases occurred in less than the last ~15-20% of the history of Venus.

This scenario presents multiple major challenges to various modeling communities: internal structure and evolution, mantle convection, thermal evolution, geodynamic, geochemical, petrogenetic, atmospheric origin-dynamics-geochemistry-evolution, ionosphere, solar system formation and evolution. We outline these here.

Planetary Perspectives: What phases of typical terrestrial planet evolution (e.g., accretion, satellite acquisition and loss, core formation, crustal segregation/growth/aftermath, magnetic field evolution, volatile acquisition and degassing to form atmosphere/oceans, impact flux and basin formation, mantle and lithospheric evolution, ionospheric structure and evolution, influence of solar and interplanetary environment) can be established, modulated or ruled out from our knowledge of Venus? If Venus transitioned from an Earth-like planet to its current state, when, over what time period, and how did this take place? What is the cause of Venus' slow retrograde rotation? Could Venus have undergone true polar wander? What is the explanation for the lack of a detectable magnetic field? What can evolutionary models say about the presence and fate of a moon(s)? What do solar system evolution models tell us about the initial position and residence time of Venus relative to its current position in the Solar System? What do spin-axis, orbital parameter (e.g., obliquity, eccentricity) evolution models tell us about the evolution of Venus? How can Venus' geologic history models inform us about how plate tectonics might have initiated Earth? How do Venus and Earth fit into the context of new models of exoplanetary system formation and evolution?

Interior Evolution, Mantle Convection and Geodynamics: Venus appears to have undergone a relatively recent distinctive global tectonic phase, followed by a near global volcanic phase, a significant reduction in volcanic flux, followed by an extended rift-dominated phase of tectonism and volcanism. What is the relative role of Pratt, Airy and flexural isostasy in accounting for the current topography of Venus? What are the more detailed, testable predictions of models of the transition from mobile lithospheric lid to stagnant lid regimes? Can geodynamic models explain the observed near-global flood basalt phase following tessera formation? What geodynamic and petrogentic models can account for the near-global distribution of small shield volcanoes? What coupled geodynamic/petrogenetic models can account for the apparently very viscous magma represented by the steep-sided domes and festoons? How can mantle convection and geodynamic models account for both global small shield volcanoes (<~20 km) and global large shields (>~200 km)? What temperature-dependent crust-mantle viscosity structure seems most consistent with the geological features and evolution? How can geodynamic models distinguish between episodic global resurfacing and a one-time mobile-lid to stagnant lid transition? What does the global and temporal distribution of coronae and large shield volcanoes tell us about mantle convection patterns and the thermal evolution of the lithosphere? Is Venus currently volcanically active? Where and why? Can the current cratering record reveal information about changes in the evolution of CO_2 atmospheric pressure? How can impact flux modeling and observations improve the chronology of Venus' recent geologic history? What does the configuration of the late stage global rift systems tell us about recent mantle convection patterns?

Surface Evolution and Relation to Atmosphere and Interior: What was the nature of the global event that produced the tessera terrain? Was it truly global and what was the duration of this event? What do models of atmospheric evolution and climate change predict about the influence of the thermal structure of the crust and lithosphere how changes could be reflected and recognized in the style of tectonic deformation? What explains the common correlation of coronae and rift zones? Are coronae causing rifting, or is rifting inducing upwelling? On the basis of comparative planetology modeling, what is the most plausible scenario for the nature and fate of water and oceans in earlier Venus history? How can impact cratering hydrocode models increase our understanding of crustal and mantle structure and evolution? How can impact cratering hydrocode models inform us about the influence of major impact events on the atmosphere? How can physical volcanology models explain the apparent dearth of pyroclastic deposits? How can volcanic eruption and impact crater ejecta modeling link Venera lander panoramas to global processes?

Ionosphere, Atmosphere, Climate and Hydrosphere: What are the most plausible current models for the history and evolution of the climate of Venus? What was the nature of the evolutionary transition to the current atmosphere? Was it gradual, or did the apparently short-term global phase of tectonism and volcanism mark an evolutionary step-function? How do variations in the solar wind over the short term and geologic time influence the atmosphere and atmospheric loss rates? What are the loss rates of water and other volatiles from the Venus upper atmosphere to space? What are the loss rates of volatiles to the surface through chemical reactions and how did these change with time? Did Venus have an ocean and if so, what was its magnitude, duration and fate? How can impact crater ejecta patterns further inform us about atmospheric vertical structure, global circulation, and evolution? What atmospheric models best predict the unique surface properties of the highest Venus elevations? How can the eolian alteration of impact crater ejecta inform us about atmospheric evolution? What do atmosphere chemistry models predict about surface weathering and can this be recognized in the Venera panoramas or global surface properties?

Conclusions: Observations from space mission to Venus over the last 55 years have established a substantial database of knowledge and raised significant new questions. Modeling from a wide range of communities to address a host of outstanding questions can lead to important new insights in the coming decades.

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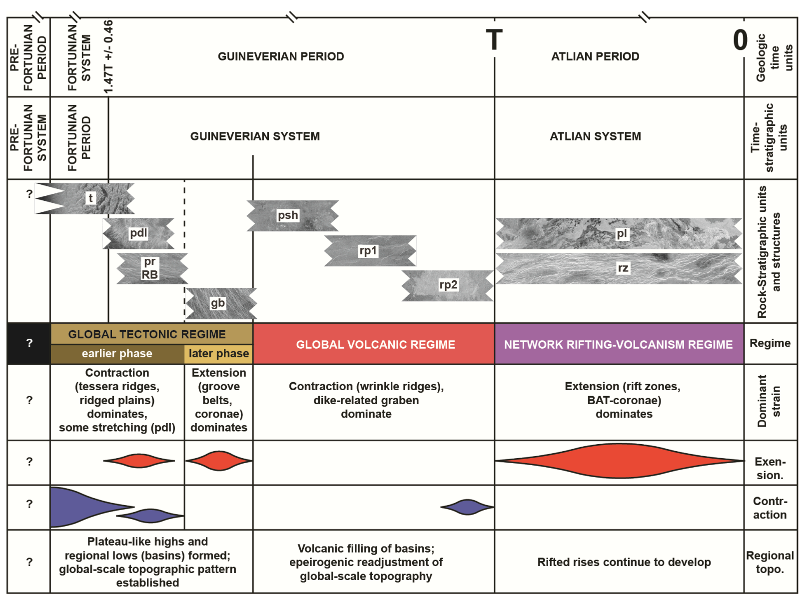

Figure 1. Stratigraphic units, sequence and timing of the geological history of Venus [1-3].

LABORATORY VENUS ANALOG SPECTRA FOR ALL ATMOSPHERIC WINDOWS. J. Helbert[1], A. Maturilli[1], M. D. Dyar[2,3], S. Ferrari[4,1], N. Müller[5], S. Smrekar[5], [1]Institute for Planetary Research, DLR, Rutherfordstrasse 2, 12489 Berlin, Germany (joern.helbert@dlr.de), [2] Planetary Science Institute, 1700 East Fort Lowell, Tucson, AZ 85719, [3] Dept. of Astronomy, Mount Holyoke College, South Hadley, MA 01075, [4]Dept. of Earth and Environmental Sciences, University of Pavia, Via Ferrata 1 - 27100 Pavia, Italy, [5]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena CA, 91109.

Introduction: Interpretation of VNIR spectroscopy data from orbiters is known to require spectral libraries acquired under conditions matching those on the surfaces being studied. This is particularly true for Venus, which has extreme conditions on the surface: 460°C and 93 bars and a dense, CO_2-rich atmosphere. The permanent cloud cover of Venus prohibits observation of the surface with traditional imaging techniques over most of the visible spectral range. Fortunately, Venus' CO_2 atmosphere is transparent in small spectral windows near 1 μm. Ground observers have successfully used these, during the flyby of the Galileo mission at Jupiter, and most recently by the VMC and VIRTIS instruments on the ESA VenusExpress spacecraft. Observations have revealed compositional variations correlated with geological features [1-6].

In particular, the spectral region near 1 μm fortuitously permits acquisition of several channels of information where most Fe and transition metals in minerals have absorption bands, making interpretations about the redox state and transition metal contents of the surface possible [7]. Such analyses rely on a solid foundation of 1aboratory data acquired at high T only. As explained in [8], it is not necessary to mimic the surface pressure in such databases because the effects of the increased P on spectra are comparatively benign compared to measurements of mantle pressures with only slight pressure effects are observed in olivine and pyroxene [9,10]. Thus the primary spectral changes will result from T.

Accordingly, we describe here the start of a spectral database for Venus analog materials. For the first time, the community has access to spectra obtained in emission, covering the spectral range from 0.7 to 1.2 μm (and beyond) and obtained at typical Venus surface temperatures of 460°C.

The Planetary Emissivity Laboratory (PEL): This project builds on several years of development at the Planetary Spectroscopy Laboratory (PSL) at DLR [11-13]. PSL successfully acquired funding from the European Union as part of the EuroPlanetRI consortium to extend the spectral coverage for high temperature measurements down to 0.7 μm.

PSL operates two Bruker Vertex 80V spectrometers, one installed in 2006 and recently upgraded and one acquired in 2015. The laboratory is located in a temperature-controlled room at the Institute for Planetary Research in Berlin. Both spectrometer are located on an optical table equipped with external chambers for emissivity measurements (**Figure 1**). The recently upgraded Vertex 80V is optimized for the near to far-infrared spectral range.

The unique feature of the PSL is a high-temperature chamber attached to the upgraded Vertex 80V that allows heating of samples to temperatures up to 1000K under vacuum conditions (medium vacuum - 10-100Pa) [14]. Samples are placed in steel cups equipped with type K thermopiles as temperature sensors. A copper induction coil installed in the chamber is connected to a Linntherm 1.5kW induction system to permit contactless heating of the ferromagnetic sample cups by induction. Spectral coverage is achieved with a combination of a liquid nitrogen-cooled MCT detector and KBr beamsplitter for the spectral range up to 16 μm and a DTGS detector with a multilayer beamsplitter for the remaining spectral range.

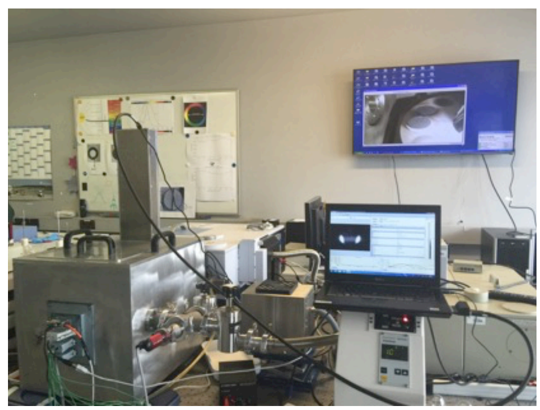

Figure 1. New setup at the Planetary Spectroscopy Laboratory (PSL) – including Venus Emissivity Mapper (VEM) prototytpe on the auxiliary port of the chamber [15].

The EuroPlanetRI financed upgrades accomplished in 2015-2016 include the new InGaAs detector with matching beamsplitter, an upgrade of the spectrometer electronics and an optimization of the optical layout in the chamber.

Laboratory experiments: Measuring emissivity at 1 μm at Venus analog temperatures is already very challenging for many reasons. As an example the emissivity of stainless steel increases strongly towards shorter wavelength at high temperatures. This results in a non-negligible contribution to total radiance from our sample cups. At the same time, many natural materials have a high transparency at 1 μm. To address this issue we have developed a ceramic enclosure (**Figure 2**) for

Figure 2. Newly developed ceramic enclosure for stainless steel sample holder for slab and granular samples.

the stainless steel that suppresses the radiation from the sample cups.

After extensive testing, the new setup at PSL for Venus analog measurements has been demonstrated to perform following our requirements. It is stable and produces reproducibility results. Therefore, we froze the design at the end of 2016 as our standard set-up for emissivity measurements of Venus-analogue samples in the visible spectral range.

Venus analog database: As a starting point for the database we obtained measurements of eight samples covering a range from felsic to mafic samples. This first set already shows that despite the limited number of available spectral channels, we will be able to map surface mineralogy from orbit with instruments like the Venus Emissivity Mapper [7, 15] (**Figure 3**).

Conclusions: Work in progress at the Planetary Emissivity Laboratory is laying the groundwork for a collection of a spectral library for rocks and minerals under Venus conditions. Once acquired, these data will be key in understanding and modeling differences in emissivity between ambient and Venus conditions, potentially enabling calibration transfer between datasets.

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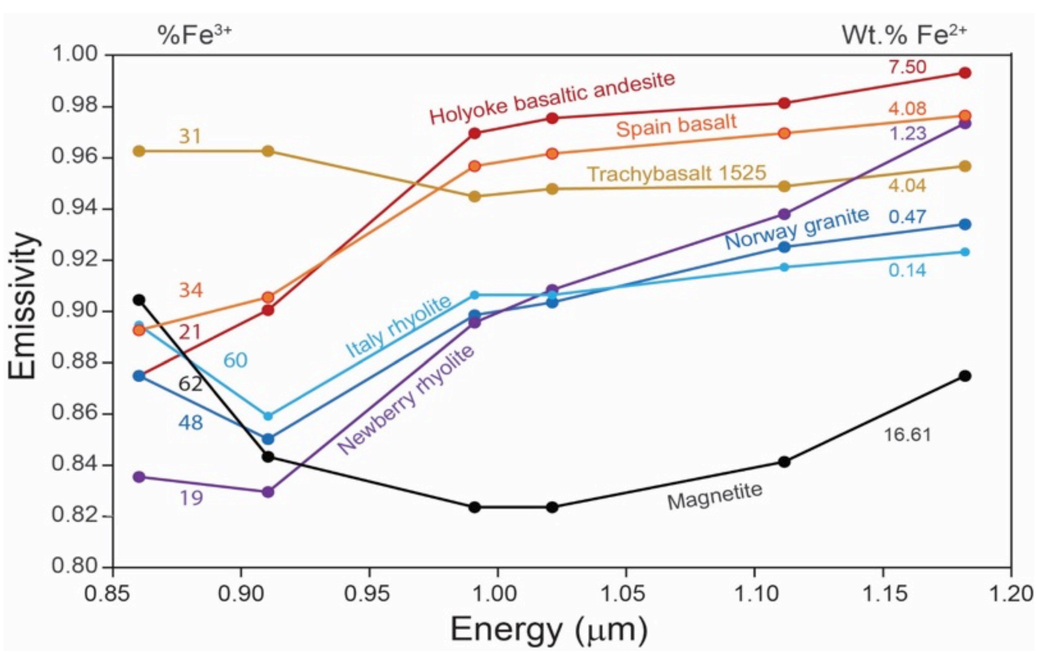

Figure 3. Spectra of Venus analog sample at all known atmospheric surface windows of Venus. Samples represent a suite of crustal differentiation and thus different Fe and Si concentrations. Additional spectral analysis techniques allow for robust identification of subtle spectral differences.

Variations in Venus Atmosphere Variability and Implications for SAR Interferometry at X-band. S. Hensley[1], C. Tsang[2], D. Arumugam[1], X. Duan[1], S. Smrekar[1] and P. Lundgren[1], [1]Jet Propulsion Laboratory, California Institute of Technoloy, 4800 Oak Grove Drive, Pasadena, CA 91109, shensley@jpl.nasa.gov, [2]Southwest Research Institute, 6220 Culebra Rd, San Antonio, TX 78238.

Introduction: High resolution radar imagery and topography are integral components to understanding how Venus evolved to its present state and in comparative planetology studies and its broader implications to exoplanet formation. The thick Venus atmosphere has implications for SAR missions particularly those planning on using radar interferometric techniques. Using a modified version of the complex permivity of the Venus atmosphere model described in [1] we quantify the sensitivity in magnitude and phase of radar measurements of the surface to variations in gas concentrations and temperature and pressure profiles of Venus atmosphere. We examined the impact of these variations both on single pass and repeat measurements used to measure topography and surface deformation respectively. We show that based on measured gas variations that both single and repeat pass measurements at X-band like those for the proposed VERITAS mission are viable [2].

Atmosphere Model: There is considerable heritage in the modeling of the Venus atmospheric composition and propagation of microwaves through the atmosphere. The simple formula used for estimating the absorption of the Venus atmosphere at microwave frequencies is $A = 0.0553*f^2/\cos(\theta)$ where A is attenuation in dB, f is in GHz, and θ is the incidence angle. This expression was derived from a more elaborate absorption model at nadir look angle, and neglects ray refraction. A more accurate model is described in Appendix A of [3] - it is a layered model using Snell's law for the ray path and models for absorption of each of the main absorbers.

The work in [1] models the complex permittivity profile of the Venus atmosphere as a function of altitude. The real part of the permittivity is obtained through its relation with the total atmospheric polarization; the imaginary part is derived from the total atmospheric absorption. Both the total polarization and the total absorption of the Venus atmosphere are modeled based on the atmospheric temperature profile [3], [4] pressure profile [3], and density profile [3]. The model of total atmospheric polarization takes into account the composition profiles of the major gases CO_2, N_2, Ar, He, Ne, H_2O, SO_2, H_2SO_4, CO and OCS as well as the H_2SO_4-H_2O clouds and the ionosphere. The total atmospheric absorption includes the absorption from the major gases CO_2 and N_2 and the minor gases Ar, H_2O, SO_2, H_2SO_4 and OCS as well as the H_2SO_4-H_2O clouds. The 2-way atmospheric attenuation, $L_{atm}(h)$, is well approximated by the quadratic polynomial $L_{atm}(h)=0.0174h^2–0.6564h+9.5072$ where h is the height in km relative to the 6051 km sphere and $-3\leq h\leq 12$ km which varies between 4 and 11.5 dB for f=7.9 GHz. A brief discussion of atmospheric effects was given in [5]; they however omitted some key considerations affecting the impact of the atmosphere to phase noise.

Sensitivities to Gas Variations: Propagation-induced range and phase delay sensitivities to gas variations are estimated using the Venus atmosphere model described in [1]. Table 1 summarizes the percent change in SO_2, H_2O, H_2SO_4, CO, CO_2 and N_2 variability that would yield a 1 m elevation error for Single Pass Interferometry (SPI) (global scale), and a 1 cm deformation error for RPI (~200 km local scale).

Sensitivities to Temperature and Pressure Profiles: We modified the the nominal Venus temperature and pressure profiles [3] with a linear delta temperature and exponential delta pressure profiles and computed for variations more than 10 times larger than the measured varaitions. Attenuation values varied by less than 0.3 dB and gas variations dominate the phase variations.

Single Pass Interferometry (SPI): Results indicate that global atmospheric variability has no significant impact on SPI measurements (only CO_2 and N_2 are significant with expected range variation of ~1 m) as shown in Table I (blue highlights) showing the sensitivity to gas variations corresponding to 1 m of elevation error for a VERITAS type radar [2].

Repeat Pass Interferometry (RPI): At the local ~200 km scale SO_2 variations dominate RPI deformation error. Although the global mean SO_2 value derived from remote sensing measurements is 130 ± 50 ppmv (30-40% variability) [6, 7], at the ~200 km scale (2° of latitude), we conservatively estimate 9% variability, resulting in a predicted RPI deformation error of 1.5 cm as inferred from (red highlight) in Table I.

As compared to terrestrial volcanoes, those on Venus are expected to exhibit similar magma-chamber depths. Topography and elevation play a role in modulating the depth, the size, and whether or not reservoirs occur at depths of neutral buoyancy [8] although other factors such as melt supply rates and external stresses can play important roles in planetary emplacement or eruption [9], [10]. Lithospheric thickness is not well constrained on Venus. Studies using the higher-

Table I. *Gas Sensitivities*

Gas	$\frac{\partial \rho_a}{\partial g_f}$ (m/Δ%)	Estimated Global/Local Variability (Δ%)	RPI Deformation (Δ%=1 cm Error)	SPI Topography (Δ%=1 m Error)
SO_2	1.64×10^{-3}	30-40 / ~9	6.10	704
H_2O	2.22×10^{-4}	10-30 / <8	45.1	5201
H_2SO_4	3.95×10^{-6}	100 / 25	2532	292329
CO	2.03×10^{-5}	15-50 / <12	493	56882
CO_2	1.87	<0.8/NA	NA	0.6
N_2	4.04×10^{-2}	<5/NA	NA	28.6

resolution stereo topography support lower lithospheric thickness for smaller features, [11].

We simulated the vertical displacement for 30 Mogi sources with depths varying from 3-24 km and volume changes varying from 1-48x10^6 m^3 that have peak displacements as shown in Table 2.

