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Allan Treiman (Lunar & Planetary Institute),
Goals, Objectives, and Investigations Lead
Constantine Tsang (Southwest Research Institute)
Tommy Thompson (JPL), Scribe
Adriana Ocampo (NASA HQ) ex officio
## Venus Goals, Objectives, and Investigations

### Atmosphere
- How did the atmosphere form and evolve?
- What controls the atmospheric super-rotation and greenhouse?
- What is the impact of clouds on climate and habitability?

### Surface & Interior
- How is heat released from the interior and has the global geodynamic style changed with time?
- What are the contemporary rates of volcanism and tectonism?
- How did Venus differentiate and evolve over time?

### System Interactions & Water
- Was surface water ever present?
- What role has the greenhouse had on climate history?
- How have the interior, surface, and atmosphere interacted as a coupled system over time?

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Were Venus and Earth alike, and if so, how and why did they diverge?
Overview

• Venus Basics
• Assertions:
  • Venus is geologically active
  • Venus was a habitable planet
  • Venus is a model exoplanet
• VEXAG activities
• A Venus Program
Topographic Map of Venus
A General Stratigraphy

Plains

Tessera

Rifts/Volcanoes

**TABLE I**
Surface Geochemical Measurements

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Venera 8</th>
<th>Venera 9</th>
<th>Venera 10</th>
<th>Venera 13</th>
<th>Venera 14</th>
<th>Vega 1</th>
<th>Vega 2</th>
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<tbody>
<tr>
<td>SiO₂</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>45.1±3.0</td>
<td>48.7±3.6</td>
<td>—</td>
<td>45.6±3.2</td>
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<tr>
<td>TiO₂</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>1.59±0.45</td>
<td>1.25±0.41</td>
<td>—</td>
<td>0.2±10.1</td>
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<tr>
<td>Al₂O₃</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>15.8±3.0</td>
<td>17.9±2.6</td>
<td>—</td>
<td>16.0±1.8</td>
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<tr>
<td>FeO</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>9.3±2.2</td>
<td>8.8±1.8</td>
<td>—</td>
<td>7.7±1.1</td>
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<td>MnO</td>
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<td>0.16±0.08</td>
<td>—</td>
<td>0.14±0.12</td>
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<tr>
<td>MgO</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>11.4±6.2</td>
<td>8.1±3.3</td>
<td>—</td>
<td>11.5±3.7</td>
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<tr>
<td>CaO</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>7.1±0.96</td>
<td>10.3±1.2</td>
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<td>7.5±0.7</td>
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<tr>
<td>K₂O</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>4.0±0.63</td>
<td>0.2±0.07</td>
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<td>0.1±0.08</td>
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<tr>
<td></td>
<td>4.8±1.5ᵇ</td>
<td>0.6±0.1ᵇ</td>
<td>0.4±0.2ᵇ</td>
<td>0.54±0.27ᵇ</td>
<td>0.48±0.24ᵇ</td>
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<tr>
<td>S</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>0.65±0.4</td>
<td>0.35±0.31</td>
<td>—</td>
<td>1.9±0.6</td>
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<tr>
<td>Cl</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>&lt; 0.3</td>
<td>&lt; 0.4</td>
<td>—</td>
<td>&lt; 0.3</td>
</tr>
<tr>
<td>U (ppm)</td>
<td>2.2±0.7</td>
<td>0.6±0.2</td>
<td>0.5±0.3</td>
<td>—</td>
<td>—</td>
<td>0.64±0.47</td>
<td>0.68±0.38</td>
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<tr>
<td>Th (ppm)</td>
<td>6.5±0.2</td>
<td>3.7±0.4</td>
<td>0.7±0.3</td>
<td>—</td>
<td>—</td>
<td>1.5±1.2</td>
<td>2.0±1.0</td>
</tr>
</tbody>
</table>

ᵇ K converted to K₂O (K₂O wt. % = 1.21 K wt. %).
• ~900 craters apparent spatially random, if only 4% embayed, consistent with rapid emplacement of surface

• yields average age of ~300 – 1 Ga

(Phillips et al., 1992; Schaber et al., 1992, McKinnon et al., 1997; Herrick and Rumpf, 2011)
Tectonics: So what will it be?

