

EXPLORING VENUS: NEVER GIVE UP, NEVER SURRENDER. L. S. Glaze¹ and J. B. Garvin¹, ¹NASA's Goddard Space Flight Center (Code 698, 8800 Greenbelt Road, Greenbelt, MD 20771, Lori.S.Glaze@nasa.gov)

Introduction: Venus is considered Earth's sister planet because of its proximity as well as its similar size and mass, but that is where the similarities end. Deciphering the divergent evolutionary histories of Venus and Earth is at the heart of understanding climate and habitability of terrestrial planets with atmospheres. The need to understand these differences is made even more imperative with the confirmation of over 3,500 exo-solar planets, many of which lie in the "Venus Zone" [1] (Fig. 1). The lack of any Venus missions selected through past Discovery and New Frontiers solicitations is increasing the sense of urgency to bring Venus science into the 21st Century to complete our comparative suite of planetary observations. The Pioneer Venus probes and Soviet Venera landers flew over 30 years ago and left significant gaps in our knowledge. Since 1978, six orbiting remote sensing missions have comprehensively mapped Venus' surface and upper atmosphere. We argue that these "seeking" missions have left numerous questions about Venus' origin and evolution that can only be addressed through new *in situ* measurements, using modern instrumentation.

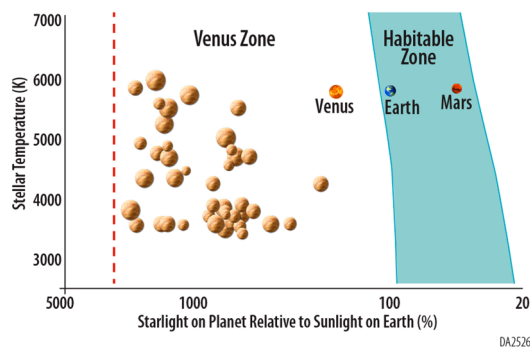


Figure 1. New observations are needed to constrain where early Venus lies within the cloud-free habitable zone (HZ) boundaries. The HZ boundaries are determined by the moist-greenhouse (inner edge, higher flux) and maximum greenhouse (outer edge, lower flux). The "Venus Zone" is the region around different types of stars where planets like Venus (or that may become Venus-like) can be found. Within our galaxy, 42% of stars similar to our sun (or cooler) have potential Venus'. Some of the currently known exoplanets thought to be in the Venus Zone are shown for comparison. [Figure after [1].]

What we know: Prior missions have shown that, in contrast to Earth, Venus is currently an exceedingly dry planet with a massive (~ 9.6 MPa = 96 bar at mean planetary radius) atmosphere composed primarily of carbon

dioxide (96.5% by volume). This dense atmosphere drives a greenhouse effect with surface temperatures up to 480° C at the lowest elevations, and maintenance of a cloud layer that is almost 25 km thick (47 - 71 km altitude) composed mostly of sulfuric acid droplets. However, when it comes to its early history, information about Venus' atmosphere is woefully incomplete. Despite forming in comparable regions of the solar system, it is not at all clear whether the original atmospheres of Venus and Earth were composed of the same material. Likewise, it is unknown whether or not Venus experienced impact events that significantly modified its atmosphere, similar to Earth and Mars.

The lowest part of the Venus atmosphere, where the greatest bulk of the atmosphere resides, is key to resolving many enduring mysteries about our sister planet. Because it has the highest temperature and pressure, the deep atmosphere is expected to have the highest rates of homogeneous and heterogeneous chemical reactions, such that some gases could approach chemical equilibrium and may interact with the surface and permeable subsurface materials. Yet, again, much of the information needed regarding the composition of the atmosphere below the clouds is missing.

There is substantial debate regarding how much water may have been present in Venus' past (Fig. 2). Knowledge of water abundance on primordial Venus is critical for understanding the planet's geologic and climate evolution, as well as the extent (or existence) of Venus' past habitable period [2-4].