Table 2. *Peak displacement (cm).*

Depth (km)	ΔV ($\times 10^6$ m^3)					
	1	**3**	**6**	**12**	**24**	**48**
3	2.7	7.9	15.9	31.8	63.7	127.3
6	0.7	1.9	3.9	7.9	15.8	31.8
12	0.2	0.5	1.0	1.9	3.9	7.9
18	0.1	0.2	0.4	0.8	1.8	3.5
24	0.0	0.1	0.3	0.5	1.0	1.9

Figure 3 shows simulated fringe patterns for these 30 sources over a spatial scale of 40x40 km with atmospheric distortion based on 9% SO_2 spatial variability at 200 km length scales and a Kolmogrovov atmosphere. ΔV is increasing horizontally across the figure and increasing depth is vertically down the figure.

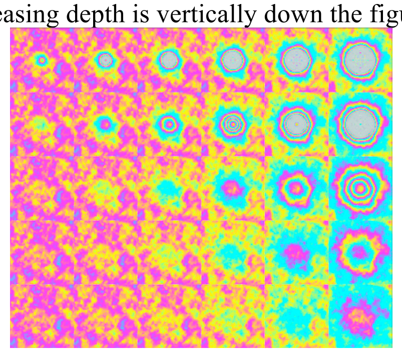

Figure 3. *Fringe patterns for 30 Mogi point sources with atmospheric distortion 2 having depths increasing down the figure and ΔV increasing across the figure corresponding to the values in Table 2.*

Shallower sources and greater delta volumes give the most visible signature above the atmospheric distortion. We then examined the signals in Figure 3 to see which could be discerned from the background noise by visual inspection and noted whether the signal was detectable or not. Note, detection at the edge of visibility could go either way and would require geologic and other context to adjudicate.

Figure 4 shows a plot of the detectable and undetectable Mogi source deformation signals as function of depth and volume change. The depth range represents the full range, 0-35 km, estimated by [12]. Detectable signals are denoted with green dots and undetectable signals with red dots. The blue corresponds to depth and delta-volume combinations that result in 2 cm of peak deformation (1 fringe). Signals at this level are detectable, while those below this level are not comparable to Earth observations.

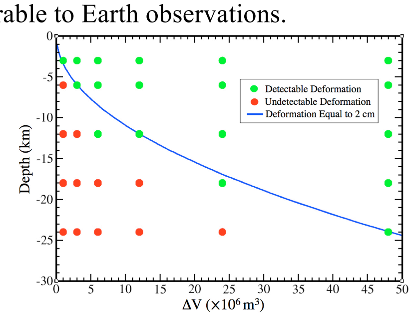

Figure 4. *The blue line shows depth and ΔV Mogi sources that yield 2 cm of peak deformation (one fringe for VERITAS radar). From 3, deformation signals above or near the detectability limit are shown with green dots and those obscured by the atmospheric distortion are shown in red. Deformation levels exceeding one fringe (or 2 cm) are visible, while those below this threshold are not.*

Acknowledgement: This research was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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Thermodynamic Modeling of the Lower Venusian Atmosphere. N. S. Jacobson[1], M. J. Kulis[2], B. Radoman-Shaw[3], R. Harvey[4], D. L. Myers[5], L. Schaefer[6], and B. Fegley, Jr.[7], [1]NASA Glenn Research Center, Cleveland, OH 44135, nathan.s.jacobson@nasa.gov, [2]NASA Glenn Research Center, Cleveland, OH 44135, michael.j.kulis@nasa.gov, [3]Case Western Reserve University, Cleveland, OH 44106, bgs21@case.edu, [4]Case Western Reserve University, Cleveland, OH 44106, rph@case.edu, [5]East Central University, Ada, OK 74820, dmyers@ecok.edu, [6]Arizona State University, Tempe, AZ 85281 lschaefer@asu.edu, [7]Washington University, St. Louis, MO 63130, bfegley@alum.mit.edu.

Introduction: The lower Venusian atmosphere is the region from the surface to the cloud deck, which is approximately 0-50 km. Typically this has been modeled with chemical kinetics [1]. Only the lowest ~10 km have been modeled with thermodynamics. However this gives the result that sulfuric acid and hydrated sulfuric acid are thermochemically unstable and can only be photochemically 'forced' to form. In this study, we introduce an increasing oxygen gradient from the surface to the cloud layer. This gradient is very small and within the experimental error of the oxygen atom content of the atmosphere, yet it makes sulfuric acid thermodynamically stable within the cloud layer.

Procedure: First we used the nominal composition of the Venusian atmosphere, given in Table 1 [2], and converted this to atoms.

Table 1. Nominal composition of the Venusian atmosphere [2].

Gas	Abundance	Elevation
CO_2	96.5 ± 0.8%	
N_2	3.5 ± 0.8%	
SO_2	150 ± 30 ppm	22-42 km
H_2O	30 ± 15 ppm	0-45 km
Ar	70 ± 25 ppm	
CO	30 ± 18 ppm	42 km
He	12 ± 8 ppm	
Ne	7 ± 3 ppm	
OCS	4.4 ± 1 ppm	33 km
H_2S	3 ± 2 ppm	< 20 km
HDO	1.3 ± 0.2 ppm	
HCl	0.6 ± 0.12 ppm	Cloud top
Kr	~25 ppb	
S_n (n=1-8)	20 ppb	
HF	5 ppb	Cloud top
Xe	~1.9 ppb	

The oxygen gradient is derived from the SO_2 gradient measured by the Vega 1, 2 probes [3]. Although controversial, the Vega 1, 2 measurements are among the only data we have at low elevations. Possible sources and sinks for oxygen in the clouds and surface, respectively will be discussed. Using the VIRA profile [4] to specify the temperature and pressure at each elevation. A free-energy minimizer is used to calculate the equilibrium composition of the atmosphere with and without the oxygen gradient every 1 km from 0-52 km [5].

Results: Results are presented as plots of elevation vs ppm for the gases H_2O, CO, OCS, H_2S, S_n, and H_2SO_4. These are compared to the available observations. The H_2O calculations and the H_2SO_4 observations show good agreement with observations. The OCS, H_2S, and S_n show only limited agreement. The CO calculations do not match the observations suggesting that the thermodynamics alone does not adequately describe the formation of this species.

Here we show the results for H_2SO_4 (Figure 1). Our calculations match the radio occulation measurements of Jenkins and Steffe [6]. We also determine the point at which H_2SO_4 liquid first appears to be 51 km, reasonably close to the measured cloud layer elevation of 48 km. We suggest the autocatalytic effects of H_2SO_4 contributes to the attainment of equilibrium near and in the cloud layer.

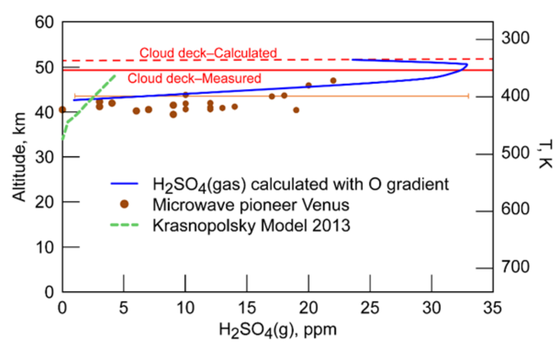

Figure 1. H_2SO_4(g) in the lower Venusian atmosphere.

References: [1] Krasnopolsky, V. A. (2007), *Icarus* 191(1), 25-37. [2] Lodders, K. and Fegley Jr., B. (1998), *The Planetary Scientists Companion*. Oxford Univ Press, NY. [3] Bertaux, J. L. et al. (1996), *J. Geophys. Res.: Planets* 101(E5), 12709-12745. [4] Seif, A. (1985), *Adv. Space Res.* 5(111), 3-58. [5] Bale, C. W. et al. (2002), *Calphad* 26(2), 189-228. [6] Jenkins, J. M. and Steffes, P. G. (1991), *Icarus*, 90(1), 129-138.

VENUS GLOBAL REFERENCE ATMOSPHERIC MODEL STATUS AND PLANNED UPDATES.
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Introduction: The Venus Global Reference Atmospheric Model (Venus-GRAM) was originally developed in 2004 under funding from NASA's In Space Propulsion (ISP) Aerocapture Project to support mission studies of the planet. Many proposals, including NASA New Frontiers and Discovery, as well as other studies have used Venus-GRAM to design missions and assess system robustness.

After Venus-GRAM's release in 2005, several missions to Venus have generated a wealth of additional atmospheric data, however few model updates have been made to Venus-GRAM. This paper serves to address three areas: (1) to present the current status of Venus-GRAM, (2) to identify new sources of data and other upgrades that need to be incorporated to maintain Venus-GRAM credibility and (3) to identify additional Venus-GRAM options and features that could be included to increase its capability. This effort will depend on understanding the needs of the user community, obtaining new modeling data and establishing a dedicated funding source to support continual upgrades. This paper is intended to initiate discussion that can result in an upgraded and validated Venus-GRAM being available to future studies and NASA proposals.

Background: Venus-GRAM is an engineering model of the atmosphere. While it does not allow for predictive forecasting capability, it does provide mean density, temperature, pressure and wind components at any height from 0 to 1000 km. The model also allows the simulation of random perturbations about the mean. This is sufficient for mission planning and system analysis.

Currently the lower atmosphere model in Venus-GRAM (up to 250 km) is based on the Venus International Reference Atmosphere (VIRA) [1]. The Venus-GRAM thermosphere (250 to 1000 km) is based on a MSFC-developed model [2]. In the lowest altitudes (below 100 km) the VIRA model only depends on latitude. In the middle altitudes (100 to 150 km) the VIRA model only depends on local solar time. At high altitudes (150 to 250 km), VIRA only depends on solar zenith angle. The MSFC-developed thermosphere model assumes an isothermal temperature profile initialized using VIRA conditions at 250 km [3]. The original version of VIRA that is included in Venus-GRAM included Pioneer Venus Orbiter and Probe data as well as Venera probe data, but it did not include a solid planet model, nor a high resolution gravity model [4].

New Sources of Data: There are several additional Venus atmosphere models and data sources available that can be utilized to update Venus-GRAM. First, work to update the VIRA model has been ongoing. Second, Earth observation data of Venus extends two decades. Third, Venus Express has collected nearly a decade of data at the planet. Fourth, Magellan data of the surface and gravity field are available. Fifth, the development of a Venus Global Ionosphere-Thermosphere Model (V-GITM) will be of benefit to future versions of Venus-GRAM.

Identifying and collecting available data is only the first part of the task for updating Venus-GRAM. Developing methods to assimilate or incorporate this data into Venus atmosphere models as well as Venus-GRAM will be needed. Verification of the model performance using this data is also necessary to verify Venus-GRAM credibility

Model Capability: Additional capability can also be included in Venus-GRAM. For example, Venus-GRAM is in the process of being upgraded from Fortran to C++. Object oriented code offers additional options not previously available. GRAM developers are also interested in hearing from the user community to identify high priority items that would enable mission modeling that is not currently available. One example would be to include a higher resolution topography model for probe mission analysis.

Looking Ahead: NASA has released the 2016 New Frontiers Announcement and there is also scheduled to be a 2018 Discovery Announcement. Both calls include Venus as a target destination. Sustained funding opportunities are being sought and are necessary to maximize the contribution that updates to Venus-GRAM can make to the mission planning phases of proposals. Additionally, NASA is interested in bringing together atmospheric modelers, GRAM users and GRAM developers to identify high priority tasks for GRAM improvements. This forum will provide an opportunity to gain insight from the Venus modeling community.

References: [1] Kliore, A.J., V. I. Moroz, and G. M. Keating, editors, (1985): "The Venus International Reference Atmosphere", Advances in Space Research, vol. 5, no. 11, pages 1-304, Pergamon Press, Oxford. [2] Justh, Hilary L., C. G. Justus, and Vernon W. Keller, (2006): "Global Reference Atmospheric Models, Including Thermospheres, for Mars, Venus and Earth," Paper AIAA- 2006-6394, AIAA/AAS Astrodynamics Specialist Conference & Exhibit, 21-24 August, Keystone, CO. [3] Guide to Reference and Standard Atmosphere Models; BSR/AIAA G-003-2010. [4] Limaye, S.S., "International Venus Reference Models Research and Mission Design" VEXAG March 21, 2012.

Comparative Planetology: Seeking the Twin of Earth's Twin. S. R. Kane[1], [1]Department of Physics & Astronomy, San Francisco State University, 1600 Holloway Avenue, San Francisco, CA, 94132, skane@sfsu.edu.

Introduction: The field of exoplanetary science has seen a dramatic improvement in sensitivity to terrestrial planets over recent years. Such discoveries have been a key feature of results from the Kepler mission which utilizes the transit method to determine the size of the planet. These discoveries have resulted in a corresponding interest in the topic of the Habitable Zone (HZ) and the search for potential Earth analogs. For example, a major product of the Kepler mission is a list of HZ exoplanet candidates from the Kepler Data Release 24 Q1-Q17 data vetting process [1]. We use a variety of criteria regarding HZ boundaries and planetary sizes to produce complete lists of HZ candidates, including a catalog of 104 candidates within the optimistic HZ and 20 candidates with radii less than two Earth radii within the conservative HZ.

However, within the Solar System we observe a clear dichotomy between Venus and Earth in terms of atmospheric evolution, likely the result of the large difference in incident flux from the Sun. Since Venus is 95% of the Earth's radius in size, it is impossible to distinguish between these two planets based only on size. In this talk I will present the latest results in the search for terrestrial-size exoplanets and the diversity of their sizes and orbital parameters. I will discuss planetary insolation in the context of atmospheric erosion and runaway greenhouse limits for planets similar to Venus. Using the ``Venus Zone'' (VZ), I will present identified potential Venus analogs from Kepler data and subsequent occurrence rates of such planets. Finally, I will discuss the general comparative planetology that is evolving from exoplanet characterization and the potential of future missions to use atmospheric signatures to distinguish between Earth and Venus analogs.

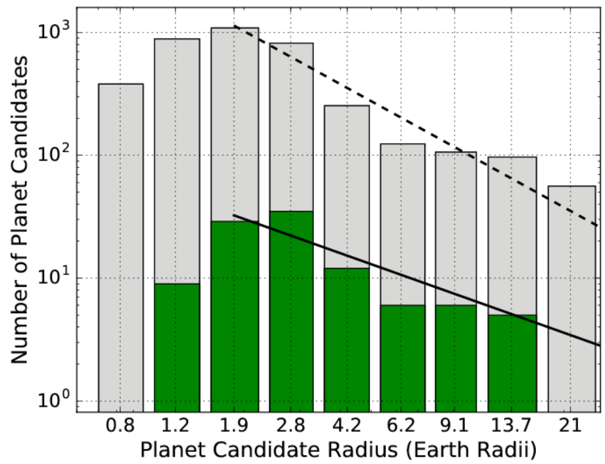

Fig. 1 - Histogram of all Kepler candidate radii (gray) relative to those candidates that are in the optimistic HZ of their host star (green). The solid lines are power law fits to the HZ candidates and the dashed lines are power law fits to the entire Kepler distribution. Statistical analysis of the distributions shows that there is little evidence of a significant difference in the populations.

References:

[1] Kane, S. R., Kopparapu, R. K., Domagal-Goldman S. (2014) *ApJ, 794,* L5.
[2] Kane, S. R., et al. (2016) *ApJ, 830,* 1.

MODELING THE AIRGLOW RESPONSE TO QUAKES ON VENUS. B. Kenda[1,2], P. Lognonné[1], A. Komjathy[2], W. B. Banerdt[2], J. Cutts[2] and J. Jackson[3], [1]Institut de Physique du Globe de Paris, Paris, France, [2]Jet Propulsion Laboratory, California Institute of Technology, Pasadena CA, USA, [3]California Institute of Technology, Pasadena CA, USA.

Introduction: The internal structure and dynamics of Venus are poorly constrained by observations. Seismology is among the best candidates for probing the interior of the planet, and it would also provide indispensable information about the present-day tectonic activity of Venus. However, due to the extreme surface temperatures, a long-duration seismic station seems to be beyond the technical capabilities achievable today. Nonetheless, the thick and dense atmosphere, which strongly couples with the ground, gives rise to the attractive option of detecting seismic waves from quakes within the atmosphere iself [1],[2], using in-situ or remote-sensing measurements [3].

Modeling: We consider the bright airglow emission of O_2 at 1.27 μm on the nightside of Venus and we model the intensity flucutations induced by Venus quakes. In the case of the Earth, airglow response to tsunamis has been measured both with ground based [4] and satellite [5] techniques. Here, we computed synthetic seismograms in the airglow layer, at 90-120 km altitude, using normal-mode summation for a fully coupled solid planet-atmosphere system, including the effects of molecular relaxation of CO_2 and a radiative boundary condition at the top of the atmosphere [6]. The corresponding variations in the volumetric emission rate, calculated for realistic background intensities of the airglow [7], are then vertically integrated to reproduce the signals that would be seen from orbit. A snapshot of the 20-sec wavefield for a M_w=5.8 quake is shown in Figure 1.

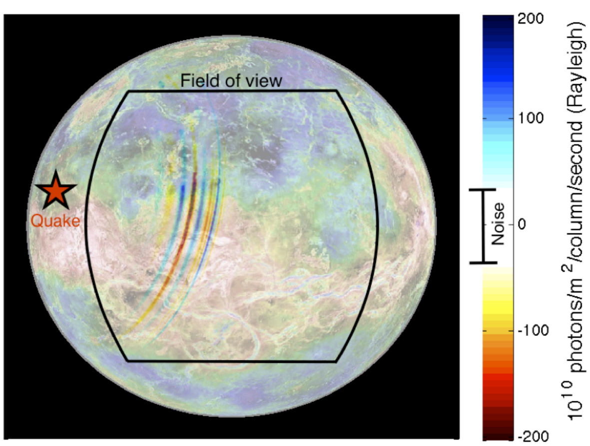

Figure 1: Airglow fluctuation on the nightside of Venus induced by a M_w=5.8 quake. The red star indicates the source location and the image shows the wavefield 30-min after the quake.

Discussion: The noise level of existing airglow cameras suggests that the Rayleigh waves generated by quakes of magnitude 5 and above occurring on the nightside of the planet may be detectable up to about 60° in epicentral distance. A significant advantage of this technique is that a single orbiting camera may be sufficient to serve the role of a seismic network. By identifying and tracking the waves it is indeed possible to locate the source, estimate the magnitude and measure the horizontal surface-wave propagation velocities on Venus. In particular, it is expected that this would significantly constrain seismicity on Venus and, through the analysis of Rayleigh-wave dispersion, the structure of the crust and upper mantle.

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IS EVIDENCE FOR RESURFACING ON VENUS BURIED DEEP WITHIN THE INTERIOR? S. D. King Department of Geoscience, 4044 Derring Hall, Virginia Tech, Blacksburg, VA.

Introduction: The surface of Venus is approximately 250-750 Myr old [e.g., 1-4]. There are two hypotheses to explain the relatively young age of the Venusian surface, progressive volcanic resurfacing or a global lithospheric overturn event [1,2,5,6]. Mantle-overturn events are controlled by a lithospheric instability whereas volcanic resurfacing events imply a plume-dominated, core-mantle boundary instability. This has significant implications for the mechanism of heat loss from the Venusian interior. The evidence consistent with catastrophic or gradual resurfacing may be buried deep within the planet.

Consider the impact of a global lithospheric instability on the deep mantle of Venus in which the entire lithosphere is subducted over a short time period. Assume a 100-km thick lithosphere became unstable 500 Myr ago for illustration, such a resurfacing event would have placed approximately 5×10^{10} km^3 (5% of the volume of the planet) of cold, dense material deep into the Venusian mantle approximately 500 Myr ago. Such a cold dense pile of material would be evident in the global geoid and topography of Venus because the cooling time for such a pile by thermal conduction is significantly greater than 500 Myrs.

While the geoid has no degree one term by construction, a hemispherical thermal (hence density) anomaly would be observable in the difference between the center of mass and the center of figure of the planet [7]. Yet, Venus is remarkable amongst the terrestrial planets for having the smallest offset between the center of mass and center of figure [8-9] (Table 1). Thus, it is highly unlikely that a single overturn event could have been responsible for Venus' young surface age.