• Stagnant Lid, Mobile Lid, or Something in Between?

• Temperature controls:
  • thickness of lithosphere
  • Strength of convection measured in
    • $Ra = g\alpha\Delta T d^3/\nu k$, or
    • Thermal expansion, thermal diffusivity
    • $Nu = \text{heat flux (convection)} / \text{heat flux (conduction)} = hL/k$
    • Convective heat flow, length, thermal conductivity

• Can change with time – ancient Venus, ancient Mars, ancient Earth

• Can vary on a single planet. Technically continents are stagnant lid.

• Water may be an important control on
  • Low viscosity zone
  • Ability of lithosphere to weaken

Höink et al.
Tesserae are our **only** record of the first 80% of the history of Venus

Wetter, mobile lid regime?
Overview

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Venus Surface Temperature and Composition
ESA Venus Express
2005-2014
Venus at 1 µm

Figure 7. Thermal emission at 1.18 µm window wavelength from the surface and the lower atmosphere. (a) A de-clouded image that is corrected the cloud-induced contrast. (b) A synthesized image based on the Magellan topographic map.

Galileo NIMS
Hashimoto et al. 2008

See also:
Basilevsky et al (2012) VMC data
Atmospheric Windows vs. Lab Spectra

Moderate SNR VIRTIS band

Low SNR VIRTIS bands

Room Temperature

Venus Temperature (DLR lab)

Emissivity = 1 - Reflectivity

Wavelength (μm)

Energy (μm)

Olivine (Mg,Fe)$_2$SiO$_4$

Diopside CaMgSi$_2$O$_6$

Plains Unit

W. Alpha Unit

Eve Corona Unit

Hematite Fe$_2$O$_3$

Microcline KAlSi$_3$O$_8$

Quartz SiO$_2$

Anorthite CaAl$_2$Si$_2$O$_8$

Anhydrite CaSO$_4$

Basaltic andesite

Basalt

Trachybasalt

Rhyolite N

Granite

Pyrite

Rhyolite I

Hematite

Magnetite

%Fe$^{3+}$
EVIDENCE FOR ACTIVE VOLCANOES ON VENUS

**ATMOSPHERIC CHANGES**

The rise and fall of sulphur dioxide (SO₂) in the upper atmosphere of Venus over the last 40 years, seen by NASA's Pioneer Venus and other spacecraft between 1978 and 1995, and ESA's Venus Express between 2006 and 2012. A possible explanation is the injection of SO₂ into the atmosphere by volcanic eruptions.

*Credits: ESA/HRSC/ESRIN*

**TRANSIENT HOT SPOTS**

Four transient hotspots were detected by Venus Express in the Ganiki Chasma rift zone in Atla Regio (labelled Objects A–D in the radar map, right). Changes in relative brightness (top row) and temperature (bottom row) are shown for Object A. Some changes due to clouds are also visible in the top row. The bottom row shows the temperature excess compared with the average surface background temperature. Taking into account atmospheric effects, hotspot A is likely only 1 square km with a temperature of 830°C.

*Credits: ESA/HRSC/ESRIN*

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**YOUNG LAVA**

Venus Express found that the area around Idunn Mons in Imdr Regio was unusually dark compared with its surroundings, suggesting a different, younger composition, pointing to lava flows within the last 2.5 million years. The map shows near-infrared emissivity; red-orange is high emissivity ( darkest), purple is the lowest emissivity.

*Credits: ESA/NASA/UV/LEIF Svalgaard et al (2015)*
Overview

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Alpha Regio
W. Alpha is deformed plains
(Gilmore & Head, 2000)
Can control for macroscale
roughness, local effects

Gilmore et al., (2015)
La Bas et al. 1986

"Our main thesis is simple. Water is essential for the formation of granites, and granite, in turn, is essential for the formation of stable continents. The Earth is the only planet with granite and continents because it is the only planet with abundant water."

