Venus Science & Exploration: Decadal Mid-Term Status

The Venus Exploration Analysis Group (VEXAG)

May 4, 2017

The Venus Exploration Analysis Group (VEXAG)

- Established in 2005 to provide scientific input and technology development plans and prioritization for the exploration of Venus.

- Current Steering Committee
  - Robert Grimm (Southwest Research Institute), Chair
  - Martha Gilmore (Wesleyan University), Deputy Chair
  - Giada Arney (NASA GSFC), Early-Career Scholars, Exoplanets Lead
  - Lynn Carter (Univ. Arizona)
  - James Cutts (JPL), Roadmap, Aerial Platforms, Venus Bridge Lead
  - Lori Glaze (NASA GSFC), Past Chair
  - Gary Hunter (NASA GRC), Technology Lead
  - Noam Izenberg (APL)
  - Kevin McGouldrick (Univ. Colorado)
  - Paul Steffes (Georgia Tech. University)
  - Allan Treiman (Lunar & Planetary Institute)
  - Constantine Tsang (Southwest Research Institute)
  - Tommy Thompson (JPL) Executive Secretary
  - Adriana Ocampo (NASA HQ) ex officio

VEXAG Activities

- Focus Groups
  - Standing
    - Goals, Objectives & Investigations
    - Technology
    - Roadmap
  - Ad Hoc
    - Venus Bridge (smallsats)
    - TBD Exoplanets
- Annual meetings
  - Usually in November @ HQ
  - Typically ~80 participants, most are in-person.

- Topical Meetings Since 2011
  - Exploring the Planetary Science Achievable from a Balloon-Based Observatory
  - *Comparative Climatology of Terrestrial Planets*
  - Venus Upper Atmosphere Investigations, Science, and Technical Interchange Meeting
  - Comparative Climatology Symposium
  - Venus Exploration Targets
  - Venus Science Priorities for Laboratory Measurements and Instrument Definition
  - Comparative Tectonics and Geodynamics of Venus, Earth, and Exoplanets
  - 2nd Comparative Climatology of Terrestrial Planets
  - Venus Modeling Workshop (May 2017)

Website Revision

- Cleaner look consistent with OPAG, LEAG, SBAG
- Clearer access to guidance documents, meeting summaries, and resources.
- Social media
- More cohesive engagement of Venus community and extended outreach to broader planetary community.

Venus in the 2013 Planetary Science Decadal Survey

- Science Themes
  - *Building New Worlds:* Accretion, water, chemistry, differentiation, atmosphere.
    - Elemental and isotopic species in atmosphere, esp. noble gases and CHNS
  - *Planetary Habitats:* Ancient aqueous environment?
    - Prior habitability, mechanisms of volatile loss, atm. circulation and chemistry, solar-cycle variations.
  - *Workings of Solar Systems:* focus on comparative climatology, plus "myriad processes."
    - Runaway greenhouse history and implications for Earth, original atmosphere states and coupled interior-atmosphere evolution.
- 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 introduced in 2013, at lowest priority among flagships.
  - Investigate atm. origin, CO_2 greenhouse, atmosphere dynamics & variability, surface-atmosphere exchange.

1a. Significant Discoveries: Venus-like exoplanets

- Frequency of Potential Venus Analogs from Kepler Data (*Kane et al., Ap. J., 2014*)
- Compares "Venus zone" to classical habitable zone.
- 43 candidates w/ occurrence rates 0.32 for M-dwarf stars and 0.45 for GK dwarfs.
- Occurrence rate of exoVenuses is comparable to exoEarths.
  - Uncertainties are smaller for exoVenuses because Kepler is biased toward planets in VZ

Atmospheric Circulation

- Aphrodite Terra launches large gravity waves *(Bertaux et al., JGR, 2016; Fukuhara et al., Nat. Geosci., 2017)*
- Polar vortex is a continuously evolving structure at least 20 km high, extending through a quasi-convective turbulent region (*Garate-Lopez et al., 2013*)
- GCM explains cloud-top warm pole and cold collar by residual mean meridional circulation enhanced by thermal tide. (*Ando et al., Nat. Comm., 2015*)
- Cloud-tracked winds show acceleration of zonal flow 2006 to 2012, with superposed periodicities and waves *(Khatuntsev et al., Icarus, 2013; Kouyama et al., JGR, 2013; McGouldrick & Tsang, 2016).*

Atmospheric Chemistry

- SO_2 above clouds has decreased 5x 2007 to 2012 *(Marcq et al., Nat. Geosci., 2012)*
  - Secular atmospheric overturn or volcanic pulse?
- OSSO (disulfur dioxide) suggested as ultraviolet absorber *(Frandsen et al., GRL, 2016).*
  - Forms from SO, peak (but not average) mixing ratio comparable to SO.
  - Removed by photolysis
- Ground-based observations can track several atmospheric constituents *(Arney et al., JGR, 2014).*