Body	*Center of mass/figure offset (km)*
Mercury	0.683
Venus	*0.280*
Earth	2.100
Moon	1.982
Mars	2.501

Table 1: Center of mass—center of figure offset

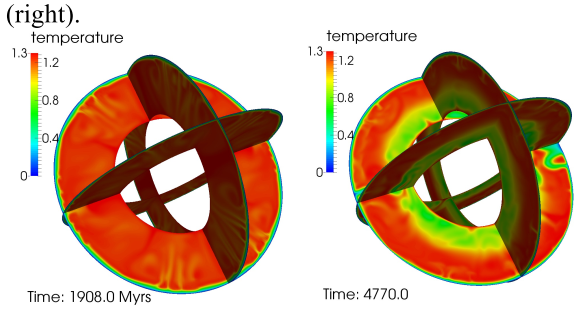
The geoid of Venus differs significantly from Earth and Mars in that the spectral power is not dominated by the longest wavelengths [c.f., 8]. Unlike Earth, there is a strong correlation between geoid and topography on Venus up to degrees 40 with a notably weaker correlation for degree 2 [e.g., 10]. The small offset between the center of mass and center of figure of Venus cannot be reconciled with the significant dense 'pile' of cold material deep in the Venusian mantle that is expected from a 'catastrophic' resurfacing event.

Geodynamic Modeling: I solved the equations for the conservation of mass, momentum, and energy in a spherical shell geometry assuming an incompressible fluid using CitcomS (version 3.3.2) with a 64x64x64 element mesh for each of the 12-cubes within the spherical shell [11]. I compared these results with calculations with a 96x96x96 element mesh for some models and found little difference in the resulting model evolution. The Rayleigh number was set to 3.2×10^8 and the velocity boundary conditions were free-slip at the surface and the core-mantle boundary. The surface temperature was held constant at 0.207 and, the core-mantle boundary temperature evolved based on a core cooling model [12]. The concentration of radiogenic elements decreased with time.

I modeled the catastrophic resurfacing mechanism by implementing a temperature-dependent rheology with a lithospheric yield stress to produce stagnant-lid convection characterized by self-generating, punctuated lithospheric instabilities [13].

Results: Shown below are the results of a calculation that begins in stagnant-lid mode (Fig. 1 left) for the first 3500 Myrs of evolution and then the model transitions into mobile-lid convection (Fig. 1 right).

Fig. 1: Stagnant lid phase of the model before the overturn (left) and mobile lid phase after the overturn (right).



The the stagnant lid versus mobile lid regimes can be identified by the mobility (Fig. 2), defined as the maximum surface velocity divided by the average mantle velocity. When the mobility is near zero, the calculation is in stagnant-lid convection mode. An overturn event, indicated by the increase in surface and mantle velocities and the mobility, occurs just after 3500 Myr in model evolution time. The pattern of the geoid and topography changes dramatically before and after the overturn event (Fig.3).

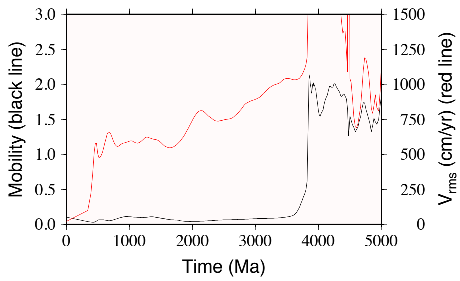


Fig. 2: Mobility (black) and RMS velocity (red).

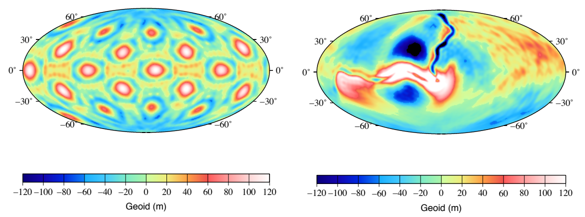


Fig. 3: Geoid before (left) and after (right) the overturn event.

The offset between Center of Mass (COM) and Center of Figure (COF) is almost zero during the stagnant lid phase of the calculation (Fig. 4). It grows to between 2,000 and 3,000 meters during the mobile lid phase of the calculation. Likewise, the difference between stagnant and active lid convection can be seen in the correlation of the geoid and topography.

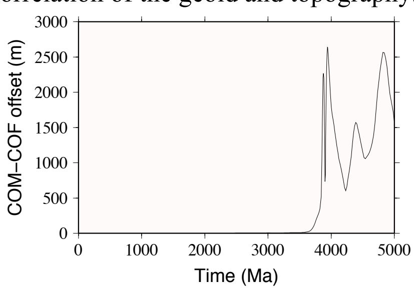


Fig. 4: Offset between center of mass and center of figure through time.

Fig 5. shows the correlation as a function of harmonic degree. In the early stagnant-lid phase of the model (red curves), there is a very strong positive correlation of the geoid and topography at all harmonic degrees and the planform is dominate by the degree l=8, order m=4 pattern of the initial condition. Once the lithosphere becomes unstable (blue curves), the correlation in the degree range 3–15 becomes weak or absent, with occasional weak anti-correlation at degrees 2-4 and good correlation beyond degree 15.

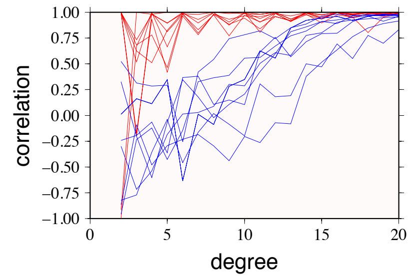


Fig. 5: Corelation of geoid and topography as a function of spherical harmonic degree.

I conclude the following: First, a cold dense pile of material from a resurfacing event would be evident in the global geoid and topography of Venus. While the geoid has no degree one term by construction, such a hemispherical thermal (hence density) anomaly would be observable in the difference between the center of mass and the center of figure of the planet (Fig. 3). Yet, Venus has the smallest offset between COM and COF [8,9]. Second, unlike Earth there is a strong correlation between geoid and topography on Venus up to degrees 40 with a notably weaker correlation for degree 2 [14]. This is consistent with the stagnant lid phase of the calculation and inconsistent with the mobile lid phase. Finally, the small observed offset between the center of mass and center of figure of Venus cannot be reconciled with the significant dense 'pile' of cold material deep in the Venusian mantle resulting from a catastrophic resurfacing event. Instead I favor a model of progressive volcanic resurfacing model [15].

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STATUS OF THE IPSL VENUS GLOBAL CLIMATE MODEL. Sébastien Lebonnois[1], Itziar Garate-Lopez[1], Gabriella Gilli[2], Sabrina Guilbon[3], Franck Lefèvre[3], Anni Määttänen[3], Thomas Navarro[4] and Aurélien Stolzenbach[3], [1] Laboratoire de Météorologie Dynamique (LMD/IPSL), Sorbonne Universités, UPMC Univ Paris 06, CNRS/INSU, France, [2] Instituto de Astrofisica e Ciencias do Espaço (IA), Lisbon, Portugal, [3]LATMOS/IPSL, CNRS/INSU, UVSQ, Sorbonne Universités, UPMC Univ Paris 06, France, [4]Department of Earth, Planet. and Space Sci., UCLA, CA, USA.

Introduction: Based on our experience of Earth and Mars Global Climate Models, a model for Venus's climate system has been developed within Institute Pierre-Simon Laplace (LMD, LATMOS) for twelve years. Thermal radiation scheme is based on Net-Exchange Rate (NER) matrices, with look-up tables for solar heating rate forcing.

Latest developments: The IPSL Venus GCM is described in details in [1]. Some recent improvements, as well as a description of the capabilities that have been under development for several years are presented in this Section.

Radiative transfer. Our latest version of the radiative scheme includes a new cloud model [2,3], used both for solar heating rates and for the NER matrices. Both take into account the latitudinal variation of the cloud structure. In the computation of the new NER matrices, updated spectral dataset and collision-induced absorptions were used. To get as close as possible to Venus thermal structure (Fig. 1), some tuning involves the properties of the haze below the clouds and its impact on solar heating rates and infrared opacities.

Photochemical model. Composition is now fully coupled [4]. The chemical module provides a comprehensive description of the CO_2, sulfur, chlorine, oxygen and hydrogen chemistries with 31 chemical species and state-of-the-art kinetics data.

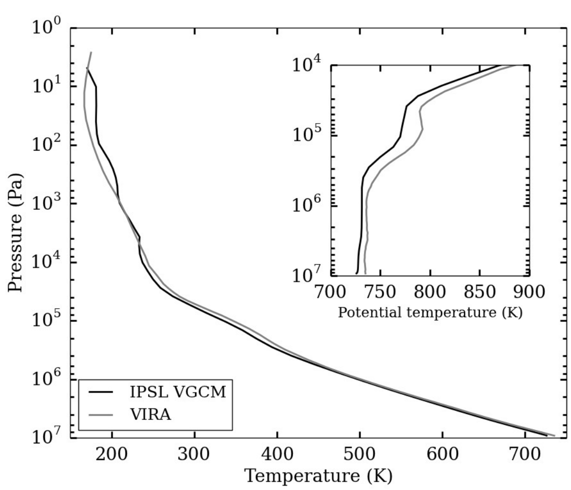

Fig. 1. *Globally-averaged temperature and potential temperature vertical profiles.*

Cloud microphysics. To allow a correct description of the sulfur and water cycle on Venus, photochemistry needs to be coupled with microphysical modeling of the cloud layer. A parameterized treatment of cloud microphysics was developed for the GCM [4]. This model computes the composition, number density, and sedimentation rates of sulfuric acid aerosols based on observed altitude-dependant size distributions.

In parallel, a full microphysical module based on the moment method is being developed for a comprehensive description of the cloud layers [5]. The geometric standard deviation of the particle size distribution is fixed. The composition of the binary H_2O-H_2SO_4 solution, which composes the cloud droplets, is computed at each time-step. Only mode 1 and mode 2, for small and medium sized particles, are represented because of the uncertain nature of the observed mode 3. The model accounts for nucleation, condensation/evaporation and coagulation. Coupling with the IPSL Venus GCM is on-going.

Upper atmosphere. The vertical extension of the model from above the clouds up to the thermosphere (100-150 km) was completed recently [6]. In particular, the role of non-LTE processes, EUV heating and thermal conduction was considered at those altitudes, and proper parameterization for GCMs implemented, following the scheme developed for the Mars GCM [7]. The model takes into account the full distribution of composition, with coupling to the photochemistry, together with the inclusion of molecular viscosity and molecular diffusion. In addition, a parameterization of non-orographic gravity waves, following the formalism developed for the Earth GCM [8], was also implemented in the IPSL Venus GCM. Those gravity waves, emitted above the convective cloud region, are believed to play a major role in Venus upper atmosphere dynamics, and their impact is still under investigation.

Reference simulation: Using the new radiative tuning, a reference simulation was run for 200 Venus days, with a horizontal resolution of 96x96 and 50 vertical levels, similar to [1], without the latitudinal variation of the cloud structure taken into account. Then 100 additional Venus days were computed with and without this variation, to study its impact.

Results with variation of the latitudinal cloud structure. Taking this feature into account has a remarkable impact on the temperature structure, on the wave activity in the lower cloud region and just below the cloud, and on the vertical profile of the zonal wind. Cold collar is now very nicely represented (Fig. 2), though a wave number one feature is visible at some times.

The zonal wind distribution is remarkably close to observations, though the high-latitude cloud jets are still too strong and located at higher latitude than observed (Fig. 3). The significant enhancement of the zonal wind in the lower cloud region, compared to the uniform cloud distribution simulation, is due to a mid-latitude wave activity that transport efficiently angular momentum equatorward in this area. This feature is currently under analysis.

This reference simulation is now running in several configurations, to explore all its capabilities: with the photochemistry (and simplified cloud model), and with the extension to the upper atmosphere.

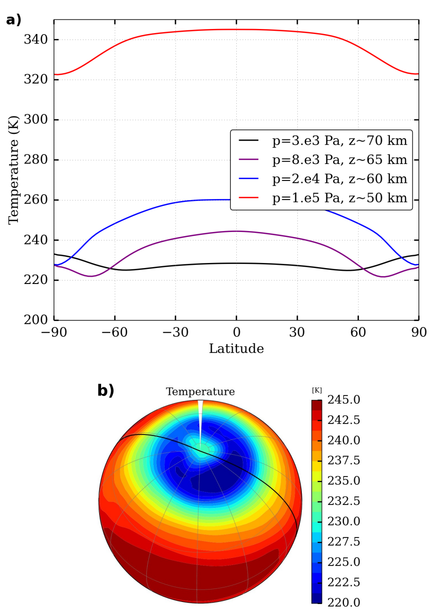

Fig. 2. (a) Zonally-averaged latitudinal temperature profiles; (b) temperature map at ~70mbar.

Perspectives: The current configuration still has troubles with the angular momentum budget, as discussed in [1]. In addition, the grid and the associated polar filter may affect processes occurring in the polar region.

An icosaedral dynamical core. A major improvement is foreseen in the very near future with the implementation of a new dynamical core, DYNAMICO, based on an icosaedral grid. In addition to a better description of the polar regions and a better behavior in terms of angular momentum conservation, the performances of this new core will also allow to increase the resolution and explore in more details the wave activity taking place in Venus's polar regions.

A hierarchy of models. The physics of the IPSL Venus GCM is also now coupled with a new mesoscale/LES model developed at LMD. This model allows to explore the fine structure of small-scale gravity waves and convective activity [9], and has a lot of potential in exploring atmospheric processes at very high resolution.

Towards data assimilation. The reference simulation presented here will be used to develop data assimilation techniques.

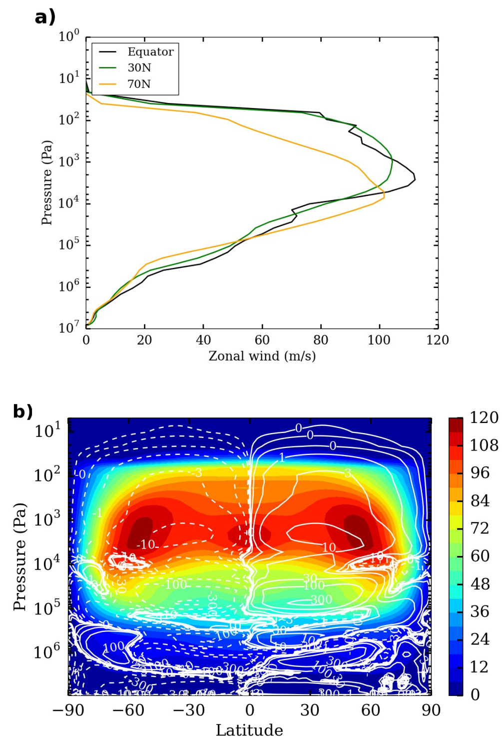

Fig. 3. (a) Zonally-averaged vertical profiles of zonal wind; (b) zonally-averaged zonal wind distribution, with mean stream function (white contours, 10^9 kg/s).

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Venus Atmospheric Maneuverable Platform (VAMP) – Pathfinder Concepts.

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Introduction: Northrop Grumman Aerospace Systems has been developing an innovative and versatile new class of vehicle that will serve as an atmospheric rover for exploration of planets and moons of the solar system that have atmospheres. The new class of vehicle is called Lifting Entry Atmospheric Flight (LEAF), which provides a new way to enter an atmosphere from space and transition to flight within the atmosphere. Additionally, the LEAF system is semi-buoyant and the on-board propulsion system provides the capability to adjust altitude on command and travel in specified directions. It is also robust to failures since it can safely float at full buoyancy should it lose power. The LEAF system further reduces mission risk by deploying prior to entry at a relatively slow pace and gently enters the atmosphere;

A planet well-suited for exploration with a system such as LEAF is Venus. Our Venus atmospheric rover is called Venus Atmospheric Maneuverable Platform (VAMP). Over the past several years, we have been developing the VAMP concept that supports long duration instruments in the Venus atmosphere, providing empirical data to inform modeling of the atmosphere. In 2015, we formulated low risk VAMP pathfinder concepts that are analogous to the Mars Rovers development.

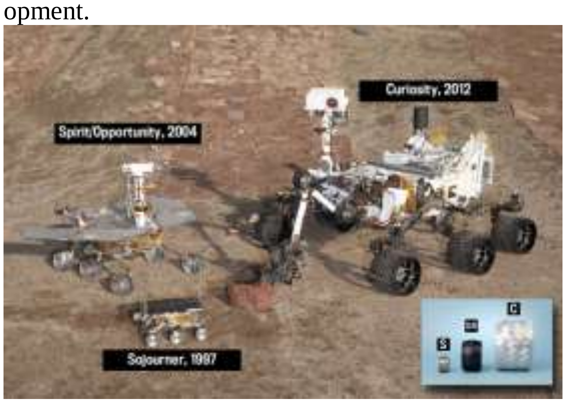

Figure 1. Mars Rover Evolution [Image Credit: NASA]

Just as the Mars Rovers evolved from the small, less capable Sojourner (11.5 kg mass and 30 sols designed lifetime) [2], to the more capable Spirit/Opportunity (174 kg and 1 km intended driving distance) [3], and ultimately to the current Curiosity (900 kg and 19 km intended driving distance) [3], the Venus Atmospheric Maneuverable Platform could be developed starting with a small version that could validate technologies and concepts of operation, to larger, more capable atmospheric science platforms as shown in Figure 2.

	Low Altitude (Small)	Mid Altitude (Mid-Size)	High Altitude (Large)
Float Alt	48 km	50 km	52 km
Minimum Power	100 w (day); 20 w (night)	300 w (day); 100 w (night)	8,000 w (day); 100 w (night)
Wing Span	6 m	30 m	59 m
Mass	90 kg including instruments	450 kg incl. 10 kg of instruments	880 kg incl. 50 kg of instruments
Tech	• Simple inflation-based deployment • TPS material for lifting entry • Sulfuric acid resistant skin material	• Mechanical plus inflation-based deployment • Autonomous navigation and hazard avoidance • Enhanced night time power • Limited propulsion capability	Next generation versions of pathfinder technologies

Figure 2. Low Risk VAMP Concepts

In this presentation we focus on the Mid-Altitude vehicle that is well suited to being a companion to a Venus lander and orbiter mission such as VENERA-D. More specifically, we discuss various VAMP configurations and atmospheric science operations for this size of vehicle, and discuss potential instruments and how they can inform Venus' atmospheric models.

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MESOSCALING MODELING OF THE VENUS ATMOSPHERE : CONVECTION AND GRAVITY WAVES. M. Lefèvre[1] , A. Spiga[1], S. Lebonnois[1] [1]Laboratoire de Météorologie Dynamique (LMD/IPSL), Sorbonne Universités, UPMC Univ Paris 06, CNRS/INSU, France.

Introduction : The impact of the cloud convective layer of the atmosphere of Venus on the global circulation remains unclear. The recent observations of gravity waves at the top of the cloud by the Venus Express mission provided some answers.

LES Model : These waves are not resolved at the scale of global circulation models (GCM), therefore we developed an unprecedented 3D turbulence-resolving Large-Eddy Simulations (LES) Venusian model [1] using the Weather Research and Forecast terrestrial model [2]. The forcing consists of three different heating rates : two radiative ones for solar and infrared and one associated with the adiabatic cooling/warming of the global circulation. The rates are extracted from the Laboratoire de Météorologie Dynamique (LMD) Venus GCM [3] using two different cloud models. Thus we are able to characterize the convection and associated gravity waves in function of latitude and local time. To assess the impact of the global circulation on the convective layer, we used rates from a 1D radiative-convective model. As we focused this study on the cloud convective layer, the vertical domain extend from 40 to 70 km.

The resolved layer, taking place (fig 1-a) between 1.0 10^5 and 3.8 10^4 Pa (48-53 km), is organized as polygonal closed cells of about 10 km wide with vertical wind of several meters per second (fig 1-b). The convection emits gravity waves both above and below the convective layer (fig 2-a) leading to temperature perturbations of several tenths of Kelvin (fig 2-b) with vertical wavelength between 1 and 3 km and horizontal wavelength from 1 to 10 km. The thickness of the convective layer and the amplitudes of waves are consistent with observations[4]|5], though slightly underestimated. As expected, the convective layer is strongly dependent on the cloud model used to calculate the heating rates, with the latest cloud model of [6] providing better comparison with observations. The variability of the model with latitude and local time is different from previous modeling. The addition of the heating rate associated with the global circulation provides an estimate of the impact of the global circulation on the convective layer and proves to be a crucial inclusion to Venus LES for the cloud layer. By warming up and cooling down the convective layer, the global dynamics tends to mitigate the convection.

