THALASSA: A MISSION TO FOLLOW THE WATER ON VENUS. Paul K. Byrne[1], Elizabeth A. Frank[2], M. Darby Dyar[3], Jörn Helbert[4], Peter Illsley[2], Attila Komjathy[5], Siddharth Krishnamoorthy[5], Robert J. Lillis[6], Joseph G. O'Rourke[7], Emilie M. Royer[8], Sean C. Solomon[9], Constantine Tsang[10], Christopher Voorhees[2], and Colin F. Wilson[11], [1]North Carolina State University, Raleigh, NC 27695, USA (paul.byrne@ncsu.edu); [2]First Mode, Seattle, WA 98121, USA; [3]Mount Holyoke College, South Hadley, MA 01075, USA; [4]German Aerospace Center (DLR), Berlin, Germany; [5]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91125, USA; [6]UC Berkeley Space Sciences Laboratory, Berkeley, CA 94720, USA; [7]Arizona State University, Tempe, AZ 85281, USA; [8]Planetary Science Institute, Tucson, AZ 85719, USA; [9]Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY 10964, USA; [10]Southwest Research Institute, Boulder, CO 80302, USA; [11]Oxford University, Oxford OX1 3PU, UK.

Introduction: There are tantalizing indications that Venus might once have possessed much more water than it does today [1–3], raising the prospect that the second planet may have long been Earth-like and thus even habitable. But when and how this water was lost, whether it ever existed in liquid form on the surface, whether geological or geochemical evidence of this water remains preserved on the surface, and even whether Venus and Earth really did start off with similar water inventories remain unanswered questions [4].

Understanding the extent to which Venus was once a water world will substantially improve our understanding of this enigmatic planet, of the geological evolution of our own world and the inner Solar System more broadly, and of the rules that govern Earth-size worlds in this and other planetary systems. Our mission concept is named for the primordial spirit of the sea in Greek mythology and traces back to our singular scientific goal: *follow the water on Venus*.

Scientific Goal: The Thalassa scientific goal is arguably *the* highest-priority goal for Venus exploration and encompasses climate, geology, and geophysics. Water is the key to Earth's habitability [e.g., 5] and likely plays a major role in plate tectonics [4]. Therefore, water is a vital clue to the mystery of whether early Venus and early Earth were similar, and, if so, when and why the geological evolution of Venus and Earth diverged. Thalassa's scientific goal is directly traceable to NASA's strategic objectives for planetary science and addresses high-priority questions from all three broad, crosscutting themes in the 2011 "Vision and Voyages for Planetary Science in the Decade 2013–2022" Decadal Survey. The Thalassa scientific goal also directly addresses many high-priority investigations from the 2019 Venus Exploration Analysis Group (VEXAG) report, "Scientific Goals, Objectives, and Investigations (GOI) for Venus Exploration" [6].

Scientific Investigations: Stemming from our "follow the water" goal, the Thalassa mission concept features four scientific investigations that explore the role of water from the upper atmosphere to the surface. Ordered here from greatest to lowest altitude at Venus, those objectives are:

1) *Characterize atmospheric water loss at Venus*, including escape rates of H and O and atmosphere–solar wind/plasma environment interactions;

2) *Determine the history of Venus' outgassing and water loss*, including its deuterium–hydrogen (D/H) ratio and noble gas concentrations, to gain new insight into the extent of outgassing of the planet's interior;

3) *Search for current evidence of volcanically emitted water on Venus* by mapping the abundance of water in the lower atmosphere to ascertain whether outgassing is occurring today; and

4) *Document the role of water in the formation of tesserae*, to test whether this distinctive terrain type formed in the presence of abundant quantities of water and is thus analogous to Earth's continents.