An Early Ocean Could Persist Until the Recent Past

Way et al., GRL, 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 310 m GEL ocean set by assuming all elevation < mean is water-filled
  - ROCKE-3D/ModelE2-R GCM
  - Current rotation, 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)

Magnetosphere and Ionosphere

- Magnetic Reconnection in the Venus Magnetotail (*Zhang et al., Science, 2012*)
  - Venus Express (VEX)-observed changes in plasma & magnetic field
  - Energetics of Venus magnetotail resemble terrestrial tail in which energy is stored and later released from magnetic field to the plasma
  - Surprising for nonmagnetized body.
- The "electric wind" of Venus (*Collinson et al., GRL, 2015*)
  - Strong ambipolar electric field formed by electron-ion separation along draped magnetic field.
  - can accelerate heavy ions (e.g., O^+)
  - Analogous to Earth's "polar wind"
  - Can cause strong atmospheric (and ocean) losses even without solar-wind stripping

Surface Composition

- Tesserae Consistent with Felsic Compositions
  (Basilevsky et al., Icarus, 2012; Gilmore et al., Icarus, 2015).
  - VIRTIS and VMC 1-μm emissivity is lower than the plains and deformed plains.
  - Tesserae may be true granites formed via plate recycling of (ancient) surface water OR via preservation of copious differentiated basaltic melt from the pre-plains era.
- Origin of Radar Brightness in Highlands (*Treiman et al., 2016*)
  - Ovda Regio SAR backscatter increases above 2 km elevation then drops sharply above 4.5 km
  - Ferroelectric behavior transitions to paraelectric
  - Consistent with chlorapatite $Ca_5(PO_4)_3Cl$ formed by reaction of phosphate in basalts with HCl in atmosphere.
  - Different pattern in Maxwell Montes remains unexplained.

Recent or Active Volcanism

- Radar-dark materials in tessera point to "lost" crater (*Whitten and Campbell, 2016*)
  - Suggests resurfacing < 80 Ma
- Transient targets in Venus Monitoring Camera (VMC) thermal emission interpreted as still-hot lava flows (*Shalygin et al., GRL, 2015*).
- Recall: High emissivity in Visible and Infrared Thermal Imaging Spectrometer (VIRTIS) interpreted as rough, unweathered lava flows (*Smrekar et al., Science, 2010*)
  - Ages likely < 1 Ma if they are the youngest surfaces on the planet.

Geological Models and Inference: Venus may not behave the way we think

- Craters can be eliminated in equilibrium resurfacing without leaving excess of non-pristine states *(Bjonnes et al., 2012; O'Rourke et al., 2014).*

- Decoupling of crust from underlying mantle convection can maintain Venus in thermal steady-state without episodic global resurfacing *(Ghail, PSS, 2015).*

1b. Technical Advances

- Thermal protection systems
  - Ames HEEET
- Venus environmental testing facilities
  - Glenn Extreme Environments Rig (GEER)
    - 28 ft^3 steel vessel can accommodate multiple gases to 1400 PSI and 500°C
  - Goddard VICI
- High-temperature electronics (NASA GRC)
  - 21-day IC demo at Venus conditions
  - Demo of chemical species (multiple), wind, temp, and pressure sensors for targeted 60 day operation
  - No thermal control required for Venus surface
- Deep-space optical communications
- Smallsats and cubesats

Advances in SAR

- Stereo
  - Topography; converts radar to optical geometry (MGN: *Herrick et al., EOS, 2012)*.
- Interferometry
  - Topography; change detection
- Polarimetry
  - Texture/composition discriminator
- SAR can unravel the stratigraphic history of Venus and answer whether or not there was a decline in geological activity

1c. Relevant Programmatic Changes

- Dissolution of the Planetary Science Subcommittee
  - Reformed as Planetary Science Advisory Council, FACA-compliant
  - Analysis Group chairs no longer members.
    - Intended to screen AGs from burdensome FACA requirements?
    - Functionally reduces AG influence in its findings to NASA.
- Addition of Ocean Worlds to New Frontiers 4 target list
  - Ocean Worlds are outside the NF scope prescribed by the 2013 Decadal Survey.
  - Congressional direction should not be masked in competed programs.
  - Decadal Mid-Term can add Ocean Worlds, but this does not change the fact that the NF-4 competition was scoped by NASA/Congress w/o NRC/community input.
- Discovery Decision

Discovery Selection Outcome

- SMD AA Zurbuchen reached out to VEXAG a few days after the selection announcement. He stated that the results were not due to lack of interest about Venus and he offered a meeting.
- Chair Grimm met in person with AA Zurbuchen and Director Green in mid-Feb, with Deputy Chair Gilmore participating remotely.
- AA Zurbuchen explained his selection rationale.
  - We were instructed not to repeat it – he will promulgate.
  - After his top selection, the remainder followed his programmatic choices.
  - All missions were selectable.
  - There was no bias against Venus or for asteroids.
- Chair/Deputy Chair: This decision rationale should be fully explained to the planetary-science community, as it affects everybody.