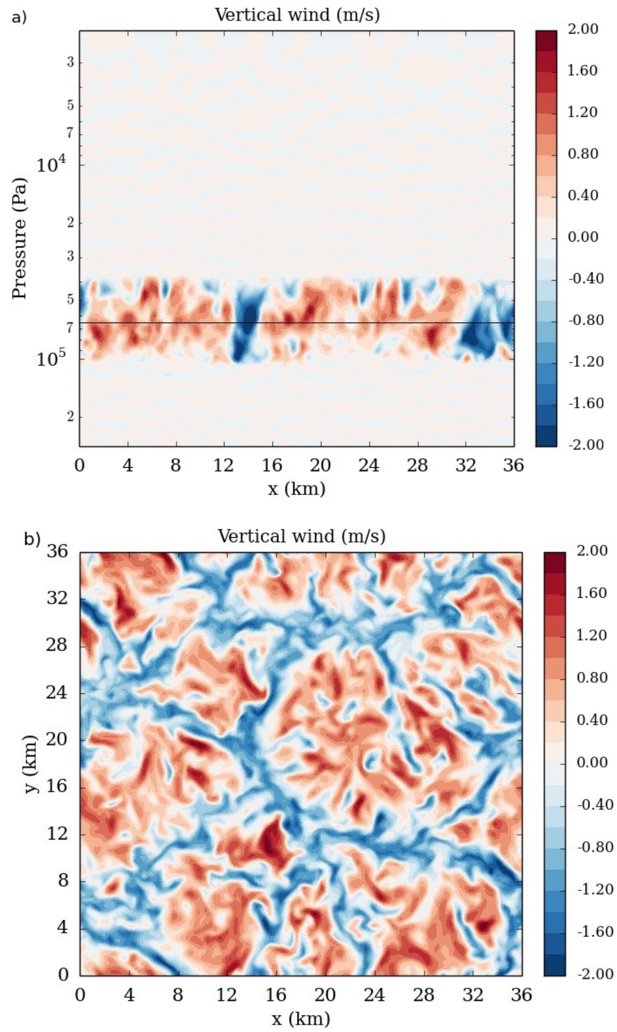

Fig 1. *Snapshots of the convective vertical motions : (a) vertical cross section and (b) horizontal cross section at 6.4 10^4 Pa of the vertical wind (m/s), for the equator at midnight. The black line represents in a) the location of the horizontal cross section.*

Latest developments : Recent improvements and description of the capabilities that have been under development .

LES model. The LMD Venus physics is now coupled with the WRF dynamical core, therefore a complete radiative scheme is implemented in the LES model with a new cloud model [6][7] that takes into account the latitudinal variation of the cloud structure. Thus the model is able to resolve radiative-photochemical-dynamical feedback.

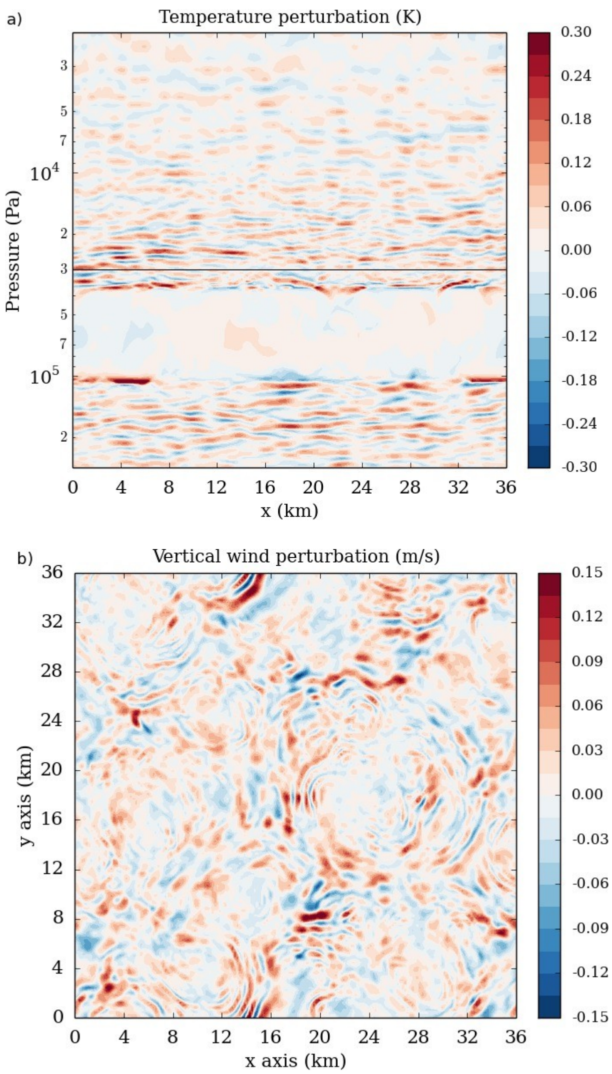

Fig 2. *Snapshots of the gravity waves : (a) temperature perturbation (K) vertical cross section and (b) horizontal cross section at 3.0* 10^4 *Pa of the vertical wind perturbation (m/s), for the equator at midnight. The black line represents in a) the location of the horizontal cross section.*

This implementation has been carried out on an extended vertical domain, from the ground to 90 km, to resolve the planetary boundary layers as well as the two convection layer (from 18 to 30 km and from 50 to 60 km). This coupling is now in a test phase to look at the convective stability. In addition of the radiative transfer, wind shear has also been implemented. Another work in progress is to make the heat capacity in the dynamical core varying with temperature as in the LMD Venus GCM.

Mesoscale model. Another current effort is the topography. Recent missions tend to show link between the topography and cloud top [8][9]. Using a Venus surface map of a resolution of 1° by 1° of latitude, the topography has been implemented in the model. A coupling between the dynamical with topography and LMD Venus physics is on-going.

Perspectives :

Photochemical model. When the coupling between WRF dynamical core and LMD Venus physics will be fully operational the IPSL photochemistry model [10] will be implemented in the mesoscale model and then it will be able to follow as much as 35 chemical species with a very fine vertical and horizontal resolution.

Cloud Microphysics. At IPSL a full microphysical module based on the moment method is being developed for a comprehensive description of the cloud layers [11]. The coupling with LMD Venus GCM is on-going and as soon as this coupling will be effective it will be couple with the WRF dynamical core.

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ULTRAVIOLET ABSORBERS AND CLOUD CONTRASTS ON VENUS. S.S. Limaye[1], A.H. Ansari[2], R. Mogul[3], D.J. Smith[4], and P. Vaishampayan[5], [1]University of Wisconsin, Space Science and Engineering Center, 1225 W. Dayton St., Madison, WI 53706, SanjayL@ssec.wisc.edu, [2]B. Sahni Inst. for Palaeobotany, Lucknow, INDIA, [3]CalPoly, Pomona, CA 91768, [4]NASA/Ames Research Center, Moffett Field, CA 94035, [5]JPL, Pasadena, CA 98104,

Introduction: There are two key questions about the global cloud cover of Venus that deserve an answer. The first question is what causes the observed spectral dependence of the absorption of solar energy below 500 nm. The second one is what causes the observed contrasts in the clouds first observed at ultraviolet (UV) wavelengths (Ross, 1927) and decades later at near infrared (NIR) wavelengths (Crawford and Allen, 1984). The absorption at UV wavelengths by the Venus clouds represents the dominant deposition of incident solar energy that drives the superrotation of the atmosphere. The global structure of the superrotation in turn has been mostly discovered from tracking cloud contrasts from UV to NIR wavelengths (Hueso et al., 2015). It is thus necessary that we understand the nature of the UV absorption and the generation of the cloud contrasts on Venus.

It has been known for decades that there must be at least two separate absorbers responsible for the lower albedo of Venus below 500 nm (Travis, 1975). A number of different molecular absorbers have been proposed to explain the observed spectrum over the decades (Krasnopolsky, 2006). Below 330 nm, sulfur dioxide has been identified as one of the two substances likely responsible for the ultraviolet (uv) absorption (Zasova et al., 1981), but the available information about its spatial distribution and temporal evolution (Encrenaz et al., 2012) and contribution to the albedo appear to be somewhat counter-indicative as the clear primary absorber below 330 nm.

Most proposed candidates for the second absorber (Esposito et al., 1983) have been discarded after analysis of the limited data from in-situ measurements (Krasnopolsky, 2016). $FeCl_3$ has been proposed as a candidate (Markiewicz et al., 2014; Zasova et al., 1981) and remains as the most likely candidate (Krasnopolsky, 2017), however its lifetime in the presence of sulfuric acid is short and its continuous replenishment is problematic. Recently another new substance (OSSO) has been proposed as another ultraviolet absorber to explain the absorption between 320-400 nm, but the lifetime of the two isomers of OSSO that are proposed as sulfur reservoirs is very short (a few seconds) and the estimates of opacity are very uncertain (Frandsen et al, 2016). It is known that the uv absorption takes place above 62 km from the probe measurements and likely begins at the cloud tops. The uv absorbers may however be present in deeper levels, at least down to 57 km based on VeGa lander measurements (Bertaux et al., 1996)

Against this uncertainty about the nature of the uv absorber, biologic origins of the absorption and contrasts have not received much attention. Although Venus has no surface water at present, atmospheric measurements from entry probes (Donahue et al., 1982) and recent Venus Express measurements indicate that the D/H ratio is enhanced when compared to Earth by as much as a factor of ~ 120 below the clouds and by more than a factor of 200 above the clouds (Fedorova et al.., 2012). The detection of hydroxyl ions by Venus Express is consistent with this interpretation. Way et al. (2016) suggested that Venus may have been the first habitable planet as it could have harbored liquid water on the surface for more than a billion years in its past.

The possibility of life in the clouds of Venus was suggested by Morowitz and Sagan (1967) and also discussed by Cockell (1999) and followed up by Shulze-Makuch et al. (2004) and Grinspoon and Bullock (2007) as *acid and uv resistant* bacteria.

Limaye et al. (2017) speculate whether microorganisms with uv absorptive properties such as those found on Earth could have evolved on Venus when it had liquid water on the surface and subsequently migrated to the clouds. The possibility that microorganisms may be extant in the clouds of Venus, perhaps in the lower cloud region where large particles have been detected (Knollenberg and Hunten, 1980), where there is more water vapor and temperatures are very suitable for some terrestrial organisms such as *A. thiobacillus ferrooxidans* cannot be easily discarded, given the similarities of its chemical, physical and spectral properties with those of the Venus cloud particles.

There are many questions about the clouds of Venus and the variations in the contrasts observed at different wavelengths as well as their short and long term evolution that we need to understand. The spatial scale and time dependence of the observed contrasts in the multispectral images need to be systematically investigated to provide additional constraints on the production of these contrasts to improve our understanding of the clouds of Venus.

Laboratory experiments are needed to consider the survival and life cycles of microorganisms that can survive in the chemical and physical conditions found in the clouds of Venus, particularly in the lower cloud region. The GEER facility at NASA/GRC is an ideal candidate for making such measurements. Spectral characteristics of different acid resistant bacteria over the 200 – 4000 nm range are needed, particularly for uv absorptive, sulfuric acid resistant species.

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CLIMATES OF VENUS-LIKE EXOPLANETS. A. P. Lincowski[1,2,3], V. S. Meadows[1,2,3], D. Crisp[2,4], T. D. Robinson[2,5,6], and G. N. Arney[2,7], [1]Department of Astronomy, University of Washington, Box 351580, Seattle, WA 98185, USA (alinc@uw.edu), [2]NAI Virtual Planetary Laboratory, Seattle, WA, USA, [3]Astrobiology Program, University of Washington, Seattle, WA, USA, [4]Jet Propulsion Laboratory, California Institute of Technology, M/S 183-501, 4800 Oak Grove Drive, Pasadena, CA 91109, USA, [5]Department of Astronomy and Astrophysics, University of California, Santa Cruz, CA 95064, USA, [6]NASA Sagan Postdoctoral Fellow, [7]NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA.

Introduction: Venus' atmosphere potentially represents a desiccated end-state of the runaway greenhouse effect, a fate facing Earth as the luminosity of the Sun increases over its lifetime. This evolutionary pathway is important for the study of exoplanets, in particular those around active stars such as M dwarfs, the most common type of star in our Galaxy. In the next several years, the *James Webb Space Telescope* (JWST) will conduct observations to characterize terrestrial planets both in and interior to the habitable zone. Such planets have already been discovered: GJ 1132 b receives 19 times Earth's insolation ($S_\oplus$) [1], and Proxima Centauri b receives $0.67 S_\oplus$ [2]. The most interesting system of planets to study will be TRAPPIST-1, where there are seven planets discovered spanning both ends of the habitable zone [3]. These include two exoVenuses that receive 2x and 1x Venus' insolation (b and c, respectively). However, even the habitable zone planets have a high probability of being Venus-like. This is due to the long, intense, superluminous pre-main-sequence evolution of M dwarf stars, which can be as high as 100x the main sequence luminosity, last for hundreds of millions of years, and evaporate ten Earth oceans of water [4,5]. Observations of these new terrestrial planets, especially the TRAPPIST-1 system, will provide new opportunities to study the evolutionary pathways of terrestrial planets.

To predict observational properties and climatic discriminants in advance of upcoming observations by JWST, we characterize the climate of Venus as an exoplanet using a generalized 1D radiative-convective-equilibrium climate model [6–8]. This model was designed for exoplanet studies, using physics derived from studies of planets in our Solar System, including Venus. It has recently been enhanced with a generalized treatment of condensable species. Here, we assume that sulfuric acid (H_2SO_4) is the primary condensable in the atmospheres of an exoVenus. Our condensate cycle includes latent heat exchange due to phase changes and vertical transport due to convection, eddy diffusion, and sedimentation. This climate model is also capable of computing multi-stream, multi-scattering radiative transfer through aerosols, which is important to accurately model the climatic effects and spectra of a Venus-like planet. With the use of linear Jacobians, for small changes in optical depth in an atmospheric layer, we can compute the radiative changes of clouds at each time step of the model. Coupling the radiative effects with the changing properties of the clouds allows us to self-consistently model a Venus-like atmosphere on exoplanets that may be observed by JWST.

Methods: The VPL Climate model, originally presented by [6], computes radiative transfer using SMART, a line-by-line, multi-stream, multi-scattering code [9]. To account for the changing physical state (e.g. temperature and optical depths of aerosols) during timestepping, we employ Jacobians describing the layer-by-layer, wavelength-dependent response of the radiative source functions and layer absorption, reflectivity, and transmissivity to changes in state [8]. Convective processes are updated more frequently than the radiative heating rates. We employ mixing length theory for heat and condensate vertical mixing and use thermodynamic data (saturated vapor pressure and temperature, and heat of formation) to determine phase changes and latent heating rates. To complete the condensate cycle, we add evaporation and sedimentation. We also add self-consistent optical depth calculation of condensates existing in the atmospheric layers at each radiative timestep for each atmospheric layer. In this way, our climate model self-consistently accounts for immediate feedback between the phase change of condensable gas and radiative effects of the associated aerosol. In addition to thermodynamic data, VPL Climate requires inputs of planetary properties (e.g. radius, semi-major axis), the atmospheric grid, gas mixing ratios, surface albedo, stellar spectral energy distribution, line data (e.g. HITRAN), collision-induced absorption data, and UV-visible absorption cross sections.

To apply this model to Venus-like planets, we begin with mixing ratios compiled from observations, such as used in [10]. We use a guess of the temperature profile based on the equilibrium temperature of the modeled exoVenus. The model starts as radiative-convective only. Aerosols are added as atmospheric layers reach the condensation point. Since our model does not compute detailed microphysics, we determine the distribution of particle sizes for Venus aerosol particle modes based on layer pressure. Mixing ratios of trace constituents are adjusted based on the actual location of cloud deck formation (i.e. in altitude, to correspond to match the changes in mixing ratios to the location of the primary cloud deck).

Results: For Venus, VPL Climate converges to yield globally-averaged temperatures and aerosol amounts in good agreement with VIRA [8]. We applied our enhanced 1D RCE climate model to potential Venus-like climates for Proxima b and TRAPPIST-1 b and c. The atmospheric composition and vertical structure of Proxima Centauri b has yet to be characterized, and the atmospheres of TRAPPIST-1 b and c are only constrained to exclude extended hydrogen envelopes [11]. We applied Venus-like climate models to these planets with both 10 and 93 bars of atmosphere. For 93 bar atmospheres, we find upper tropospheric convective zones form and are associated with H_2SO_4 condensation, consistent with the Venus cloud deck. We compare the vertical distribution of sulfuric acid with more detailed microphysical calculations conducted for Venus.

The pressure-temperature structure and vapor-condensate distribution results of our model can be used in detailed spectral studies. Such studies can yield spectroscopic signatures that could be used to characterize these worlds with future observations from JWST.

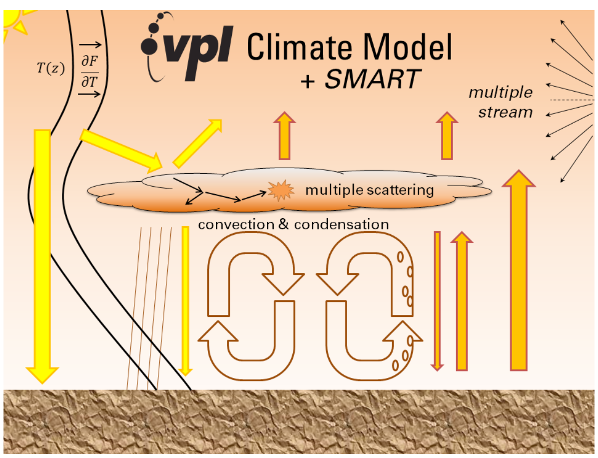

Figure 1: Diagram of our generalized exoplanet 1D RCE climate model, which includes multi-stream, multi-scattering, line-by-line radiative transfer, mixing length convection, full generalized condensate cycle with surface reservoir, vertical mixing, condensation, evaporation, and sedimentation. This versatile model has been validated on Solar System terrestrial planets and can be applied to a variety of terrestrial exoplanets, including those very different than Earth, such as Venus.

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STOCHASTIC MODELS OF LIGHTNING AND LIGHTNING DETECTION ON VENUS.

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Introduction: Observations regarding lightning on Venus are mutually discrepant, with positive and negative reports. A model of lightning as a pure random process with a uniform rate appears to be incompatible with the observation set. While a plausible thesis is that one or more observations are 'wrong' in asserting an interpretation, here I explore models of possible temporal and/or spatial variability of lightning in an attempt to maximize agreement with observations while minimizing the number of model parameters.

Clustered Occurrences: The first-order analysis of any phenomenon not unreasonably posits a Poisson process with a single, uniform occurrence rate λ. An observation is then a set T of Bernouilli trials (detect ? Y/N) which attempt to constrain λ as ~Y/T. A major challenge in reconciling observations to date is that the detection threshold (typically, a top-of-atmosphere light flash energy) is not always accurately quantified, and is typically different for different searches, and without taking this into account (wherein the population of lightning events has some distribution that yields different counts for different thresholds) the comparisons are largely meaningless.

Some progress has been made in recent years in addressing analogous challenges in planetary meteorology, namely assessing the population of dust devils on Earth and Mars. A simple and physically-based observation-dependent threshold detection with a plausible (power law) distribution of dust devil diameters [1] was able to reconcile reported dust devil occurrence rates (devils/km2/day) which differed by four orders of magnitude! These surveys were all conducted, however, at locations/times expected a priori to have dust devils, and typically with long enough periods that day-to-day variations were averaged out.

Inspection of dust devil occurrences (e.g. the number of devils in single orbital Mars images) shows a strongly non-Poisson distribution, with the number of 'many-devil' images disproproportionate to an extrapolation given the number of single- and few-devil images. In other words, there is at least one 'hidden variable' determining whether conditions are favorable for dust devils or not (typically the ambient wind speed).

This paradigm seems appropriate for lightning on Venus, if it exists, as indeed it seems to be true for lightning on Earth. Casual observation indicates that if one sees one lightning flash, one is likely to see many, because there is a storm, whereas overall storms are rare.

Even with very poor statistics (7 flashes), the optical survey by Hansell et al. [3] found *'an indication that Venus undergoes quiet times and noisy times'* since on four nights of observation the counts were [2,2,0,3], with the last 3 occurring within 10 minutes of each other. On the other hand, in part such stochasticity may also be due to variations in the detection efficiency (such as the claimed dependence of Venus Express magnetometer signatures of lightning on the geometry of the magnetic field lines) : Russell et al. [4] note only 61 detections in some 12,223s of observation, but consider that the observations only access Venus 1/4 of the time, and over only a few hundred km (0.027% of the planet's area) : their extrapolation of a 18/s global flash rate (20% of Earth) based on the wholly unsupported assumption that the flash rate is uniform.