I.H. Campbell* and S.R. Taylor

NO WATER, NO GRANITES - NO OCEANS, NO CONTINENTS

“Our main thesis is simple. Water is essential for the formation of granites, and granite, in turn, is essential for the formation of stable continents. The Earth is the only planet with granite and continents because it is the only planet with abundant water.”
Atmospheric Origin and Evolution

- Radiogenic isotopes -> degassing history
- Non radiogenic isotopes -> acquisition and loss
- Stable isotopes HCNO -> origin and evolution of water, accretion scenarios
- The study of Venus also informs the multiple scenarios proposed for Earth and Mars
- In situ measurements required
Chassefière et al. 2012

In a global perspective, the only way to reconstruct the detailed history of volatile reservoirs on Venus, from accretion to the end of the heavy bombardment, that is during the first billion years, is to constrain numerical models of the interior-magma ocean–atmosphere–interplanetary space system evolution with present-day noble gas abundances and isotopic fractionation patterns, and with ratios of stable isotopes through the use of the powerful techniques of isotopic geodynamics. If any evidence for past liquid water is found at the surface by future landers, the mineralogical record could be used to better constrain such evolution models.
Early water

Deuterium on Venus: Observations From Earth
Catherine de Bergh, Bruno Bézard, Tobias Owen, David Crisp, Jean-Pierre Maillard, Barry L. Lutz

Absorption lines of HDO and H$_2$O have been detected in a 0.23–wave number resolution spectrum of the dark side of Venus in the interval 2.34 to 2.43 micrometers, where the atmosphere is sounded in the altitude range from 32 to 42 kilometers (8 to 3 bars). The resulting value of the deuterium-to-hydrogen ratio (D/H) is 120 ± 40 times the telluric ratio, providing unequivocal confirmation of in situ Pioneer Venus mass spectrometer measurements that were in apparent conflict with an upper limit set from International Ultraviolet Explorer spectra. The 100-fold enrichment of the D/H ratio on Venus compared to Earth is thus a fundamental constraint on models for its atmospheric evolution.

1991, Science

Fig. 1. Mass and location of the final planets in the six Grand Tack simulations of this study. The actual planets of the Solar System are shown at the top for comparison. The colored segments show the proportions of accreted material that originates from 0.5 to 1.2 AU (brown), 1.2 to 3 AU (green) and 6 to 9.5 AU (blue), respectively. Note that no material originates between 3 and 6 AU because the formation of Jupiter and Saturn cleared all bodies from this region. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
### Venus Stratigraphic Column

<table>
<thead>
<tr>
<th>Hadean</th>
<th>Archean</th>
<th>Proterozoic</th>
<th>Phanerozoic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eoarchean</td>
<td>Paleoarchean</td>
<td>Paleoproterozoic</td>
<td>Paleozoic</td>
</tr>
<tr>
<td>Neoarchean</td>
<td>Mesoproterozoic</td>
<td>Mesozoic</td>
<td>Cenozoic</td>
</tr>
</tbody>
</table>

#### Current Knowledge

- **3.8 Ga** - Oldest evidence of life on Earth (Mojzsis et al., 1996)

#### Key Observations

- **D/H Venus atmosphere = 150X terrestrial**
- Assuming Earth and Venus started with the same inventory...
- ~0.6 – 16% Earth ocean’s worth of water (Donahue et al., 1997)
- Ocean may have persisted…. For a billion years? (Kasting & Pollack, 1983)
- Recent model (Way et al., 2016) predicts ocean for 2-3 Ga.

#### Hypotheses

- Wetter, mobile lid regime?

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**Notes:**

3/28/18 VEXAG at CAPS 24

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**References:**

- Mojzsis et al., 1996
- Donahue et al., 1997
- Kasting & Pollack, 1983
- Way et al., 2016
An Early Ocean Could Persist Until the Recent Past
Way et al., 2016

- Slow rotation produces dayside clouds that keep the surface cool and maintain the ocean – positive feedback loop.
- Assumes Earth-like atmosphere, current Venus rotation
- Assumes all elevation < mean is water-filled, yield 310 m ocean
- Insolation at 2.9 and 0.7 Ga tested (yields 11°C vs 15°C, respectively).
- Some dependence on topography (modern Earth 23°C, modern Venus 15°C)
Life in the Clouds of Venus?