VEXAG Programmatics: New Guidance Documents

- Over 20 Venus missions have been submitted throughout the history of the New Frontiers and Discovery Programs
  - Venus In Situ Explorer was specified in 2003 and 2013 Decadal Surveys as one of the prescribed New Frontiers missions.
  - Seven Venus proposals were submitted to Discovery 2010. The Venus community was criticized as not having a consistent message. We interpreted the record number of proposals as evidence of sustained interest in Venus even decades after the last US mission.
- In response, VEXAG developed **3 guidance documents** published in 2014 (Goals, Objectives, and Investigations; Technology; Roadmap) with the express purpose of providing clear mission relevance.
  - Links to 2013 Decadal Survey are clear, but new directions are undertaken too.
- We believe these efforts helped propel 2 Venus proposals into Step 2 in the 2015 Discovery competition.

VEXAG 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?

VEXAG Technology Plan

- Near-Term, in priority order
  - ✓New thermal protection systems (TPS).
  - ✓High-temperature subsystems and components for long-duration (months) surface operations.
  - – Aerial platforms for similar long-duration operations in the atmosphere
  - ✓Deep-space optical communications
- Mid- and Far-Term, in priority order
  - – Advanced power and cooling technology for long-duration surface operations.
  - – Advanced descent and landing.
- Impact of smallsats and cubesats will be assessed in technology & roadmap updates.

VEXAG Roadmap

- Near-term (2014-2019, now targeting 2023-2030)
  - Orbital remote sensing
    - Radar imaging, infrared emissivity, gravity, topography
    - VERITAS, EnVISION (all); Venus Design Reference Mission (VDRM: radar, grav, topo); Venera-D (no radar)
  - Sustained aerial platform
    - VDRM, **Venus Climate Mission (VCM),** Venera-D
  - Deep probe
    - DAVINCI, **VCM**
  - Short-duration lander
    - VDRM, **VISE**, Venera-D
  - Multiple probes/dropsondes
    - **VCM**
  - Fly-by opportunities
    - VeGASO
- Mid-term (2020-2024, now targeting 2030-2040)
  - Multiple deep probes
  - Short-duration tessera lander
  - Long-lived geophysical lander
- Far-term (>2025, now targeting >2040)
  - Surface or near-surface platform with regional mobility
  - Long-lived seismic network
  - Sample return

Earliest US mission will be 35 years after Magellan

Venera-D Joint Science Definition Team

- Orbiter
  - Atmospheric superrotation, radiative balance, composition.
- Lander
  - Chemistry and mineralogy of surface materials, atmospheric composition during descent.
- Subsatellite or Aerial Platform?
- Launches in 2026-2029 studied
- See Announcement for Moscow Workshop, 5-7 Oct 2017.
- JSDT active for 2 more years

Venus Gravity Assist Science Opportunity (VeGASO)

- Study aeronomy and atmosphere from fly-bys
  - Atmospheric structure and loss, induced magnetic fields
- Up to 15 gravity assists 2017 – 2028.
  - BepiColombo (ESA) - 2
    - Instruments will be active
  - Solar Probe Plus (NASA) – 7
    - Negotiations ongoing with Heliophysics
  - Solar Orbiter (ESA) – 6
    - TBD
- HQ must develop Participating Scientist program and Proposal Information Package. BepiColombo splinter meeting May 2017.

Medium Class Missions

- EnVision
  - R. Ghail, Lead Proposer
  - SAR, Subsurface sounder, IR mapper
  - Submitted to ESA M5 Call: passed initial technical review, in science review
  - Phase A selections this fall
- New Frontiers 4
  - Venus In Situ Explorer (VISE) specified by 2013 Decadal Survey
  - Step 1 proposals due April 28
  - Step 2 selections by end of CY.