Although ultimately it may be necessary to develop a spatial variability model to explicitly track the migration of "storms" and the intersection of those lightning-favorable regions with an observation process, a first step is simply to posit two additional variable – a characteristic duration S of a storm, and an occurrence rate R, and to adopt λ as a conditional quantity (i.e. $\lambda=\lambda o$ during a storm, $\lambda=0$ otherwise). If (as is presently the case) the observation duty cycle is small, it is possible to find many nondetections that are not inconsistent with a few high-rate detections.

Conclusions: Efforts are underway to develop a reasonably parsimonious model of lightning variability and detection on Venus to reconcile at least some observation claims. This modeling will help interpret results from the Lightning and Airglow Camera (LAC) on the Akatsuki Venus Climate Orbiter.

Acknowledgement: This work was supported by NASA Venus Climate Orbiter Participating Scientist Grant NNX16AC78G.

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A KINNETIC STUDY OF THE GAS PHASE NEUTRAL-NEUTRAL REACTIONS BETWEEN SULFUR- AND CHLORINE-CONTAINING MOLECULES PRESENT IN THE ATMOSPHERE OF VENUS. D. M. Maffucci[1] and D. E. Woon[2], and E. Herbst[1] [1]Department of Chemistry, University of Virginia (dmm2br@virginia.edu), [2]Chemistry Department, University of Illinois at Urbana-Champagne.

Introduction: Updated potential energy surface characterizations of reaction pathways involving sulfur- and chlorine-containing molecules provide the structural data (moments of inertia, vibrational frequencies, permanent dipole moments, polarizibilities, etc.) to calculate the temperature-dependent rate constant for reactions that have not been included in kinetics models of the Venusian atmosphere yet likely occur due to the abundance of the reactants and the energetics of the reaction pathway. For exothermic reactions with barriers, we consider the transition state theory (TST) rate constants for reactions of potential importance in the atmosphere of Venus. We explicitly calculate the partition functions for each degree of freedom of the reactants and transition state (eg. the reaction between the hydroxyl radical OH and HSCl leading to sulfur monochloride SCl and water H_2O) along the reaction coordinate. We discuss the contributions of each type of separable motion to the molecular partition functions, and we calculate the entropy factor for formation of the transition state to reconcile the TST rate constant values. We further discuss the deviation from Arrhenius behavior the TST rate constant exhibits due to the temperature dependence of the rate constant pre-exponential factor. For exothermic reactions with no identified barriers above the entrance channel, we place upper limits on the reaction rate constant by utilizing a classical capture theory to calculate the rate constants for reactions which are likely to occur as a result of the long-range interaction potential of the neutral species. Finally, we discuss the effect additional considerations of the Venusian atmospheric conditions (eg. high temperatures and pressures) has on our kinetic reaction rate constants.

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Simulations of Vertical Profiles and Time-of-day Variability in Vertical Profiles of SO and SO_2 on Venus. F. P. Mills[1,2], J. B. Petrass[1], M. Allen[3,4], K. L. Jessup[5], B. J. Sandor[2], and Y. L. Yung[4], [1]Fenner School of Environment and Society, Australian National University, Forestry Building, Linnaeus Way, Canberra, ACT 0200 Australia, Frank.Mills@anu.edu.au, [2]Space Science Institute, Boulder, CO 80301 USA, [3]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91125 USA, [4]Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125 USA, [5]Southwest Research Institute, Boulder, CO 80302 USA.

Introduction: Sulfur dioxide (SO_2) plays many important roles in Venus' atmosphere. It is a precursor for the sulfuric acid that condenses to form Venus' global cloud layers and is likely a precursor for the unidentified UV absorber, which, along with CO_2 near the tops of the clouds, appears to be responsible for absorbing about half of the energy deposited in Venus' atmosphere. Photochemically, SO_2 on Venus is analogous in many respects to O_3 in the terrestrial stratosphere [1]. Most published simulations of the chemistry in Venus' mesosphere have used one-dimensional numerical models that are intended to represent global-average or diurnal-average conditions [e.g., 2, 3, 4]. Observations, however, have found significant variations of SO and SO_2 with latitude and local time throughout the mesosphere [e.g., 5, 6, 7, 8], indicating more nuanced modeling is required. Some recent simulations have examined local time variations of SO and SO_2 using analytical models [5], 1-d steady-state solar-zenith-angle-dependent numerical models [8], and 3-d general circulation models (GCMs) [9]. No quantitative comparison has been made yet amongst the results from these different types of models. As an initial step towards this, we compare simulated SO, SO_2, and SO/SO_2 from global-average, analytical, and steady-state solar-zenith-angle (SZA) dependent models.

Methods: The Caltech/JPL photochemical model [10] is used for the numerical simulations. It applies a common core of atmospheric physics to all planets, drawing planet-specific information from custom databases, and converges to a steady-state solution via a finite-difference iterative algorithm. For these simulations, the 1-d continuity equation is solved simultaneously for all species over 58–110 km altitude. Vertical transport via eddy diffusion is set based on observations, as are the lower boundary conditions for HCl, CO, and OCS. Solar fluxes are based on measurements obtained by SORCE SOLSTICE and SORCE SIM on 26 December 2010 [11, 12]. These are the closest match to HST observations obtained on 28 December 2010 [8].

For the global average simulation, photodissociation rates were calculated at 45 deg latitude and local noon then divided by two to average them over the day and night sides.

The results from the global average simulation were used to identify the reactions that account for at least 95% of the production and loss of SO, SO_2, and SO_x (= SO + SO_2) at 70–100 km altitude. Reactions that produce or destroy short-lived species but do not result in net production or loss of SO, SO_2, or SO_x were then excluded to yield simplified algebraic relations for the equilibrium abundances of SO, SO_2, and SO_x.

For the SZA-dependent simulations, the calculations are run to steady-state using the solar flux expected for a specified local time on Venus' equator.

Preliminary Results: A common set of input data is being developed to facilitate comparisons amongst the differing types of models. Selected results from previous studies, using varying input data are shown in Fig. 1, which gives the SO_2 vertical profiles from global-average [14] and SZA-dependent [8] models, and in Equations 1 and 2, which give the approximate relations for the SO_2/SO ratio derived from the analytic model [5] for the day and night sides, respectively.

$$(1)\quad \left(\frac{[SO2]}{[SO]}\right)_{day} \approx \frac{[O]}{J_{73}}\left(k_{154}[CO2] + k_{165}\frac{[ClO]}{[O]} + k_{255}\frac{[ClCO3]}{[O]}\right)$$

$$(2)\quad \left(\frac{[SO2]}{[SO]}\right)_{night} \approx \frac{\left(k_{154}[CO2] + k_{165}\frac{[ClO]}{[O]} + k_{255}\frac{[ClCO3]}{[O]}\right)}{\left(k_{160}[CO2] + k_{162}\frac{[OH]}{[O]}[CO2] + k_{256}\frac{[ClCO3]}{[O]}\right)}$$

The SZA-dependent SO_2 profiles illustrate the upward shift with increasing SZA of the altitude at which optical depth unity is reached for the wavelengths where SO_2 absorbs strongly [8]. The global-average SO_2 profiles show a much more gradual decrease in SO_2 mixing ratio with altitude due to the inclusion of sulfur species (besides SO and SO_2) that have sufficiently long lifetimes to be transported vertically via eddy diffusion [15]. The large difference in SO_2 values in the upper cloud region (< 70 km) is due to choosing different lower boundary conditions for SO_2 in these simulations. These differences exemplify the need to compare simulations that have used common input data and photochemical schemes to isolate the effects due to the type of modeling considered.

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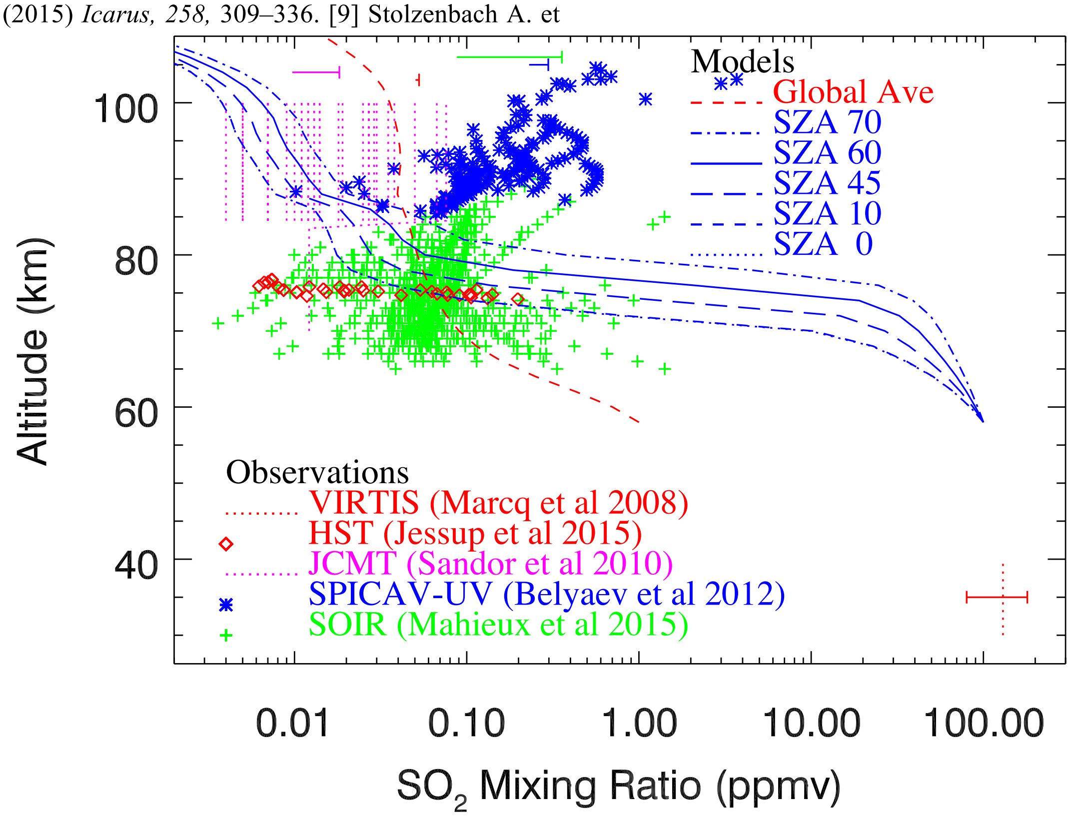

Figure 1: Observed and modeled SO_2 (after [13]). Typical uncertainties on the observations are indicated by the half-error bars at the top. The global-average result is the nominal model from [14]. The SZA-dependent results are updated versions of the results presented in [8].

VENUS: NO BREAKS FROM AN EXTENDED CHILDHOOD W. B. Moore[1,2] and D. G. J. Kankanamge[1], [1]Department of Atmospheric and Planetary Science, Hampton University, 23 E. Tyler St., Hampton VA 23668, william.moore@hamptonu.edu, [2]National Institute of Aerospace, 100 Exploration Way, Hampton VA 23666.

Introduction: The solidus temperature of mantle rocks places a limit on the amount of heat a terrestrial planet's mantle can remove before beginning to melt significantly. If the planet is producing heat at a rate that exceeds this limit, melting and volcanism take over the heat transport process in a process known as heat-pipes [1,2]. In terrestrial planet thermal evolution, this transition is encountered from the hot side, since terrestrial planets begin their lives both hot and strongly heated as they transition out of the magma ocean regime while both short- and long-lived radionuclides are relatively abundant. Thus the heat pipe mode is a universal early stage in terrestrial planet evolution prior to the onset of plate tectonics or the more common rigid-lid convection era.

By providing magma a direct route to the surface, heat pipes short-circuit the lithosphere, which is no longer restricted by the requirement to remove the internal heat by conduction. Instead, the lithosphere thickens at high heat flow due to the rapid downward advection caused by continuous resurfacing. The imposition of a pressure-dependent limit on the temperature (the solidus) also prevents the lid from developing large slopes, reducing lithospheric stress. Both of these factors suppress plate breaking and a transition to plate tectonics (Figure 1) [3].

Extended Childhood: For any terrestrial planet, the difference between the surface temperature and the solidus determines the maximum amount of heat that can be transported without melting the mantle. For a planet with an increased surface temperature, then, the heat pipe mode will be reached at lower heat production rates. Since planets cool from a hot state and gradually lose heat producing elements, it therefore takes longer to reach the heat pipe transition from a given initial heat production rate. This results in an extended period of heat-pipe volcanism for planets with high surface temperature relative to otherwise similar planets with cooler surfaces.

Heat-Pipe Transition: As can be seen in Figure 1, the transition to convection leads to an increase in stress that then decreases with decreasing heat flow. The stresses in this regime are independent of solidus temperature, since the heat pipes have shut off by this point. If a high surface temperature causes the transition out of heat-pipes to occur at a lower heat production rate, then the peak stress reached will be lower.

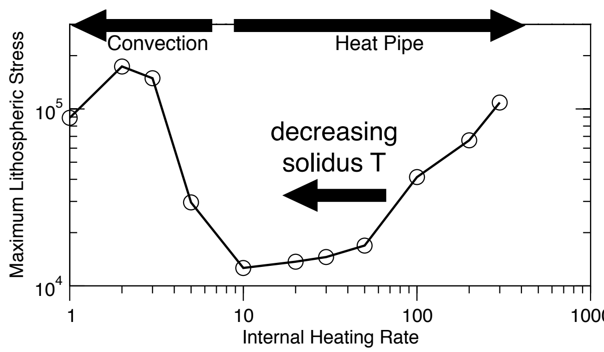

Figure 1. Lithospheric stress vs. Internal Heating showing the large increase in lithospheric stress upon transitioning out of the heat-pipe mode. The arrow indicates how the curve shifts for decreased solidus or increased surface temperature (adapted from [2]).

No Breaks: Plate breaking requires a certain stress level to be achieved in the lithosphere. If this level is not reached, the mantle convects in a rigid-lid fashion. We argue that Venus' high surface temperature maintained by the extreme greenhouse conditions has prevented the onset of plate tectonics by delaying the transition out of the heat pipe mode until the heat production had declined below that required to produce plate-breaking stress.

This hypothesis explains a number of features of Venusian geology that heretofore have been explained by strongly non-monotonic behavior which is difficult to reconcile with evolution from a hot initial state. Instead, the extensive plains volcanism, the apparently thick lithosphere, the uniform crater distribution, and the relatively old age of elevated crust are all explained by the rapid cessation of heat pipe volcanism approximately 1 billion years ago, a delay of about 2 billion years relative to Earth [2]. Venus' extended childhood has therefore caused it to miss its window of opportunity to undergo plate tectonics and it is now stably trapped in the rigid lid state.

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DATA ASSIMILATION OF THE ATMOSPHERE OF VENUS T. Navarro[1], G. Schubert[1], and S. Lebonnois[2], [1]Dept of Earth, Planetary and Space Sciences, UCLA, USA (tnavarro@epss.ucla.edu), [2]Laboratoire de Météorologie Dynamique (LMD/IPSL), Sorbonne Universités, UPMC Univ Paris 06, CNRS/INSU France.

Introduction: Data assimilation is a technique used to reconstruct as accurately as possible the state of the atmosphere using both observations and a Global Climate Model (GCM) [1]. With the help of the model, observations of any kind can be interpolated in space and time. This approach, initially developed for weather forecast on Earth, has been used for many different geophysical systems, including the meteorology of the planet Mars [2]. The rationale is to take the best of observations and a model. Observations are more reliable than results of a GCM. However, they are scattered or with a limited spatial resolution or time coverage and restricted to observable quantities only, such as winds or temperature. The advantage of a model, in contrast, is the possibility to have access to any physical variable at any location and at any time.

In concrete terms, data assimilation is an iterative process, alternating insertion of observations into the model, then integrating the model, and then inserting the observations again, etc... as shown in Figure 1. The output of the assimilation scheme, called the analysis, combines the advantages of both model and observations, by extending observations in space and time using the GCM grid.

By closing the gap between model and observations, data assimilation addresses very well the investigation I.B.1 defined by NASA's Venus EXploration Analysis Group (VEXAG): *"[…] Use global circulation models to comprehensively connect observations acquired over different epochs, altitudes, and latitudinal regions."* [3]; thus helping us to improve our understanding of the current atmospheric processes at work in the Venusian atmosphere.

Current status: As of today, the development of an assimilation for Venus has been initiated, but it is very preliminary. Results are expected in the near future.

Model: The model used for this study is the Institut Pierre-Simon Laplace (IPSL) Venus GCM [4]. It is a state-of-the-art model, including a full parameterization of the physics. See the corresponding abstract [5] for more details.

Assimilation Technique: Over the years, many different assimilation techniques have been developed for Earth meteorology. The simplest one is a correction scheme, consisting of a parameterized nudging of the model towards the observations. More advanced techniques solve a minimization problem, taking into account both model and observation errors.

Although oversimplified and obsolete on Earth, the nudging method has the advantage of making easier the exploration of the behavior of the assimilation on Venus with its particularities: super-rotation, cyclostrophic equilibrium, etc ...

Observations: Since December 2015, the Akatsuki spacecraft has produced observations with 4 cameras in infrared and ultraviolet bands [6].

Given the orbit of Akatsuki, a global view of Venus during most of the orbit enables derivation of global maps of winds, for day and night for the upper cloud region, and for night for the lower cloud region. Such a product is well designed for data assimilation due to its wide spatial coverage and continuous acquisition.

Alternatively or complementary, Venus Express observations could also be assimilated.

Motivation and objective: The current objective is to understand under what conditions data assimilation is feasible for Venus by addressing two questions:

1) What is the necessary density of observations needed to have a successful assimilation? If there are not enough observations to assimilate, the GCM cannot be forced to follow a trajectory that converges to the true atmospheric state. The effective amount of wind vectors retrieved with Akatsuki's cameras does not guarantee that assimilation could be successful. Also, the question of whether the Venus Express data could be sufficient for this task is open.

2) What exactly could be learned from data assimilation? For instance, observations of the cloud deck could have some constraints for the poorly observed deep atmosphere, unraveled by the GCM thanks to the assimilation. Going beyond the spatial and temporal range of observations may allow us to complete specific aspects of our knowledge of the wave activity, the global circulation, energy budget, etc ...

To address these questions, the use of synthetic observations is necessary. Synthetic observations are observations created from a reference run of the GCM, allowing us to study the behavior of the assimilation while having a total control on the observations. Assimilating synthetic observations is a classic and mandatory step before assimilating actual observations in order to design and assess an assimilation scheme, especially in a totally new context as it is the case here with Venus.

Also, addressing theses issues could be of interest for the design of future missions (orbit, instrumentation, number of measurements).

