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# New-Frontiers Class In-Situ Exploration of Venus: The Venus Climate and Geophysics Mission Concept


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The information presented about the VCG mission concepts is pre-decisional and is provided for planning and discussion purposes only

**INTRODUCTION AND MISSION GOALS:** We discuss a class of Venus New Frontiers mission concepts that effectively and affordably address the majority of priority science objectives dealing with Venus' formation, evolution, interior, surface, and atmosphere promulgated by the Venus Exploration Analysis Group (VEXAG) [1]. Collectively called Venus Climate and Geophysics Missions (VCGMs), this mission class incorporates both in-situ and orbital elements to obtain an optimum science return within the New Frontiers ~$1B cost constraint. A companion Decadal Survey white paper has advocated broadening the current criteria for the Venus New Frontiers mission to allow mission concepts with orbiters and aerobots to compete on an equal footing with landers, which have, since the inception of New Frontiers, been the default platform for addressing Venus science. This white paper does not specify a single mission concept, but instead describes a suite of possibilities that could fit in the New Frontiers envelope. A detailed study could be carried out under the auspices of the Planetary Science Decadal Survey to guide the Survey on the potential of such a New Frontiers mission.

**SCIENTIFIC GOALS:** The overarching goal of VCGM is to combine measurements of the atmosphere and near-surface to understand Venus as a planetary system and why its atmospheric circulation/dynamics, evolution and geophysical properties are unique in general and different from Earth in particular. The Science Objectives are summarized in Table 1. A summary of potential elements and some of the impactful measurements enabled by high-science-return VCGMs is depicted in Figure 1.

Table 1: Science Objectives of VCGM Mission Concept

**I. Understanding the Atmosphere's Dynamical and Chemical Processes and Potential Habitability**

A. Provide Fundamental New Insights into the Physics of Super-Rotation

1. Determine energy deposition in the clouds, a key unknown needed for GCM's
2. Determine the characteristics of meridional transport over a significant range of altitudes
   - Characterize Hadley Cells
3. Characterize stability in the clouds: Variability with time-of-day, power of convection and turbulence
4. Characterize gravity waves over a significant range of altitudes
5. Characterize P/T and $N_2$ abundance in the Surfacel Boundary Layer

B. Provide Fundamental New Insights into Chemical/Dynamical Processes in the Clouds

1. Investigate cloud/gas chemical cycle: Investigate the relationships between the composition, and Local mass density of cloud particles and the local abundances of associated gases; Across all times-of-day and large ranges of altitudes and latitudes
2. Investigate association of cloud particle size and composition with local dynamics (convecton, gravity waves) and energy deposition
3. Determine the nature of UV-absorbing aerosols: Composition, local abundance, and genesis
   - Determine contituents important to habitability
4. Constrain lower atmosphere thermal chemical processes via vertical profiles of reactive gases down to the surface

**II. Origin/Evolution Objectives: Understanding how the planet originated and evolved**

1. Origin: Determine major supplier of volatiles and materials; Compare to to Earth, Mars, and Moon.
2. Evolution: Determine early water abundance circa 4.1 Gyr ago and loss from that era

**III. Geophysics Science Objectives: Interior, Sub-Surface and Surface Geologic Processes**

1. Characterize seismic activity
2. Characterize depth of Lithosphere
3. Characterize surface minerology of major geologic features
4. Constrain interior processes via remanant magnetic field mapping and high-fidelity search for planetary magnetic field underneath the ionosphere
5. Characterize rotation rate change between Magellan and Venus Express epochs

**Variable-Altitude Mid-Cloud Aerobot:** Taking our initial direction from the most recent VEXAG Roadmap [1] supplemented by two Venus community workshops on the science return, complexities, and risks of a variety of aerial platforms [2], we center our mission around a key element: a long-lived, altitude-varying balloon-borne instrumented science platform (hereafter, "aerobot"). Utilizing the large (~60 m $s^{-1}$) zonal winds found at all latitudes equatorward of ~ 60°, the aerobot would circle the planet more than a dozen times over a notional 90-Earth-day science phase. Global Circulation Model simulations [3] indicate that the aerobot would sample a wide range of latitudes between the equator and 50°.

To further enhance the flight duration, data volume and altitudes sampled over previously proposed battery-powered super-pressure balloon missions, the aerobot will utilize solar cells for power and operate throughout the mid cloud region from 52 to 62km. The technology for accomplishing the variable-altitude balloon mid-cloud platform can be made ready early in the time frame of interest for the upcoming decadal survey 2023 to 2032 [in 1].