HAROLD MOROWITZ & CARL SAGAN

doi:10.1038/2151259a0

Received: 04 August 1967
Published: 16 September 1967

Life on Venus

Charles S Cockell

Limaye et al. forthcoming

OSSO (disulfurdioxide) suggested as ultraviolet absorber (Frandsen et al, 2016)
Kane et al. 2014 and white paper to NAS Exoplanet Science Strategy

~40% of Sun-like stars may have Venus-like planets

Venus Zone

Runaway Greenhouse

Maximum Greenhouse

Habitable Zone

~40% of Sun-like stars may have Venus-like planets

VEXAG@CAPS

Starlight on planet relative to sunlight on Earth

Image Credit: Chester Harman
Planets: NASA/PL

3/28/18
Venusian Exoplanets

- Temperature
- Clouds - CO₂ spectrum (H₂O? Other?)
- Atmosphere Variability
- Star-Planet Interactions
  - Atmosphere – Stellar Wind
  - Atmosphere ablation

“Once you break a planetary atmosphere...[it's] almost impossible to unbreak,” Kane says. “Venus could be the eventual outcome of all atmospheric evolution.”

– Stephen Kane
How are oceans lost?

• Idea has been early loss followed by solar wind stripping of light elements

• VEx shows primary species escaping in Venus plasma tail are H and O ions in water-like ratio of 2:1 [Svedhem et al., 2009]

• Collinson et al. [2016] measured “electric wind” about Venus 5x Earth which facilitates loss of ions <18 amu
The discovery of a powerful electric wind at Venus, an Earth-like terrestrial planet, also has important consequences for the study of exoplanets by missions such as Kepler. If, for example, the electric potential drop in Earth’s (or another Earth-like planet’s) ionosphere was a Venus-like +12 V, then a similar direct loss of heavy ions would likely occur, regardless of the presence or absence of a planetary dynamo magnetic field, leading to higher rates of loss. Significant changes to planetary escape rates could impact the ability of a planet to retain an atmosphere [Zahnle and Catling, 2013; Cohen and Glocer, 2012] and maintain liquid water oceans and increase the likelihood that a planet loses its oceans during the moist greenhouse phase [Chassefière, 1997]. Such a strong escape mechanism could also impact the redox evolution of a planetary surface [Caitling et al., 2001]. Given that we believe Venus’ stronger polarization field may arise from its closer proximity to the Sun, and that most known exoplanets have been found relatively close to their stars (since these are easier to detect), the possibility of a strong electric wind must be considered when assessing planetary evolution or the potential for habitability on exoplanets.
Based on our surface–atmosphere equilibrium model, we can say that planets similar to Venus (i.e., thick CO$_2$ atmospheres with only trace water) are more likely to be colder than Venus rather than hotter. Hotter planets should have significantly more water in their atmospheres and generally will have higher total pressures. Hot felsic planets will have relatively large pressures and HF abundances, with less water and HCl than similar mafic planets. Planets colder than Venus are more geochemically plausible. These planets will generally have lower total pressures than Venus and may have water vapor abundances similar or larger than Venus. Cold felsic planets will have higher total pressures, HCl, and HF abundances, but lower H$_2$O abundances than similar mafic planets.
VEXAG Activities & Agenda

• Identify scientific priorities and opportunities to NASA.

• Develop & update guidance documents
  • Goals, Objectives, and Investigations (GOI) TBR 2018
  • Technology Plan TBR 2018
  • Roadmap TBR 2018

• Propagate priorities to NRC Decadal Surveys (next: 2020)
  • Flagship study 2018-19, white papers 2019.

• Foster next generation of researchers
Venus in the 2013 Planetary Science Decadal

- Science Themes
  - *Building New Worlds*: Accretion, water, chemistry, differentiation, atmosphere. Elemental and isotopic species in atmosphere, esp. noble gases and CHNO

- New Frontiers: *Venus In Situ Explorer (VISE)*
  - Carryover from 2003 Decadal Survey, but simpler mission profile.
  - Examine physics and chemistry of Venus’ atmosphere and crust. Emphasis on characterization that cannot be done from orbit, including detailed composition of lower atm. and elemental & mineralogical composition of surface materials.