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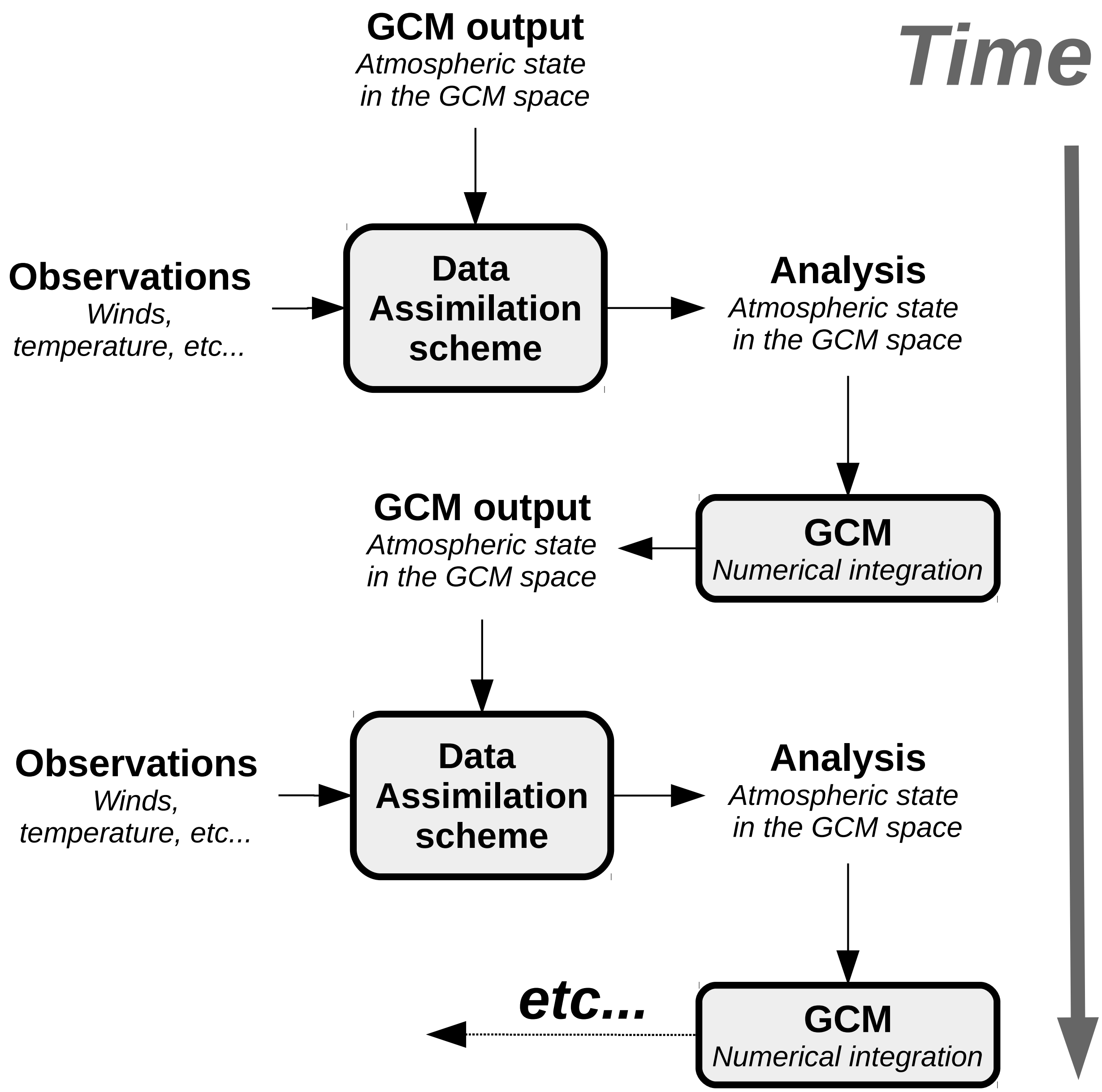

Figure 1: *A very simple view of a data assimilation framework. The analysis serves as an initial state for the GCM.*

NEW PERSPECTIVES ON THE ACCRETION AND INTERNAL EVOLUTION OF VENUS FROM GEOLOGY AND MAGNETISM. Joseph G. O'Rourke, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California 91125, USA (jorourke@caltech.edu).

Introduction: Debate rages over how the interior dynamics of Venus have shaped atmospheric properties and surface habitability over geologic time. In particular, no consensus exists about whether Venus once resembled Earth—potentially for billions of years—or if unique circumstances during their accretion placed these celestial cousins on divergent paths from the start. Even the recent history of volcanism and tectonics remains murky. Here I explore which available and achievable observations best discriminate between various plausible scenarios. High-resolution imagery and topography are universally considered vital, for instance, to decide if resurfacing has been catastrophic or more uniformitarian. Measurements of radiogenic isotopes like argon-40 in the atmosphere are often prioritized, but seem quite permissive unless crustal and mantle chemistry are better known. Crucially, new modeling and observations related to the core arguably deserve increased emphasis to obtain unique constraints on formation processes and total heat budget.

Geology for Geodynamics: Catastrophic resurfacing occurring ~750 Myr ago was proposed to explain why only ~10% of impact craters are obviously embayed in SAR images from NASA Magellan [e.g., 1]. However, impact craters with radar-dark floors (~80% of the population) may have also suffered post-impact volcanic modification [e.g, 2], which is consistent with new statistical analyses of the size and spatial distributions of both dark- and bright-floored craters [3]. Geologic mapping is also non-unique at present—a global stratigraphy supports discrete stages of massive volcanism [e.g., 4], but features with similar morphologies may actually have formed at different times [5]. Numerical models of mantle convection and lithospheric dynamics of Venus are likewise capable of reproducing periodic overturns [6] or more steady-state evolution in the stagnant-lid regime [7] with different sets of underlying assumptions. An accurate geologic history of Venus would thus contribute to general understanding of possible convective regimes in terrestrial planets, applicable also to Earth and small, rocky exoplanets.

Degeneracies for Degassing: The percentage of the total argon-40 that volcanism has degassed from the interior to the atmosphere is often quoted as ~25 ± 10%, roughly half the accepted value for Earth [e.g., 8]. However, a more plausible range is ~10-50% considering realistic uncertainties in the K/U ratio and overall abundance of uranium [7], not to mention controversy over the partitioning behavior. Almost any scenario for crustal production consistent with the cratering record can reproduce the measured mixing ratios unless we assume or obtain at least Earth-like precision on bulk abundances of key elements [7].

Core for Constraints: Spacecraft have failed to detect evidence of an internally generated magnetic field at Venus over the past few decades. In contrast, Earth's dynamo has survived for ~3.5 billion years and possibly even longer. Two hypotheses explain this dichotomy. First, sluggish mantle convection could reduce modern core/mantle heat flow below the value required to sustain a dynamo. Second, Venus could have accreted more gradually than Earth, initially developing compositional stratification that opposes convection [9] or completely solidifying over time. Violent events during Earth's birth like the Moon-forming impact arguably homogenized our core [9] and delivered light elements to drive compositional convection.

Both quiescence after catastrophic resurfacing and continuous stagnant-lid evolution at present imply suppressed core convection unless the thermal conductivity and ohmic dissipation are both low and the radius of the inner core lies within a specific, narrow range. However, these end-member scenarios predict elevated heat flow in the past, which would produce a dynamo if Venus and Earth formed in a similar fashion. Detection of crustal remnant magnetization near the north pole of Venus was recently claimed from low altitude Venus Express data [10], although untangling any signal from the induced field is complicated. Sophisticated numerical simulations with coupled atmosphere-crust-mantle-core dynamics—under development based on [11]—will return the amount of crust that survives below the Curie point until the present after production in earlier epochs with an extant dynamo. Incorporating magnetism into the next generation of Venus models should permit broad conclusions that are impossible to achieve based on geologic and atmospheric studies alone.

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Abstract for Venus Modeling Workshop May 09-11 2017 Cleveland, OH

Understanding Thermal Convection effects of Venus Surface Atmosphere on the Design and Performance of Venus Mission Hardware

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Venus holds the clues to the Earth's and the Solar System's past, present and future. Several key science questions about the planet's surface evolution and interaction with its atmosphere require missions to its surface. The harsh surface environment of Venus poses severe challenges for mission and subsystem designers. To extend mission life for future Venus surface missions, it is required that components/packaging operate in the high temperature/pressure environment have high efficiency thermal control systems. The transient effects of thermal interaction between Venus surface atmosphere and spacecraft bodies designed to operate on its surface is not well understood. This is because the dominant mode of heat exchange, thermal convection, (which is driven by the complex turbulent dynamics of the atmosphere's supercritical fluid state) requires elaborate thermofluid modeling and laboratory testing of relevant hardware geometry in Venus like conditions to predict the subsystem and overall performance. This requirement aligns well with Goals II and III laid down in NASA Venus Exploration Analysis Group (VEXAG)'s *Goals, Objectives and Investigations for Venus Exploration Report*. These goals focus upon studying the structure and evolution of Venus's interior surface and its interaction with the atmosphere. VEXAG's *Venus Technology Plan Report* calls for extensive modeling capability development to enhance the life and performance of future surface missions to Venus.

The presented work focuses on reviewing a list of relevant Computational Flow Dynamic (CFD) modeling strategies of supercritical flows with emphasis on use of high accuracy state equations. Computational inefficiencies and inaccuracies in conventional real gas state equations for supercritical and simultaneous super and subcritical thermodynamic property calculations severely affect modeling capabilities for transient and turbulent cases. A set of possible workarounds and modifications for these are compiled and presented. Several insights gained from the review of supercritical CO_2 internal flow modeling in other industrial applications is presented. A proposed plan to conduct convective heating rate experiments of lander module concepts within the GEER chamber is presented. The heat exchange correlations resulting from the presented work between Venus surface conditions and exposed hardware aim to not just to inform future mission designs but also investigations on Venus surface-atmosphere thermophysical interactions.

MODELING VENUS' ATMOSPHERE AT CLOUD ALTITUDES WITH A NEW MIDDLE ATMOSPHERE GCM. H. F. Parish[1] and J. L. Mitchell[2,1,3], [1]Department of Earth, Planetary and Space Sciences, University of California Los Angeles, 595 Charles Young Drive, Los Angeles, CA 90095, hparish@epss.ucla.edu, [2]Westmont College, 955 La Paz Road, Santa Barbara, CA 93108, [3]Department of Atmospheric and Oceanic Sciences, University of California Los Angeles, Box 951565, Los Angeles, CA 90095, jonmitch@ucla.edu.

Introduction: One of the most prominent but poorly understood features of Venus' circulation is the strong westward cloud-level superrotation, with velocities ~100 m/s, around 60 times faster than the surface rotation. The mechanisms involved in generating this circulation at cloud altitudes and maintaining westward superrotation with observed magnitudes below the clouds are not well understood. Wind velocities between the ground and cloud altitudes cannot be observed remotely and the only in-situ wind profiles come from a few entry probe observations on the Venera [1] and Pioneer Venus [2] missions, and are limited in spatial and temporal coverage: they were all in the midnight to noon timeframe and all but one was at latitudes between +/- 30^0 [3]. Measurements from the Visible and Infrared Thermal Imaging Spectrometer (VIRTIS) and Venus Radio Science Experiment (VeRa) instruments aboard Venus Express have been used to infer temperatures and winds within the ~40 to 90 km altitude range [4], [5], [6], [7]. Temperature measurements are available in the 0 to 10 km altitude range and composition is available within limited altitude ranges between 0 and ~35 km from VIRTIS [8], [9]. However, details of the circulation and dynamics below 40 km altitude are scarce. Significantly, the circulation and dynamics in the lowest scale height (~16 km) above the surface of Venus are very poorly known since the winds are small compared with the accuracy of the few measurements. To date, no numerical models have succeeded in simulating the superrotation between the surface and cloud levels with magnitudes comparable to those observed.

Simulations: We have therefore taken a different approach in this work and have developed a new Venus Middle atmosphere Model (VMM), which simulates the atmosphere from just below the cloud deck to around 100 km altitude, with the aim of focusing on dynamics at cloud levels and above. We present preliminary results from the VMM using a simplified radiation scheme, with the goal of benchmarking against available observations, including those from the Venus Express and Akatsuki missions. Using our validated simulations, we aim to constrain poorly-measured atmospheric parameters including winds and temperatures close to the lower boundary.

Observations show waves with a wide variety of periods and wavelengths at cloud altitudes, including gravity waves [10], [11], [12], thermal tides [13], [14], [15], Rossby waves [16] and Kelvin waves [17], [18]. In the near term, we plan to implement a wave forcing scheme to determine the influence waves may have on the cloud-level atmosphere. We will use sensitivity tests to infer wave forcing amplitudes by comparing results of simulations with data at higher altitudes, including observations from the Venus Express and Akatsuki missions.

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Experimental and Thermodynamic Study of the Stability of Pyrrhotite under Simulated Venusian Surface Conditions. S. T. Port and V. Chevrier, University of Arkansas, Fayetteville, AR, 72701; (saraport@email.uark.edu)

Introduction: In the late 1970s sulfur was discovered to be a major part of the atmosphere of Venus when its signature was first discovered via ultraviolet spectrometry [1-3]. It is now known that the majority of the sulfur found in the atmosphere is bound in such molecules as SO_2, H_2SO_4, and COS, among many others [1-3]. Since then researchers have been attempting to determine the sources and sinks of sulfur on Venus via thermodynamic modelling and experimentation [1-6].

Thermodynamic modelling completed by researchers in the past has revealed that pyrrhotite (Fe_7S_8) may be one of several common sulfur minerals on the surface of Venus [6]. Through the use of both experimental and theoretical research it has been revealed that pyrrhotite may oxidize so slowly that it could survive for millions of years on Venus [7]. Pyrrhotite is also of interest because it may be a source of COS with evidence of increasing concentrations of COS with decreasing altitude on Venus [6, 8]. We present here a combination of modelling and experiments to determine the stability of pyrrhotite on the surface of Venus. By using both methods we can compare and contrast our results to better determine the stability and behavior of pyrrhotite on the surface of Venus.

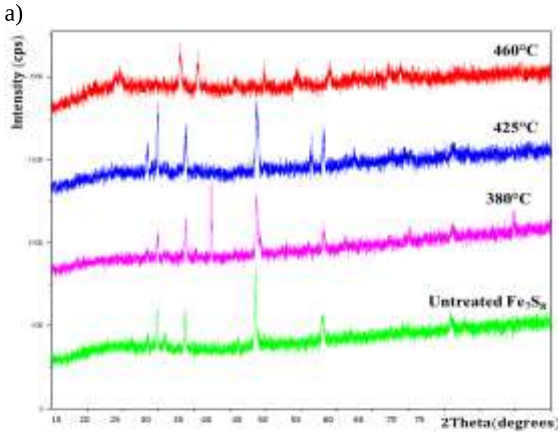
Methods: The effects of Venusian temperature and gas mixtures were tested on monoclinic pyrrhotite (Fe_7S_8). Two grams of pyrrhotite was inserted into a Lindberg Tube Oven at three different temperatures correlating to different altitudes on Venus: 460°C (0 km), 425°C (4.5 km), and 380°C (11 km). The pyrrhotite was placed in one of three different gas mixtures: pure CO_2, 100 ppm of SO_2 in CO_2, or 100 ppm of COS in CO_2. Each experiment lasted a total of 24 hours after which the samples were removed and weighed. The samples were then analyzed via X-Ray Diffraction using the X'Pert MRD to reveal if there were any compositional changes to the sample.

Using the thermodynamic modelling program, THERMO-CALC, we began to model the conditions observed in the experiments to compare with our experimental results.

Results: When pyrrhotite was heated to 380°C in pure CO_2 some of the pyrrhotite formed troilite (FeS). However when the sample was heated to 425°C troilite was not present, but instead magnetite (Fe_3O_4) formed. When the sample was heated to 460°C the sample fully turned into mikasaite ($Fe_2(SO_4)_3$) and hematite (Fe_2O_3) (Fig 1a). In the experiment completed in CO_2 /COS heated to 380°C both pyrite and hematite formed. However when it was heated to 425°C and 460°C all the pyrrhotite turned into hematite and mikasaite (Fig 1b). In the experiments completed in CO_2/SO_2 heated to 380°C pyrite and hematite were both present, but only hematite was present at 460°C. The 425°C experiment has not been completed at this time.

Preliminary modelling completed at pure CO_2 with a mix of 50 ppm of SO_2 (Fig 2a) and a mix of 100 ppm of SO_2 (Fig 2b) showed the stability of magnetite, pyrite, and pyrrhotite, but no hematite. Mikasaite was not taken into account in the calculations. There was a small change in temperature stability, about 10 degrees, for both magnetite and pyrite as a result of the change of 50 ppm of SO_2 to 100ppm of SO_2.

a)



b)

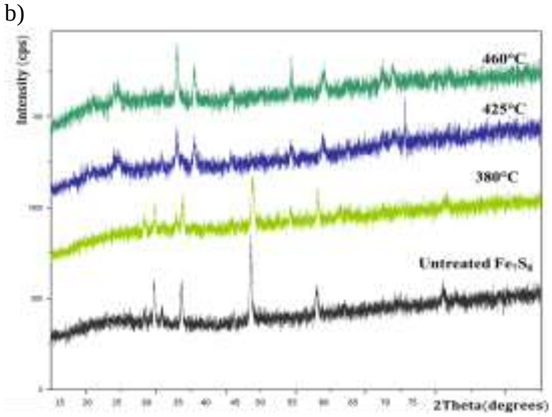
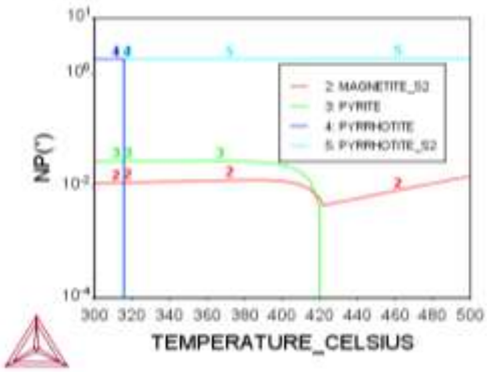


Figure 1: XRD results of the pyrrhotite experiments. Untreated pyrrhotite is graphed at the bottom, followed by pyrrhotite heated at 380°C, followed by pyrrhotite heated in 425°C, and followed by 460° a) completed in pure CO_2 b) completed in 100 ppm of COS in CO_2

Table 1: a) Mineralogical results of the pyrrhotite experiments completed in pure CO_2, 100 ppm of SO_2 in CO_2, and 100 ppm of COS in CO_2. Dashed lines represent experiments that have not yet been completed. Results are

listed in order of how well the spectra matched the XRD database.

	460°C	425°C	380°C
CO_2	Fe_2O_3 $Fe_2(SO_4)_3$	Fe_7S_8 Fe_3O_4	Fe_7S_8 FeS
CO_2 **COS (100 ppm)**	Fe_2O_3 $Fe_2(SO_4)_3$	Fe_2O_3 $Fe_2(SO_4)_3$	$Fe_{1-x}S$ FeS_2 Fe_2O_3
CO_2 **SO_2(100 ppm)**	Fe_2O_3	--- --- ---	FeS_2 Fe_7S_8 Fe_2O_3



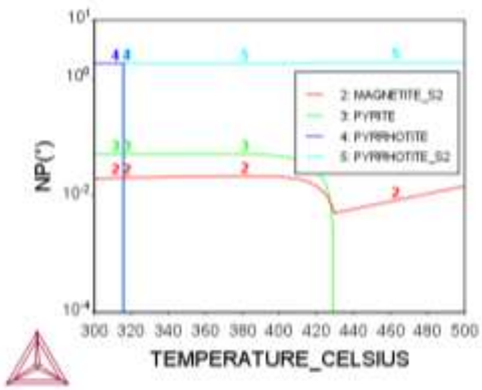


Figure 2: Preliminary THERMO-CALC data. The y-axis is the mole fraction of phases and the x-axis is the temperature. Magnetite, hematite, pyrrhotite (monoclinic), pyrrhotite_S2 (hexagonal), and pyrite were all taken into account a) 50 ppm of SO_2 in CO_2 and b) 100 ppm of SO_2 in CO_2

Discussion: Pyrrhotite was found to be unstable at high temperatures. This can be observed by the formation of troilite at the lowest temperature experiment (380°C) in pure CO_2. This is a direct result of the increasingly larger Fe/S ratio as the sulfur continually vaporized [7]. At 425°C the pyrrhotite reacted with the CO_2 thus forming magnetite. The 460°C experiment resulted in the formation of mikasaite and the oxidation of magnetite into hematite [7]. These experimental results are very similar to those obtained by past experiments, except for the formation of mikasaite [7].

In the 380°C experiments completed in CO_2/COS and CO_2/SO_2 both hematite and pyrite formed, which was unexpected as previous experiments have detected pyrite to convert into pyrrhotite at higher temperatures [7]. The presence of oxidized minerals at all temperatures was unexpected. This is likely because COS and SO_2 require less energy than CO_2 to dissociate. The oxygen then readily reacts with pyrrhotite to form the various oxidized minerals observed. Though the oxidation of pyrrhotite is thought to release COS, it cannot be confirmed at this time.

The preliminary models do not demonstrate the stability of hematite. More work needs to be done to determine why this is the case. Though the stability of pyrrhotite does not change, the stability of magnetite and pyrite does alter slightly under different amounts of SO_2. As more SO_2 is added to the system both minerals become more stable at higher temperatures.

Conclusion: The pyrrhotite experiments resulted in several oxidized minerals: magnetite, hematite, and mikasaite. Our experiments show that pyrrhotite oxidizes in all gases, but begins to oxidize at lower temperatures when the gas is mixed with COS or SO_2. These results show that even with a small amount of COS and/or SO_2, their interaction with sulfur minerals is not negligible.

It is important to use both experimental and modelling techniques in order determine the reactions that could occur on Venus. By comparing our experimental and modelling results we can use it to better interpret our results and to strengthen our conclusions. Our results may also be used to correct or modify the databases used by the model or the XRD.

Future Work: Pyrrhotite will be tested in the Venus Simulation Chamber located at the University of Arkansas. The chamber is vital to our experiments because it can simulate the temperatures and the corresponding pressures found on Venus, thus adding accuracy to our experiments. More modelling will also be completed to compare with our experimental results.