Investigation 1—Water Loss: The D/H ratio in the atmosphere of Venus is about 100 times that of Earth [e.g., 7]. This enrichment in deuterium can be interpreted as either the signature of a lost primordial ocean of at least 0.3% the volume of an Earth ocean, or of a steady state in which water is continuously supplied to the surface of Venus by comets or volcanic outgassing, balancing loss through hydrogen escape [8]. Nevertheless, the extreme aridity of Venus' current atmosphere (with a water vapor content of 0.003%) compared with Earth led numerous workers to conclude that large amounts of water have been lost from Venus since its formation [e.g., 7].

But major uncertainties remain about atmospheric loss mechanisms at Venus. Acquiring well designed and continuous observations of the Venus upper atmosphere will provide vital information on the rates at which H and O, and thus water, are lost to space at present (**Figure 1a**). Such observations will contribute to a comprehensive understanding of how hydrogen and oxygen atoms are transported through the bulk of the atmosphere before escaping from the upper atmosphere, and will act as invaluable constraints for global circulation models.

Investigation 2—Outgassing: The middle and lower atmosphere of Venus contain critical information on the past and current outgassing history of the planet. Determining whether liquid water was ever present can be in part answered by characterizing atmospheric species in the modern bulk atmosphere. By doing so, we can address such outstanding questions as how much water was in the interior of Venus in the past, when these outgassing events occurred, and if and when outgassing and water loss ended.

Measuring isotopic ratios of atmospheric noble gases such as He, Ar, Kr, and Xe will allow us to constrain the sources and sinks of the past atmosphere (**Figure 1b**). Because these noble gases would have outgassed together with large reservoirs of water vapor, measuring the abundances of these gases will help us understand when and how much water was injected from the interior to the surface and atmosphere, offering a critical insight into Venus' primordial water content.

Investigation 3—Volcanic Activity: The Venus deep troposphere (from ~15 km to the surface) contains a minute abundance of water vapor; as yet, no spatial or temporal variability has been detected [9]. On Earth, volcanic eruptions are a leading mechanism by which water vapor is injected into the atmosphere, with modern volcanic plumes containing large amounts of H_2O [e.g., 10]. Water vapor plumes should be easier to detect on Venus than on Earth because of the low background variability of tropospheric water vapor abundances. *By studying near-surface atmospheric water vapor concentrations we will search for evidence of recent or ongoing volcanism, with the main objective of determining whether Venus's interior contains amounts of water comparable with Earth* (**Figure 1c**).

Investigation 4—Tessera Formation: Tessera terrain occupies ~8% of the planet's surface and is interpreted as the locally oldest material on Venus [11] (**Figure 1d**). Tesserae are tectonically complex geological units with styles of deformation not observed on any other planetary body (other than, perhaps, the continents on Earth). These units occur as both large plateaus thousands of kilometers across and as smaller inliers (isolated, high-standing regions hundreds of kilometers in breadth that are embayed by later younger volcanic deposits) [11].

On the basis of morphology, gravity signature, and inferred composition, tesserae have been proposed to be the Venus counterparts of continents on Earth [12–14]. Although fractional crystallization can yield felsic rocks from mafic (or ultramafic) source rock, this process is highly unlikely to account for the estimated volume of tesserae on Venus [e.g., 15]. This conclusion bolsters the hypothesis that the tesserae are analogous to granitic continental materials on Earth, which form via crustal recycling in the presence of substantial volumes of subsurface water [16]. Because felsic rocks have proportionately more silicon and less iron than silica-poor mafic rocks, *characterizing the total iron abundances of Venus' tessera terrain offers a direct measure of whether they are compositionally similar to continental materials on Earth* [17].