***Atmospheric Investigations:*** Onboard instrumentation would sample the environment over all times of day including (1) the winds in all three dimensions, (2) the pressure/temperature structure, and (3) the composition of the air and aerosols [4], including (A) UV-absorbing material which possibly may be linked to astrobiology [5,6], (B) the reactive sulfur-cycle gases that create the aerosols, and (C) the noble gases, their isotopes and the isotopes of light gases. - key to understanding the formation of the planet and the evolution of its atmosphere (e.g., [7]). The aerobot, capable of multiple altitude traverses of up to 10 km centered near an altitude of 55-km (~0.5 bar, 25C), will enable three-dimensional maps of these environmental characteristics, as well as the dynamically and chemically influenced size distribution of aerosol particles via a nephelometer (e.g., [8]) and/or particle counter [9]. These traverses also reveal the vertically-varying characteristics of atmospheric stability, gravity and planetary

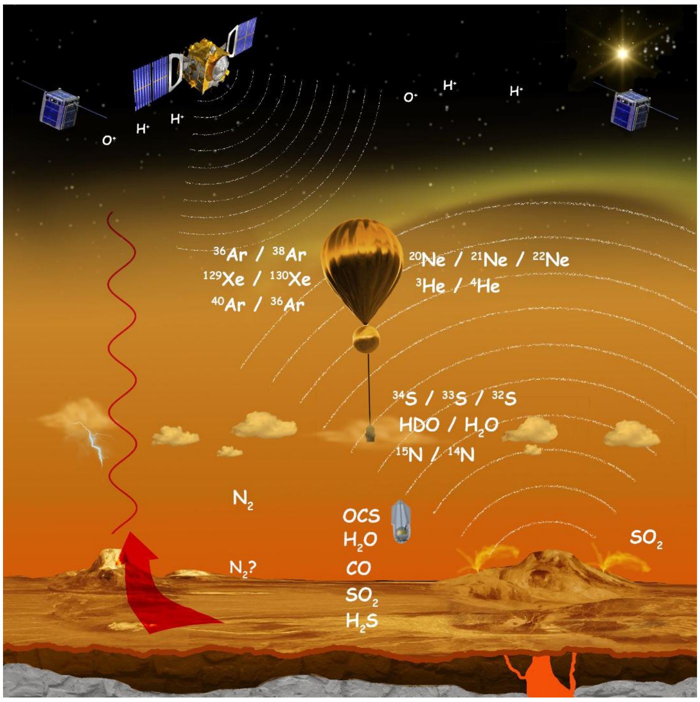


Figure 1. VCGM potential architectures involve a variable-altitude balloon-borne aerobot, a science and communications orbiter, CubeSat(s), and drop sonde(s) to achieve a broad array of in-situ and remote-sensing measurements to achieve many geophysical and most atmospheric and origin/evolution goals, objectives and investigations of VEXAG [1]. A sampling of potential VCGM investigations shown here are (1) Evolution: atmospheric escape of H and O ions, and abundances of noble gases and their isotopes; (2) Atmospheric processes: winds, waves, cloud formation processes via dynamics data and aerosol- and gas-sampled species abundances; lightning, and Surface Boundary Layer properties such as the $N_2$ profile; and (3) Geophysics: seismic-generated infrasound and airglow measurements and lithospheric depth.

waves, and Hadley cells, all important for understanding the mechanisms that power and sustain the planet's strong super-rotation. As well, these altitude excursions enable measurements of the radiative balance and solar energy deposition via a Net Flux Radiometer [10], another key to understanding super-rotation.

***Geophysical investigations:*** As it circumnavigates Venus every 5 days, the aerobot monitors the terrain that it passes over from 50-60 km in altitude. Geophysical investigations of the interior of the planet take advantage of (1) the proximity to the surface relative to an orbiter and (2) the contact with the atmosphere which enables infrasound to be observed in situ. Electromagnetic measurements of the thickness of the lithosphere using excitation by the Schumann resonance [11], surveys of remanent magnetism [12,13] evidence of an early Venusian magnetic field, and an infrasound survey of seismic activity [14] are envisioned.

**Orbiter:** To enhance the scientific return over mission concepts with just an aerobot (e.g., the proposed VALOR Discovery Mission [15]), VCGM will be coupled with an orbiter. The orbiter will 1) relay data from the aerobot to greatly increase data return in a similar fashion to the way orbiters enhance data return from Mars rovers. The orbiter will also locate and track the aerobot, particularly on the farside of Venus when out of view of Earth-based radio telescopes [16]. The orbiter will also be equipped to make science measurements synergistic with those from the aerobot. These will include imagers/spectrometers for both atmospheric and surface science support, à la Venus Express and Akatsuki. In particular, near-infrared imaging spectrometers/imagers (e.g., [17, 18]) would be included for their capability to spectrally image (1) clouds and trace gases at depth [19], and (2) a large portion of the surface that was relatively poorly covered by Venus Express. Seismic investigations of the interior can also be conducted that are complementary to those carried out by the aerobot through the detection of infrared radiation produced when infrasound emanating from Venus quakes interacts with the upper atmosphere [14,20]. Other spectral imagers would map the UV-absorbing clouds and signals of the interaction of the solar wind with the upper atmosphere and ionosphere [21, 22], as well as the thermal structure and tides and waves of the middle atmosphere in the thermal IR [23]. Finally, An INMS [24] would sample the atmospheric loss of hydrogen and oxygen over a wide range of latitudes (likely > 70$^o$) under varying solar wind conditions over the expected orbiter lifetime of several years.