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THE STABILITY OF MINERALS AND VOLCANIC GLASSES ON THE SURFACE OF VENUS. B. G. Radoman-Shaw[1], R. P. Harvey[1], G. C. C. Costa[2], N. S. Jacobson[2], A. Avishai[3], and L. M. Nakley[2], [1]Department of Earth, Environmental, and Planetary Science, Case Western Reserve University, 10900 Euclid Avenue Cleveland, OH 44106 (bgs21@case.edu). [2]NASA Glenn Research Center, 21000 Brookpark Road Cleveland, OH 44135. [3]Swagelok Center for Surface Analysis of Materials, Case Western Reserve University, 10900 Euclid Avenue Cleveland, OH 44106.

Introduction: Crust/atmosphere interactions are thought to play an important role in the evolution of Venus' atmosphere [1]. Limited *in situ* analysis of the surface of Venus and minimal determination of major and minor constituents in the lower atmosphere provide limited insight into possible dominant solid-gas reactions that can occur. Prior experimental modeling provides conflicting hypotheses as to the importance and chemical stability of certain mineral phases on the surface of Venus such as sulfides, silicates, and carbonates [2,3,4]. There is also debate over the influence minor atmospheric components have over these phases, including sulfur and carbon bearing components, even fluorine and chlorine.

We are currently conducting experiments that expose a variety of material to simulated Venusian temperature, pressure and atmospheric chemistry conditions using the Glenn Extreme Environment Rig (GEER) at NASA Glenn Research Center. From this exposure, we can experimentally suggest which mineral phases are more or less likely to be stable on the surface, and which are more reactive with the atmosphere.

Samples: For our initial 42-day experiment we exposed a total of 14 mineral phases and 11 amorphous phases. These included several common basaltic silicates, along with iron oxides, siderite and calcite, and iron sulfides pyrrhotite and pyrite. Glasses included basaltic and calc-alkaline compositions and included both natural and synthetic varieties. The sample chips of each phase averaged 40 mg in mass and were roughly 1 square cm in size. Two opposing faces of each sample were polished to create a common surface texture for pre- and post-exposure electron microscopy. These samples were then attached to custom 316 stainless steel mounts using gold wire. We verified the mineralogy and crystallinity of each sample through powder x-ray diffraction.

Methods: The Glenn Extreme Environment Rig (GEER) at the NASA Glenn Research Center in Cleveland, OH, provides unparalleled high fidelity simulation of Venus atmospheric pressure, temperature and chemistry. The temperature and pressure for this experiment were kept at 460°C and 92 bar (1334 psi) for 42 days, thereby keeping the simulated atmosphere above the supercritical point for CO_2 and within accepted near-surface temperature and pressure conditions for Venus.

The gas fill for the experiment, in order of abundance, included CO_2, N_2, SO_2, OCS, H_2O, CO, H_2S, HCl, and HF. SO_2 concentration was monitored during the experiment. The concentration dropped below the desired level of 180 ppm twice and was subsequently boosted both times in order to maintain the desired levels.

Results: Preliminary analysis of chips exposed during this experiment has begun using secondary electron (SE) imagery and EDS elemental mapping to search for textures and secondary mineralization consistent with reactivity. Here we report the results for several phases suggested to be important in the literature as well as some phases rarely considered in the literature that appear to be highly reactive.

Minerals – Wollastonite and Calcite: Urey (1952) [5] first suggested the importance of Venus atmosphere/crust interactions by suggesting reactions involving wollastonite and calcite could buffer the CO_2 abundances in the atmosphere. Our results suggest neither is inherently stable under Venus surface conditions; both show extensive secondary mineralization and a key product of one of these reactions (SiO_2) is apparently missing. As shown by Figure 1, wollastonite exhibits botryoidal secondary mineral growth in some instances and in certain areas almost appears faceted. On the edges of the sample this material is clumped together. On the surface however, the material looks more separate, like an immiscible fluid beading up on the surface (Figure 1b). This material is silica absent and sulfide rich (Figures 1c-d). Due to the small grain-size of the material, its exact composition is unclear but it is most consistent with calcium sulfate (anhydrite). Our exposed calcite sample similarly shows secondary mineralization to form a "vermiform" texture of semi-faceted material connected in a disjointed way (Figure 2). The surface texture is varied, with the vermiform material above smaller pseudo-faceted material and some almost acicular textured phases (Figure 2c). As with wollastonite, elemental mapping suggests strong sulfur and oxygen peaks suggesting the production of

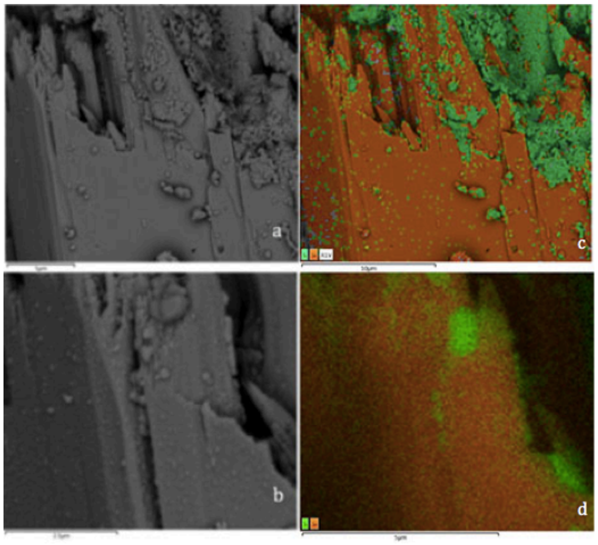

Figure 1: Images 1a and 1b are SE images of the reacted NMNH-8243801-Wol-R1v specimen. XEDS map 1c of corresponds to the electron image 1a and 1b corresponds to the XEDS map 2d. Sulfur is green and silicon is in orange in both maps.

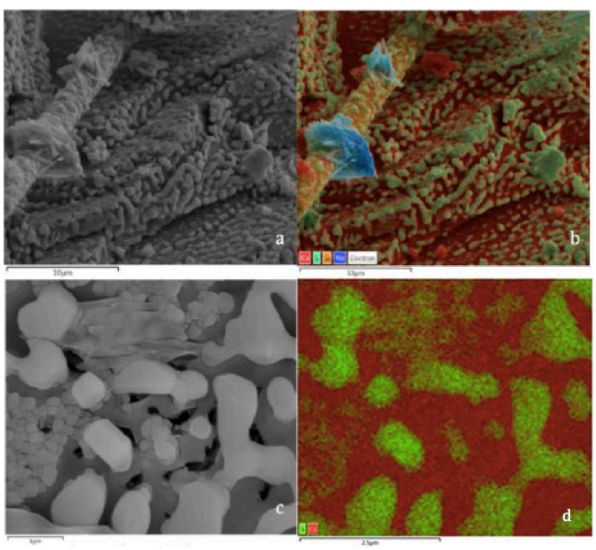

Figure 2: The two electron backscatter images are of the reacted CWRU-Cal-R2b sample and image 2a and 2c correspond to the XEDS maps 2b and 2d respectively. The elements shown in both maps are calcium, sulfur, silicon, and sodium corresponding to red, green, orange and blue respectively.

secondary sulfate (Figure 2d).

Glass – Venera 13 synthetic glass: A key component of our experiment is to explore volcanic glasses as a reactant in Venus crust/atmosphere interactions. A glass synthesized to match Venera 13 *in situ* analyses exposed to Venus surface conditions exhibited significant growth of euhedral secondary crystals largely made of iron, calcium and sodium (Figure 3). The full stoichiometry of this phase is not yet known.

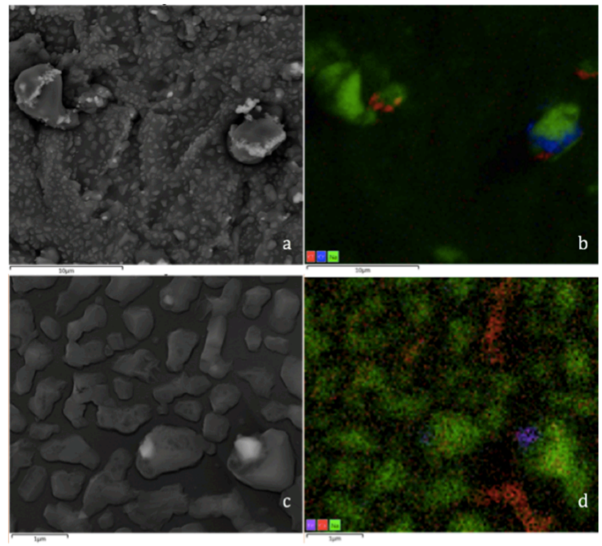

Figure 3: Images 3a and 3c are BSE images of the reacted Venera 13 synthetic glass specimen. XEDS map 3b corresponds to the electron image 3a and 3c corresponds to the XEDS map 3d. In XEDS map 3b red, blue, and green are chlorine, chromium, sodium and respectively. On map 3d purple is iron, red is calcium and green is sodium.

Discussion: The most common secondary minerals formed in our experiments are sulfur-bearing compounds, suggesting sulfur plays an exceptionally active role in crust/atmosphere interactions. Our results are consistent with FactSage calculations [6] suggesting both calcite and wollastonite are unstable under Venus surface conditions; the high reactivity of sulfur effectively dominates carbonate/silicate interactions. SiO_2 appears to have been lost to solution within the supercritical fluid that is the Venus surface atmosphere. Glasses (including samples not discussed here) appear to be highly reactive, with many cations behaving in a highly volatile fashion. Understanding the behavior of these components should be priorities for future models of Venus crust/atmosphere interactions. A second, longer exposure with better control of gas chemistry is scheduled to begin mid-March 2017.

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VISAGE Rock Sampling Drill. F. Rehnmark[1], E. Cloninger[1], C. Hyman[1], K. Zacny[1], K. Kriechbaum[2], J. Hall[2], J. Melko[2], J. Bailey[1], B. Wilcox[2], K. Sherrill[2], [1]Honeybee Robotics (398 West Washington Blvd, Ste 200, Pasadena, CA 91104, rehnmark@honeybeerobotics.com), [2]JPL (4800 Oak Grove Dr, Pasadena, CA 91109, jeffery.l.hall@jpl.nasa.gov).

Introduction: A rock sampling drill capable of operating in the high temperature environment found on the surface of Venus has been built and tested at JPL's Venus Materials Test Facility (VMTF). The drill is powered by two brushless DC motors and includes a planetary gearbox and drilling depth sensor. The drill is designed to break up surface rock (0-5cm depth) into fine powder that can be pneumatically transported via an airlock into the cool interior of a lander, where science instruments can analyze the sample. The paper will discuss the results of drilling trials and how the data may be used to interpret physical properties of the surface rock including rock hardness and specific energy required to drill through it and reduce it to fines as a function of depth.

History of Surface Sampling on Venus: Despite their similar size, composition and distance from the Sun, Venus and Earth have dramatically different climates. With an extremely dense (~92 bar pressure) and hot (average 462°C) surface atmosphere consisting mainly of carbon dioxide, Venus today is inhospitable to life as we know it and more difficult to explore than our other neighbor Mars. This has been confirmed by a handful of missions to Venus, including the Soviet Venera and Vega landers, which succeeded in reaching the planet's surface and operating for a record 127 minutes before overheating. Several of these landers were equipped with a rotary drill used to collect surface rock samples for analysis. The drill was mounted outside the lander pressure vessel and, therefore, completely exposed to the Venus atmosphere. Special high temperature (HT) actuators were developed to run the drill for 120 seconds to a depth of 30 mm. The collected sample was then transported through an airlock to an x-ray fluorescence (XRF) spectrometer instrument located inside the spacecraft for analysis. From drill deployment to sample delivery, the whole operation lasted only 200 seconds [1]. Due to the difficulty of collecting data in this challenging environment, important questions remain about Venus's past and why it developed differently than our own planet.

Relevance of High Temperature Sampling Mechanism Technology for Venus: The NRC's Planetary Science Decadal Survey 2013-2022 recommends a mission called VISE (Venus In-Situ Explorer) to study the surface composition of Venus as a candidate for the next NASA New Frontiers program selection [2]. NASA's Venus Exploration Analysis Group (VEXAG) lists HT actuators (comprising motors, sensors and gearing) and mechanisms for surface sample acquisition and handling as subsystem technologies critical to the future exploration of Venus [3]. Extending Venus surface mission capabilities beyond the current state-of-the-art will require new HT actuators and mechanisms to enable mobility [4], manipulation and, eventually, sample return. An additional benefit is the possibility of 100% microbial decontamination of sampling tools for any destination by means of autoclave sterilization. NPR 8020.12D Planetary Protection Provisions for Robotic Extraterrestrial Missions defines the time and temperature required for absolute sterility as follows: spacecraft organisms and their associated environment must reach a temperature of at least 500°C and must remain at this temperature for at least one half second.

Development of High Temperature Actuators and Mechanisms for VISE/VISAGE: Although the Soviet landers were equipped with rock sampling drills that apparently worked and provided useable samples, the hardware, design documents and test results are not available for review so the technology must be considered relatively immature and an area of active research. Previous development work at Honeybee Robotics produced and characterized HT actuator components by operating them in an environmental chamber simulating ambient conditions on Venus [5][6]. These tests confirmed material selection and yielded useful performance data including torque, speed and efficiency available at Venus temperature and pressure (VTP). To study the effect of temperature on drilling performance in various rock formation materials, early HT drilling tests were conducted using an existing prototype planetary drill and a commercial drill bit by means of a mechanical feed-through into a HT oven. Although the drill was underpowered for the sample collection requirements of a Venus mission, the test revealed a 75% decrease in rate of penetration (ROP) at elevated temperature as compared to room temperature (RT) [1]. Other studies have demonstrated the increased drilling efficiency gained by augmenting rotary drilling with percussive hammering when drilling in hard rock formations [7]. Building on this prior work, Honeybee Robotics has developed a rotary percussive drill for a proposed Venus mission known as VISAGE (Venus In Situ Atmospheric and Geophysical Explorer).

Venus Surface Modeling: One of the science objectives listed in VEXAG's 2014 Roadmap for Venus Exploration is to study the surface geochemistry and mineralogy in the highly deformed and possibly ancient tessera regions [8]. In order to determine the composition of these regions, VISAGE will require sampling capabilities and autonomous control similar to Venera. Some design assumptions must be made about the desired sampling parameters and the strength of the hardest rock that the VISAGE drill could encounter. Venera soil sampler telemetry data was analyzed to obtain indirect measurements of the physical and mechanical characteristics of the surface rock at the landing sites. From the drill speed, depth of penetration and motor current, the physical strength of the rock was estimated to be similar to weathered porous basalt or volcanic tuff [9]. Accordingly, the VISAGE drill is being tested in Saddleback Basalt, a readily available terrestrial analog with an unconfined compressive strength (UCS) of ~120 MPa.

Testing at VTP: Drilling trials are being conducted to compare the penetration rates observed when drilling at VTP vs. RT and when drilling in weathered basalt vs. freshly exposed basalt. **Fig. 1** shows the VISAGE drill attached to the lid of the Venus chamber before and after exposure to the Venus environment.

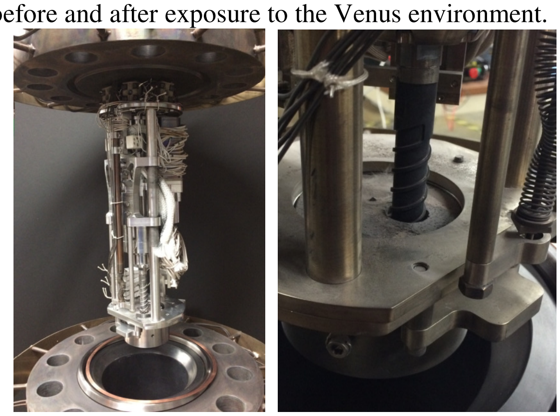

Figure 1. VISAGE drill before (L) and after (R) drilling at VTP.

Drilling depth is measured during each trial using an LVDT (Linear Variable Differential Transducer). The plot in **Fig. 2** shows preliminary LVDT data from one of the VTP drilling trials using freshly exposed basalt. In this trial, an average drilling rate of penetration (ROP) of 3.9 mm/min was observed, corresponding to a specific energy of 0.7 Whr/cc. In comparison, a room temperature drilling trial performed using the same rock specimen resulted in a higher average ROP of 4.3 mm/min, which may be attributed to the increased stiffness of the spring driving the percussor at room temperature vs. high temperature. Thus, we did not observe the anticipated 75% loss in drilling efficiency reported earier in [1].

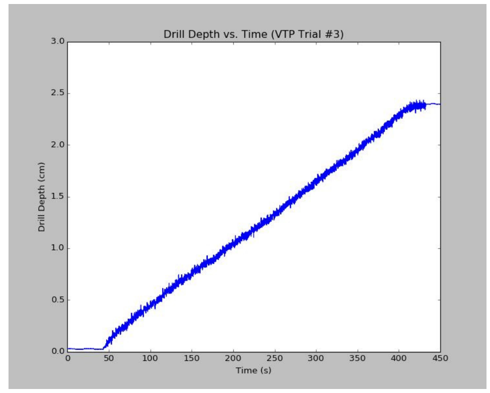

Figure 2. Drill depth data from a test performed at Venus temperature and pressure.

Additional tests of the VISAGE drill are planned for the near future, including drilling on a natural, weathered surface at both RT and VTP and characterization of specific energy required to drill through Venus analog rocks of varying hardness.

Summary: The VISAGE rock sampling drill has demonstrated penetration rates at VTP compatible with a Venus mission timeline. Characterizing the drilling performance in Venus analog rocks of varying hardness can aid in interpretation of drilling data during the VISAGE mission.

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MONITORING AND MODELING EFFUSIVE VOLCANISM ON VENUS. J. A. Richardson[1] and L. S. Glaze[1], [1]Planetary Geology, Geophysics, and Geochemistry Lab, NASA Goddard Spaceflight Center, Greenbelt, Maryland, USA; jacob.a.richardson@nasa.gov.

Introduction: Effusive volcanism on Venus is responsible for a wide variety of volcanic landforms including small ~1 km shields that are potentially monogenetic, steep sided "pancake domes," and large shield volcanoes [1]. While the compositions of these landforms are not precisely known, most lava flows on Venus are basaltic while some volcanic terrains might be felsic. Change in silica content is the most efficacious parameter in determining final lava flow morphology. Future Venus science will enable lava flow modeling that is already possible on Earth, the Moon, and Mars.

On Earth, lava flow modeling is used to monitor active lava flows, constrain volumetric flow rates, and forecast final extents of flow inundation [2,3]. On Venus, lava flow modeling has been used to constrain flow rate and viscosity for circular pancake domes [4]. Numerical lava flow models can be used to model Venus flows either in real time, in the event an active flow is identified, or as a comparison to observed flows. Probabilistic lava flow simulation can provide insights including: pre-flow topographic uncertainty [5], bulk viscosity, and flow rate [4]. Bulk viscosity in turn relates to silica content and thermal history of the flow.

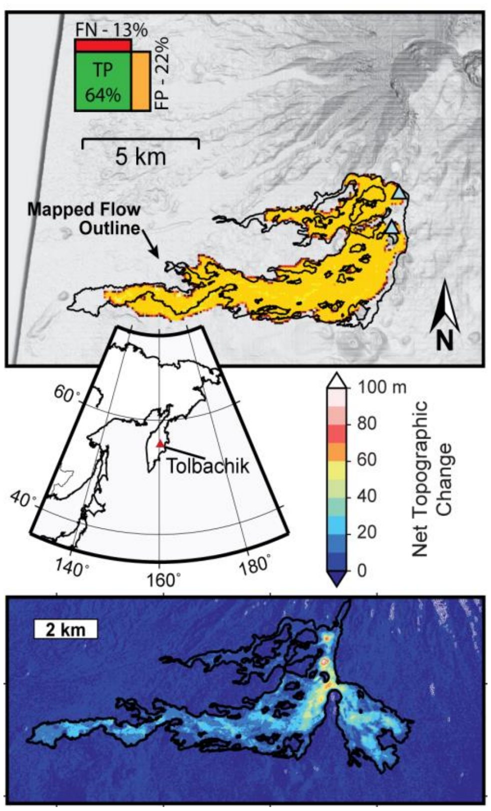

Figure 1. (above) Lava flow simulators have been validated against real lava flows [5]. (below) InSAR can aid in volume calculation during active flows [2].