Notional Implementation: An instrument suite based on MAVEN's heritage [e.g., 18] and carried on an orbiter element will address Investigation 1. The orbiter will also search with a near-infrared (NIR) spectrometer [cf. 17] for evidence of recent water injection into the lower Venus atmosphere for Investigation 3, and will characterize the iron content of major tessera units across the surface for Investigation 4. An aerial platform, taking inspiration from the Soviet VeGa balloons (which explored Venus' clouds in 1985) but incorporating contemporary capabilities [19] will

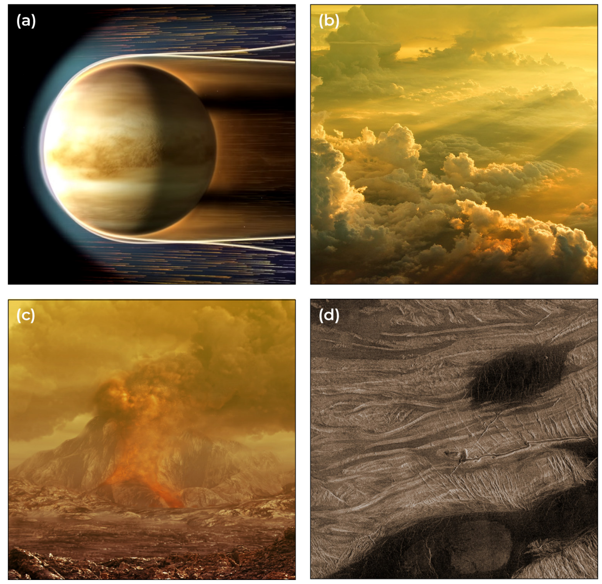

Figure 1: (a) *Thalassa will characterize atmospheric loss mechanisms at Venus to an unprecedented precision.* **(b)** *By accurately measuring middle-atmosphere composition, Thalassa will establish Venus' degassing history.* **(c)** *Thalassa will search for evidence of injections of water into the atmosphere, helping to answer whether Venus is volcanically active.* **(d)** *Are the tesserae akin to Earth's continental materials? Thalassa will tackle this question head on.*

characterize the bulk composition of the middle Venus atmosphere for Investigation 2. And a set of miniaturized, NIR-instrumented dropsondes will deploy from the aerial platform to target a subset of the tesserae resolved by the orbiter for Investigation 4.

Our proposed combination of orbiter, aerial platform, and dropsondes *represents a novel approach to Venus exploration on the scale of a New Frontiers mission*. Venus offers us a natural laboratory in which to understand how large rocky planets form and evolve—so isn't it time we went back?

References: [1] Treiman A. H. (2007) in *Exploring Venus as a Terrestrial Planet,* Esposito L. W. et al. (eds.) AGU Geophys. Monograph Ser., *176*, 7–22. [2] Elkins-Tanton L. T. et al. (2007) *JGR*, *112*, E04S06. [3] Way M. J. et al. (2016) *GRL*, *43*, 8376–8383. [4] Smrekar S. E. et al. (2007) in *Exploring Venus as a Terrestrial Planet,* Esposito L. W. et al. (eds.) AGU Geophys. Monograph Ser., *176*, 45–71. [5] Tosi F. et al. (2017) *EGU General Assembly*, *19*, abstract 7375. [6] VEXAG *Goals, Objectives, and Investigations for Venus Exploration* (2019). [7] Donahue T. M. et al. (1982) *Science*, *216*, 630–633. [8] Grinspoon D. H. et al. (1993) *PSS*, *41*, 515–542. [9] Haus R. et al. (2015) *PSS*, *105*, 159–174. [10] Burton M. E. at al. (2001) *JGR*, *106*, 30,099–30,107. [11] Ivanov M. A. & Head J. W. (2011) *PSS*, *59*, 1559–1600. [12] Hashimoto G. L. & Sugita S. (2003) *JGR*, *108*, E002082. [13] Hashimoto G. L. et al. (2008) *JGR*, *113*, E003134. [14] Romeo I. & Capote R. (2011) *PSS*, *59*, 1428–1445. [15] Gilmore M. S. at al. (2017) *SSR*, *212*, 1511–1540. [16] Campbell I. H. & Taylor S. R. (1983) *GRL*, *10*, 1061–1064. [17] Dyar M. D. et al. (2018) *VEXAG Meeting*, *16*, abstract 8015. [18] Jakosky B. M. (2018) *Icarus*, *315*, 146–157. [19] Cutts J. A. et al. (2018) *Venus Aerial Platform Study*, JPL D-102569.