- Flagship: *Venus Climate Mission (VCM)*
  - New mission study at lowest priority among flagships.
  - Investigate atm. origin, CO₂ greenhouse, atmosphere dynamics & variability, surface-atmosphere exchange.

- Requested investments in high temperature technologies
Welcome NASA Investments

• The Hot Operating Temperature Technology (HOTTech) program

• Thermal protection systems Ames Heat Shield for Extreme Entry Environment Technology (HEEET)

• Glenn Extreme Environments Rig (GEER)

• GRC: High temperature SiC systems that enable long-lived surface missions.
Venus Proposed Missions and Studies

- 2 of 5 Discovery Phase A finalists in 2016 were Venus, but neither selected.
  - NASA assures no bias against Venus
- Three Venus proposals to New Frontiers 2017—none selected for Phase A.
  - VOX was Cat 1
- 4 Venus PSDS3 studies - final reports to be delivered to HQ in March/April
- Venus Bridge study – $200M cap, report to AA in April.
- Flagship study – authorized by HQ for 2018 (GSFC)
- VeGASO (ESA BepiColombo, NASA Parker Solar Probe, ESA Solar Orbiter)
  - Only BC is committed
- Venera-D (Russia) – Joint SDT; include US flight element (aerial platform?); launch 2026 to 2031
  - Pending funding, completion of lunar program, and selection ahead of Phobos.
- EnVision (ESA) – M5 Phase A selections anticipated in May.
- Akatsuki (JAXA) – continues to astound after 2015 rescue, likely ext. into 2021.
Venus SmallSat Concepts

Cubesat UV Experiment
V. Cottini, U. Md

Venus Airglow Monitoring Orbiter for Seismicity
A. Komjathy, JPL

Seismic and Atmospheric Exploration of Venus (SAEVe), T. Kremic, GRC

VEXAG at CAPS

Cupid's Arrow, C. Sotin JPL
Venus Bridge

- Outcome of AA inquiry “what can you do for $200M?” post-Disco-decision.
- Focus Group convened summer 2017 and assessed useful science and technology architectures likely to fit within nominal cost cap.
  - Decided on linked orbiter + in situ element, launch in early-mid 2020s
- Separate design studies by GRC and JPL
  - GRC: “V-BOSS” orbiter and long-lived lander
  - JPL: 5 orbiter mission types + atmospheric skimmer, probe, or balloon
- Mission concepts include robust, complementary science
- $200M target likely requires some technology development and operations costs outside cap.
Venus Flagship Study

• Identify science objectives, investigations and mission architectures for a Flagship-class mission to Venus
• Nominal schedule to begin late 2018 and last ~one year
• Report to be ready prior to Decadal Survey scheduled to commence early 2020
• Science Definition Team led by two co-chairs TBD
• SDT membership solicited by NASA and selected with input from co-chairs
• Architecture study will be done at GSFC
A US Venus Program is essential to address Decadal Survey goals.

**US Missions**

- NASA Magellan 1989-1994
- ESA Venus Express 2005-2014
- JAXA Akatsuki 2010-present
- ESA Venus Express 2025?
- RSA Venera D 2026+?
- Venus Bridge 2025?

**International Missions**

- NASA Magellan 1989-1994
- ESA Venus Express 2005-2014
- JAXA Akatsuki 2010-present
- ESA Envision 2031?

**Future Missions**

- Discovery New Frontiers 2026-2028?
- SmallSats?
- Venus Flagship?

- A 40-year timeline of Venus exploration initiatives.
We’re Ready to go to Venus

• The Venus community continues to demonstrate the fundamental planetary science that can and must be done at Venus
  – Mature Cat 1 mission concepts in Discovery and New Frontiers
  – Healthy technology development concepts in HOTTECH, PICASSO, MATISSE
  – Innovative papers in the Venus literature and strong conference attendance. Links to planetary habitability and exoplanets.

• The Venus science community is poised with mature mission concepts, intellectual capital, and experience. We must continue to build NASA advocacy and recognition by planetary scientists and the public at large.