Modeling Active Volcanism: Recent thermal anomalies in the Ganiki Chasma rift zone have been identified as potential lava flows [6]. If higher resolution topography (100s of meters spatial resolution) were available, on a first order, simulations could forecast direction of flow propagation and could be compared against thermal anomalies to see if they are realistically shaped. With InSAR data, volume and areal extent can be modeled. Physical parameters, such as viscosity, effusion rate, and initial temperature, within lava flow simulators could be inverted to find best fit values.

Modeling Volcano Clusters: Venus has been recently resurfaced by expansive volcanic plains [7]. Modeling plains using lava flow simulators can constrain the lava flow volume distribution. Volume and cadence of flows will impact lava plain morphology.

Volumes of lava flows can be compared to Earth to understand the overall magma productivity of Venus. Small volcanic vents within clusters on Venus that have been identified with Magellan data are spaced an order of magnitude farther from each other than on Earth (Fig. 2). If volumes are similar to Earth's small volcanoes, then the magma production per unit area would be fundamentally different from Earth. Higher resolution imaging data could reveal clusters that may or may not be more similar to Earth.

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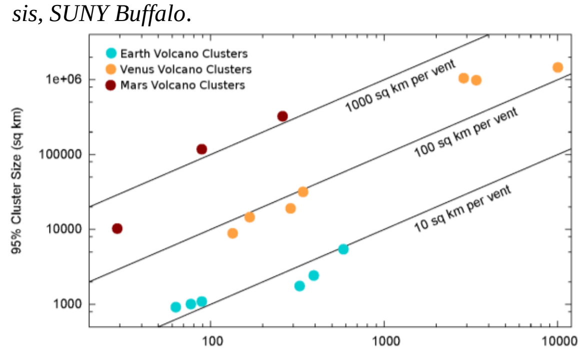

Figure 2. Volcano clusters on Venus are packed at 100 sq km per vent, an order of magnitude less packed than analogous Earth clusters [5].

MODELING VENUS THROUGH TIME. M.J. Way[1,2] AND A.D. Del Genio[1] AND D.S. Amundsen[1,3], [1]NASA/Goddard Institute for Space Studies, 2880 Broadway, NY NY, USA michael.j.way@nasa.gov, [2]Department of Astronomy and Space Physics, Uppsala University, Uppsala, Sweden, [3]Department of Applied Physics and Applied Mathematics, Columbia University, New York, NY, 10025, USA

Introduction: In a recent paper [1] we demonstrated that the climatic history of Venus may have allowed for surface liquid water to exist for several billion years using an atmosphere similar to modern day Earth. The key ingredients to Venus's ability to sustain temperate surface conditions in our model consistened of:

1.) Using a solar spectra from 2.9 billion years ago, and 715 million years ago for the incident radiation.
2.) Assuming that Venus would have had the same slow modern retrograde rotation rate throughout the 2.9 to 0.715 Gya history explored.
3.) Using atmospheric constituents similar to modern day Earth.
4.) Giving the planet a shallow ocean constrained by published D/H ratio observations.

The original simulations in [1] had to include O_3 as an atmospheric constituent because the only radiation scheme possible under the ROCKE-3D GCM [2] at that time could not be run without it.

In the meantime further simulations have been carried out using the SOCRATES [3] radiation scheme which is newly coupled to ROCKED-3D. This allows the omission of O_3 and the possible exploration of a wider range of atmospheric constituents

Methods: We have utilized ROCKED-3D coupled with SOCRATES to continue to explore paleo-Venus in the context of the Faint Young Sun and the few other constraints we have on Venus' early history:

1.) We have confirmed the validity of our earlier results [1] with SOCRATES.
2.) We have explored other possible atmospheric constituents in the same manner they have been used to explain the Faint Young Sun Paradox for paleo-Earth climate [4,5].
3.) Since the D/H ration on Venus is poorly constrained giving estimates between 4 and 525m of liquid water if spread evenly across the surface of Venus [6] we explore the effects different amounts of surface water (and corresponding changes in topography) within this range would have on the ancient Venus climate.

Conclusions: Using ROCKE-3D with the SOCRATES radiation scheme but utilizing the same topography, water content, and atmospheric constituents as in [1] we have confirmed our earlier conclusions that a paleo-Venus under the same conditions would have had a temperate climate over the same period of time previously modeled. Changing the amount of water on the surface, and hence the topographic relief does have an effect on the climate of paleo-Venus as we will demonstrate.

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EnVision, a proposed ESA Venus orbiter mission. R. C. Ghail[1], C. F. Wilson[2] and T. Widemann[3,4], [1]Department of Civil and Environmental Engineering, Imperial College London, London, SW15 3HA, UK, *r.ghail@imperial.ac.uk*, [2]Department of Atmospheric, Oceanic and Planetary Physics, Oxford University, Oxford, OX1 3PU, UK, *Colin.Wilson@physics.ox.ac.uk* [3]Observatoire de Paris – LESIA UMR CNRS 8109, 92190 Meudon, France, [4]Université Versailles St-Quentin - DYPAC EA 2449, France, *thomas.widemann@obspm.fr*.

Introduction: The EnVision Venus orbiter proposal is currently under consideration by ESA as a potential mission for launch in 2029. Following the primarily atmospheric focus of Venus Express, EnVision focusses on Venus' geology and geochemical cycles, seeking evidence for present and past activity. The payload comprises a state-of-the-art S-band radar which will be able to return imagery at spatial resolutions approaching 1 m, and capable of measuring cm-scale deformation; this is complemented by subsurface radar, IR and UV spectrometers to map volcanic gases, and geodetic investigations.

Although the launch date is over a decade away, there are many modelling investigations to be carried out, to develop hypotheses to be tested using data from Envision, from lab testing of surface materials and surface-atmosphere interaction, to computational models charting how Venus and its climate have evolvedthrough time.

Science Payload:

The science payload comprises three instruments, as well as additional geodesy investigations using radio science.

VenSAR. The largest payload instrument is a phased array S-band radar, developed from the UK's low-cost NovaSAR-S instrument, with ERS, ENVISAT and Sentinel-1 heritage, optimized for Venus. Use of spacecraft pointing for side-looking, instead of a fixed slant, simplifies the observation strategy (Fig 1) to three pairs of ~9 minute/orbit (~36° latitude, ~3800 km) pass-to-pass InSAR swaths (or opposite-look swaths after Cycle 1), two ~9 minute/orbit multipolar (HH-HV-VV) swath at lower incidence angle for stereo mapping, two ~3 minute/orbit (~12° latitude, ~1300 km) high resolution swath and 1 to 2 S-band emissivity swaths per day.

InSAR swaths are contiguous to meet the repeat-pass requirement while gaps in the StereoPolSAR,

HiRes and emissivity are filled in during later passes, providing a full suite of data for specific targets totaling ~25% of the surface. ~1 m resolution sliding spotlight images, each ~50 km2 in area, will also be obtained at the Venera landing sites and other locations identified during the mission. In addition, InSAR will be acquired along a narrow equatorial strip and across the North Pole to measure variability in the spin rate and axis.

EnVision has not been designed to provide global VenSAR coverage; rather, the VenSAR investigation has been designed to provide nested datasets of target regions, including topography, radiometry and polarimetric imagery as well as high-resolution imagery at 1-10 m resolution. This combination of data products will allow detailed study of targets which represent different terrain types.

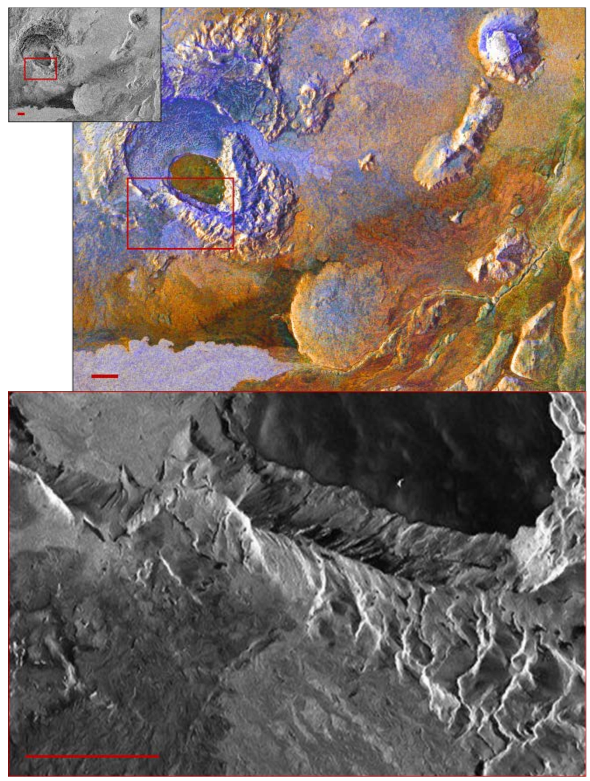

Fig. 1 Simulated VenSAR image products from Holuhraun, Iceland. Top Left: Simulated Magellan 110 m resolution SAR image (derived from Sentinel 1a data). Notice low contrast from 2-bit BAQ compression and foreshortening due to lack of appropriate DEM. Upper Right: Simulated 30 m resolution HHVHVV StereoPolSAR image (derived from Sentinel 1a data). Note the new lava flow in blue at lower left. Bottom: Simulated 6 m resolution HiRes image (derived from TerraSAR-X data). Scale bar in all images is 2 km.

VEM. The Venus Emissivity Mapper suite comprises two UV and IR spectrometer channels in addition to the VEM-M IR mapping. VEM-M global IR-mapper [3] incorporates lessons learned from VEx/VIRTIS: band-center and width-scatter are ~5 × more stable, with decreased scattered light and improved sensitivity; a filter array provides wavelength stability and maximizes signal to the focal plane array (FPA). VEM-H is high-resolution, nadir-pointing, infrared spectrometer, the ideal instrument to enable characterization of volcanic plumes released from the surface of Venus by observing SO2, H2O and HDO through the 1 µm, 1.7 µm, and 2-2.3 µm atmospheric windows. Specifically, VEM-H is a redesign of the LNO (Limb, Nadir and Occultation) channel of NOMAD, retaining much heritage from the original with minor modifications to meet the science objectives of the M5 EnVision mission. The third channel, VEM-UV is an upper-atmosphere UV spectrometer dedicated to global SO2 & sulfur cycles.

SRS. The Subsurface Radar Sounder will image faults, stratigraphy and weathering in the upper ~100 m of the areas mapped by VenSAR, to identify structural relationships and geological history.

Radio Science. EnVision will provide an improved global gravity map, by tracking orbital perturbations using the spacecraft's communications system. Simulations indicate that the resulting global gravity map will have degree and order in excess of 120, and improve the accuracy of the Love number k_2 from +/- 0.07 to +/- 0.01, enabling better constraints on Venus' internal structure.

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QUANTUM CHEMICAL STUDIES OF REACTIONS INVOLVING SULFUR AND SULFUR-CHLORINE COMPOUNDS FOR VENUS ATMOSPHERIC MODELING NETWORKS. D. E. Woon[1], D. M. Maffucci[2], and E. Herbst[2], [1]Chemistry Department, University of Illinois at Urbana-Champaign (davidewoon@gmail.com), [2]Department of Chemistry, University of Virginia.

Introduction: The atmosphere of Venus is known to contain SO, SO_2, OCS, H_2SO_4, and HCl and is suspected to also contain H_2S and elemental sulfur oligomers, S_n. ($n = 2, 3, 4, \ldots$). Atmospheric models indicate that a variety of other compounds containing sulfur or both sulfur and chlorine may also be present on Venus, formed by chemistry initiated via solar photolysis in the upper atmosphere. Atmospheric modeling studies rely on accurate reaction rate coefficients, but many reactions involving species known or thought to be present in the atmosphere of Venus have not been characterized experimentally. We are characterizing a large number of relevant reaction surfaces with density functional theory and ab initio RCCSD(T) calculations and then calculating reaction rate coefficients using applicable theory. The chemistry of sulfur- and chlorine-containing compounds is often a competition between abstraction reactions with no intermediate and addition-elimination reactions involving very stable intermediates that are often hypervalent. Although conditions in the upper regions of Venus's atmosphere are not as extreme as in the interstellar medium, temperatures and densities are low enough that the most important reactions are expected to have very small reaction barriers or no barrier at all. Significant reactions are likewise also expected to be exothermic and to not rely on a third-body to remove excess reaction energy. The presentation will feature a number of reactions that involve common compounds like OCS and SO as well as exotic compounds such as HSCl and HSO.

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VENERA-D - A MISSION FOR THE COMPREHENSIVE STUDY OF THE ATMOSPHERE, SURFACE AND PLASMA ENVIRONMENT OF VENUS. L. Zasova[1], D. Senske[2], T. Economou[3], N. Eismont[1], L. Esposito[4], M. Gerasimov[1], N. Ignatiev[1], M. Ivanov[5], K. Lea Jessup[6], I. Khatuntsev[1], O. Korablev[1], T. Kremic[7], S. Limaye[8], I. Lomakin[9], A. Martynov[9], A. Ocampo[10], [1]Space Research Institute RAS, Profsoyuznaya 84/32, Moscow 117997, Russia, [1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, [3]Enrico Fermi Institute, University of Chicago 933 East 56th Street, Chicago, IL 60637, [4]University of Colorado, 1234 Innovation Drive, Boulder, Colorado 80303, [5]Vernadsky Inst. RAS, Kosygin St., 19 Moscow, Russia, [6]Southwest Research Institute 1050 Walnut, Suite 300 Boulder CO 80302, [7]Glenn Research Center, 21000 Brookpark Rd, Cleveland, OH 44135, [8]Univ. of Wisconsin, 1225 W Dayton St Madison, WI 53706, [9]Lavochkin Assoc. 24, Leningradskaya Str. 141400 Khimki, Russia, [10]NASA Headquarters, Washington, DC.

Introduction: Our knowledge of Venus' basic atmospheric properties (composition, thermal structure, clouds, winds, etc.), and how different it is from Earth has come through the success of the Soviet, US, ESA and now, JAXA missions to Venus as well the Earth-based observations of last decades. Venus was formed in the inner solar system out of the same protoplanetary material as Earth, and considered Earth's twin. Although these siblings have nearly the same size, mass, and density, unlike Earth, which has a comfortable condition for the life, Venus' climate presents a "hellish" condition, fueled by a massive (90 atm) CO2 atmosphere which is responsible for enormous greenhouse effect and a near-surface temperature of 470°C, sulfuric acid clouds, lack of water and young surface, sculpted by volcanism and deformed by folding and faulting resulting in belts of mountains and rifts. The lack of an intrinsic magnetic field suggests the planet's interior structure may also be different than that of the Earth.

Why did Venus take an evolutionary path so different from that of the Earth, why and when the evolutionary paths of these twin planets diverged so much? Were there ever favorable conditions for starting life on Venus.

Venera-D baseline concept: The Venera-D mission is devoted to detailed study of the atmosphere, surface and plasma environment [1]. Envisioned as launching in the post-2025 timeframe and consisting of an orbiter and lander with advanced, modern instrumentation, this mission would build upon the Venera, VEGA, Pioneer Venus, and Magellan missions carried out in the 1970's and 1990's [2,3,4] along with the more recent Venus Express [5].

Venus science goals: NASA and IKI/Roscosmos established in 2015 a Joint Science Definition Team (JSDT), a key task of which was to codify the synergy between the goals of Venera-D with those of NASA. The group established traceability of the goals of Venera-D to the NASA Planetary Decadal Survey [6] and the VEXAG goals, objectives, and investigations [7]. Specific areas of investigation would address questions focused on the dynamics of the atmosphere with emphasis on atmospheric superrotation, the origin and evolution of the atmosphere, and the geological processes that have formed and modified the surface with emphasis on the mineralogical and elemental composition of surface materials, and the chemical processes related to the interaction of the surface and the atmosphere.

The goals of Venera-D baseline mission component: *Orbiter Goals.* Study of the dynamics and nature of superrotation, radiative balance and greenhouse effect; the thermal structure of the atmosphere, winds, thermal tides and solar locked structures; composition of the atmosphere; clouds, their structure, composition, and chemistry; nature of the 'unknown' UV-absorber; investigation the upper atmosphere, ionosphere, electrical activity, magnetosphere, and the escape rate

Lander Goals. Detailed chemical analysis of the surface material; study the elemental and mineralogical composition of the surface, including radiogenic elements; characterize the geology of local landforms at different scales; study the interaction between the surface and the atmosphere; investigation the structure and chemical composition of the atmosphere down to the surface, including abundances and isotopic ratios of the trace and noble gases; direct chemical analysis of the cloud aerosols;

To fill the "science gaps", where important VEXAG science may not be addressed by the baseline concept, JSDT generated a list of contributed options: from specific instruments such as a Raman Spectrometer and an Alpha-Particle X-Ray Spectrometer (APXS) to possible flight elements such as a maneuverable aerial platform, small long-lived surface stations, a balloon and a small sub-satellite.

In situ measurements, both in the atmosphere and on the surface were not carried out for more than 30 years. Venera-D mission is proposed to correct that gap. The long-time measurements in the atmosphere (from several weeks to several months) will help to understand the processes that drive the atmosphere. The mobile platform or balloon with changing altitude of flying in the clouds will help understand ‘puzzles’ of the UV-absorber, its nature, composition, vertical and horizontal distribution as well the key trace and noble gases and their isotopes, meteorology and cloud properties, composition, etc., depending on scientific payload. Another high priority augmentation that is considered is a small long-lived station on the surface (possibly 1-5 stations with an operation life time from 60 days to up to one year).

Technology assessment: The extremes of temperature and pressure make the operation of a spacecraft in the Venus environment a unique challenge. Key areas where technology maturation is required are: (1) the lander sample acquisition and handling/processing system, (2) the need for facilities to test and qualify a full-scale lander, and (3) maturation, testing, and validation of instruments that would need to operate under Venus conditions.

To ensure scientific success of the Venus science goals, laboratory experiments will be fundamental to validating scientific results. Among the high priority analyses needed to be performed include studies of (1) spectral line profiles under high pressures and temperatures (orbiter), (2) optical properties of the lower Venus atmosphere in the visible to near infrared (lander), (3) evaluation of the compositional change of the trace gas components due to temperature and pressure drop during atmospheric sampling (lander); (4) trace and noble gas enrichment procedures (lander); (5) atmosphere (pressure/temperature) effects on remote sensing instruments (lander); (6) supercritical properties of Venus-like atmospheres (lander); (7) UV absorption experiments to aid in constraining the identity of the unknown UV absorber and identify insolation energy deposition (aerial platform).

JSDT findings and recommendations: The JSDT identified priorities for the science goals and objectives for the comprehensive scientific exploration of Venus. Based on these priorities, a baseline Venera-D mission would consist of a single highly capable orbiter and a single highly capable lander. In addition to the baseline mission, the JSDT identified potential “contributed” augmentations that would enhance the science return.

In formulating a strategy for the development of Venera-D, the JSDT identified areas where investments would need to be made to bring the mission concept to fruition. For an anticipated launch in the post-2025 time frame, activities of the following nature would be needed to start immediately to ensure mission success:

- The types of instruments, including lander sample collection and handling to achieve the science objectives, require various levels of validation and maturation to ensure robust and successful operation in the Venus environment (470° C and 90 atm.)
- Laboratory work to characterize the chemistry of the Venus atmosphere at high temperatures and pressures.
- Development of capable facilities to test mission enabling instruments and the spacecraft at the component and system level in a simulated Venus environment.
- Continued development regarding aerial platforms and long-lived surface stations.

Framework for future work: The next phase of development of the Venera-D concept would focus on a more detailed examination of the science measurements and potential instrumentation along with the specifications of the spacecraft requirements. Within this context, specific areas that deserve attention include the following:

(1) Definition of a focused mission concept
(2) Definition of the concept of operations for the lander including a timeline of science observations, strategy for sample acquisition, handling and analysis, data collection and downlink
(3) Refinement of instrument capabilities relative to the ability to achieve the science goals
(4) Refinement of the envelope (mass, power, volume) for a potentially aerial vehicle or long-lived surface station(s)
(5) Assessment/modeling of the surface properties in potential landing site
(6) Maturation of the small station concept; instrumentation and concept for targeting and deployment
(7) Aerial platform accommodation and deployment optimization along with science priorities and instrumentation

The JSDT considers the importance of information from the modeling workshop to identify the possible gaps in the planned Venera-D data return, and how it may be possibly filled by additional measurements or even instruments. In turn, any high-value data obtained by Venera-D, may return for future modeling work, including the development of new GCM, which will help for interpretation of the Venera-D measurements.

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