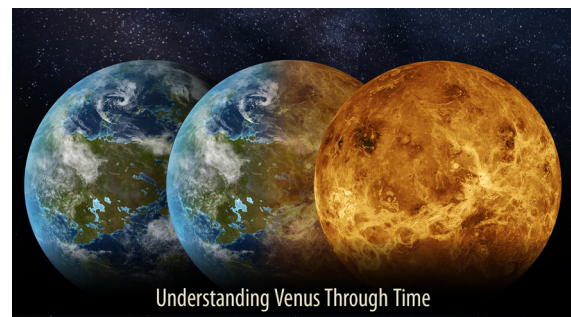


Figure 2. A better understanding of Venus' water history will resolve fundamental questions about how a planet on the inner edge of the habitable zone evolves from a potentially habitable ocean world to become the desiccated Venus of today.

The tessera highlands likely represent the only remnants of the surface pre-dating the volcanic plains, and may provide clues to Venus' past. In addition, infrared emissivity of the tessera are consistent with composi-

tions that are more silica-rich than the plains, with implications for increased water [11].

What we need: Venus provides an easily accessible natural laboratory to explore one possible extreme outcome of terrestrial planetary evolution. Yet, despite global radar imaging by Magellan, discoveries by the Pioneer Venus probes and Venera landers, and observations of the cloud layer by Venus Express (VEx) and Akatsuki, many significant questions regarding Venus' atmosphere, surface, and interior remain unanswered. The last two Planetary Decadal Surveys [5-7] as well as the Venus Exploration Analysis Group's Goals, Objectives and Investigations document [8] have clearly stated the high priority observations that are needed to answer these questions.

At the top of this list is a complete suite of measurements for noble gases (He, Ne, Ar, Kr, Xe), nitrogen, and their isotopes. Because the noble gases have no spectral signature, these measurements can only be made directly from within the Venus atmosphere. In addition, to ensure measurements are representative of the bulk Venus atmosphere, it is critical that samples be taken from the well-mixed atmosphere below the homopause (which varies as a function of species) for even the heaviest noble gases.

The history of water plays an important role in not only understanding Venus' habitability over time, but also in understanding Venus' transition to a runaway greenhouse climate. Although the deuterium/hydrogen (D/H) measured by Pioneer Venus indicated that Venus once had much more water than is present today, large uncertainties in that value, combined with discrepancies relative to Venus Express measurements above the clouds, preclude the ability to constrain the volume of water present in Venus' past or the timing of its loss. Thus, high precision measurements of the D/H within and below the clouds are needed.

75% of Venus' atmospheric mass is contained in the deepest atmosphere (from the surface up to about 20 km). Yet, the chemical composition of this part of the atmosphere is almost completely unmeasured. Estimates of the mixing ratios for key trace gases such as H₂O, SO₂, OCS, and CO are based on models, assumptions, and interpolations from higher altitude measurements. Measurements of these species, including possible vertical gradients, are needed to constrain the chemical cycles and to understand how the surface interacts with the atmosphere.

Finally, tessera highlands hold the key to understanding the geologic history of Venus. Measurements of the bulk chemical composition and mineralogy of tessera can answer fundamental questions about the origin of these rocks as well as whether these surfaces were exposed to climate conditions significantly different from today.

What's next: Despite being passed over in every

competed NASA mission category to date, there are several upcoming opportunities to acquire the highest priority *in situ* measurements identified by the last two Planetary Decadal Surveys [6,7]. It is expected that there will be another NASA call for Discovery concepts in 2019. In addition, NASA expects to release one more call for New Frontiers concepts (including the Venus In Situ Explorer target) prior to 2023. It is imperative that Venus continue to compete in these categories.

But there are other opportunities as well! The Russian space agency, Roscosmos, is currently engaged in a joint study with NASA of the Venera-D mission (where "D" stands for Dolgozhivushaya, meaning "long-lived"). The current conceptualization for Venera-D includes a Russian lander (similar to the Vega landers) and an orbiter [9]. The study team have included a NASA-contributed long-lived (up to 120 days) surface package [10] as part of the baseline mission. An option has also been considered that includes a NASA-contributed aerial platform that could achieve much of the high priority *in situ* Decadal science.

In addition to Russia, ESA is also currently assessing mission concepts for their M-5 call, including EnVision. EnVision is a Venus orbiter mission that carries a radar and infrared spectrometer. If this mission is selected to move forward, a NASA contributed ride-share opportunity may present itself that could potentially carry an *in situ* probe or lander to Venus.

Conclusion: Although no Venus missions are currently funded by any international space organization, several future opportunities exist. We will continue to advocate for new Venus exploration opportunities, and in particular continue to stress the importance of completing the *in situ* science called for by the Decadal Survey.

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