VISAGE Concept (L. Esposito) →

Venus Bridge

- Outcome of AA inquiry "what can you do for $200M?"
- New VEXAG Focus Group to determine if one or more small missions can accomplish useful science or tech demo within nominal cost cap.
  - Gap-filling with broadest impacts; launches in early to mid 2020s
  - Launch, transfer, and comm requirements.
  - Develop alternative mission sequences.
- Community responses include orbiters for IR, aeronomy, airglow, gravity; atm entry probes, landers
  - PSDS3 "Phase A" selections: Cupid's Arrow (C. Sotin), Cubesat UV Experiment (V. Cottini).
  - Focus group may consider these and other concepts.
- Schedule: preliminary concept reviews spring 2017; NASA center mission design summer, report to VEXAG in Fall, final report to NASA early 2018.

Venus Aerial Platforms

- Only near-term VEXAG technology priority (among 4) that has seen little recent progress.
- Study Goals
  - Identify science goals for aerial vehicles for studies of the atmosphere, surface, and interior, and for access and return of surface and atmospheric samples.
  - Compare and contrast the capabilities of different vehicle types to address the scientific goals.
- Schedule: Two 4-day study team meetings (May and Oct 2017), Final Report by Jan 2018.
- Feed-forward to Venera D, US Flagship, Discovery

2. Degree to Which NASA's Current Planetary Science Program Addresses the Decadal Survey

- Pretty well given the PSD Director is self-professed "Decadal Zealot"

3. NASA Progress Toward Realizing the Decadal Survey

Strategies, goals, priorities, and effectiveness in maintaining programmatic balance.

- Technology: called for stable technology investment program

  → Good

- High temperature survivability called for Venus and Mercury

  → Very Good: NASA-center investments, HOTTech awards

- Abandonment of ASRG

  → Poor

- New scientific instruments and sampling systems

  → Fair: Reorganization into Matisse & Picasso has clarified technical-readiness path, but these programs have some of the lowest award rates in ROSES.

- R&A

  → Good (overall &Venus proportion)

Programmatic balance is questionable.

4. Recommendations to Optimize the Program

How to take account of emergent discoveries since decadal in context of current and forecasted resources available.

- Detection of H_2 in Enceladus plume and discovery of intermittent plume on Europa demonstrate that close inspection or direct sampling is possible of material from potentially habitable subsurface liquid water.
  - Enceladus Orbiter and Europa Lander now high priority.
- Get New Frontiers back on 5-year cadence by releasing next AO in 2020.
- Clarify criteria for mission selection, esp. Discovery.
- Expand smallsat and cubesat opportunities (PSDS3, Venus Bridge)
  - Test new technologies at Venus
- Develop tighter connection between planetary-science and exoplanet communities.
- Increase R&A.

5. Implementation of Decadal-Recommended Mission Portfolio

- Flagship cadence pretty good considering there were way too many for one decade anyway.
  → Very Good
- Discovery mission cadence ~3 yr, longer than desired 2 yr.
  → Good
- Gap between New Frontiers 3 and 4 is 7 years
  → Fair
- It is disappointing that no Venus missions have yet been selected, but this is not inconsistent with the portfolio as framed and prioritized.

6. Recommendations to Prepare for Next Decadal Survey (Venus)

- Review VEXAG Goals, Objectives, and Initiatives
  - Priorities rooted in, but are distinct from, 2013 Decadal Survey
    - Then: emphasis on atmospheric composition, ancient ocean, and runaway greenhouse
    - Now: balance between atmosphere, geology, and their interactions, esp. role of water.
  - Maintain separation for mission science traceability? "Worked" for Disco 13-14 Step 1.
- Technology: exploit new capabilities to improve TRL and enable new science opportunities
- Roadmap
  - Assess results of Venus Bridge and Venus Aerial Platforms studies.
  - Request new Flagship study from NASA prior to next Decadal Survey
    - VCM did not optimize instrument maturity, new concepts in aerial platforms, or innovations in geophysical methods.
    - All Flagships except VCM have seen new start, new study, or new impetus.
- Programmatic balance is needed.

The Fading Evening Star

- Venus is the key to understanding where Earth-sized means Earth-like elsewhere in the Universe. Venus is the cornerstone of comparative planetology.
  - It is our sister planet, closest and nearly equal mass, yet has massive, super-rotating CO_2 atmosphere, complex geology not organized into plates, and no surface water.
  - Was Venus always this way or did it experience one or more transitions in climate, geology, or both? Is there evidence for past oceans?
- With no NASA mission since Magellan in 1989, the Venus science workforce and technical heritage in the US has steadily declined.
  - The grad students and post-docs of Magellan will be mid- to late-career by the time of the earliest possible mission in the mid-2020s.
  - There is little incentive for young scientists, and fewer are participating.
  - Feedback loop: Planetary scientists are attracted to active missions and subsequently generate communities and advocacy for further missions to the same or similar targets.
- The Venus science community is poised now with mature mission concepts, intellectual capital, and experience. Venus exploration needs active recognition by planetary scientists at large and programmatic balance by NASA.