**Auxiliary Platforms:** In addition to the two primary platforms, the VCGM may include two types of auxiliary platform. Their contributions still need to be assessed.
***CubeSats:*** These would be released from the main orbiter after it enters orbit but before it reaches its final orbit. Their primary goals would be to provide (1) more complete positional coverage of the aerobot and (2) enhanced radio occultation coverage of the atmosphere [25].
***Dropsondes:*** These lightweight (~2–4 kg) elements could be released from the aerobot and probe deeper into the atmosphere than the aerobot, perhaps even down to the surface. They could measure the vertical profiles of winds, pressure, temperature, and stability, and measure chemical species [26]. Another possibility would be to measure the vertical variability of $N_2$ (via a speed-of-sound/attenuation sensor [27]) throughout the atmosphere down to the surface including within the ~ 7 km-thick surface boundary layer, a critical measurement for understanding the stability and dynamics of the lower atmosphere [28].

**RELATIONSHIP TO VEXAG's VENUS STRATEGIC PLAN:** In 2019, the Venus Exploration Analysis Group (VEXAG) updated three guiding documents for Venus Exploration – the Goals Objectives and Investigations, the Roadmap for Venus Exploration and the Technology Plan. All of these can be found co-located on the VEXAG site [1].

**VEXAG Goals Objectives and Investigations:** The prime science objectives for potential VCGM missions stem from the community-endorsed VEXAG Goals, Objectives and Investigations (GOI) document one of three documents that comprise the VEXAG Venus Strategic Plan [1] and discussed in a VEXAG-led white paper [29]. The VEXAG GOI document identifies three major goals: I. Early Evolution and Potential Habitability; II. Atmospheric Dynamics and Composition; and III. Geologic History and Processes, and specifies the objectives and investigations needed to accomplish each goal. There is a great deal of congruence between the VEXAG GOI and the scientific objectives for VCGM set out in Table 1.

- ***VCGM Goal I Atmospheric Science – Understanding the planets Dynamical and Chemical Processes & Potential Habitability:*** This maps directly on to VEXAG Goal II.
- ***VCGM Goal II Understanding how Venus Originated and Evolved;*** This has a significant overlap with VEXAG Goal I.
- ***VCGM Goal III Geophysics Science Objectives: Interior, Sub-Surface and Surface Geological Processes.*** This addresses a substantial subset of the investigations in both VEXAG Goals I and III that involve the nature of the lithosphere, magnetism, the core, crustal structure and geologic activity.

In order to address how completely, the VCGM mission addresses VEXAG objectives we rely on an assessment made by VEXAG [1] of the degree to which three types of mission elements – an orbiter designed for atmospheric investigations, a mid-cloud aerobot and a sonde deployed by the aerobot – address the VEXAG GOI (Table 2). We note again that the evaluations presented in Table 2 are those made by the VEXAG GOI developers and involve certain assumptions about (1) the instruments carried by each platform and (2) the independent nature of the platforms, including a lack of cooperation and synergy.

**VEXAG Roadmap for Venus Exploration:** In its Roadmap for Venus Exploration, VEXAG Roadmap developers did consider the value of platforms operating cooperatively in multiplatform missions and noted the scientific and technical benefits:

- Launching several platforms to Venus on a single platform is generally less costly than launching them separately.
- Inserting several in situ platforms (surface and aerial platforms and probe) into the atmosphere of Venus is less costly than for separate entry systems.
- For concepts with long duration in situ operations, the presence of an orbiter may be required for returning data or enhance data return.
- The ability to acquire orbital context data will be valuable to the interpretation of the in situ data.
- Conversely, the in situ observations may provide validation of orbital measurements e.g. for wind velocity or surface temperature.
- Orbiters can provide a vital role in monitoring the position of an aerial platform particularly when the platform is on the far side of Venus relative to the Earth

Table 2. Comparison of VEXAG GOI with the capabilities of Aerobot, Orbiter and Sonde developed by VEXAG [1]. Assessment of composite mission by VCGM team.

| VEXAG Goals, Objectives and Investigations | | | | | Contribution to Investigation | | | |
|---|---|---|---|---|---|---|---|---|
| Goals | Objectives | Investigations | GOI Code | GOI Rating | Aerobot | Orbiter | Sonde | Composite |
| I. Early Evolution, and Potential Habitability | A. Did Venus have liquid water? | Hydrous origins | I.A.HO | 1 | | yellow | | yellow |
| | | Recycling | I.A.RE | 1 | yellow | | | yellow |
| | | Atmospheric Losses | I.A.AL | 2 | | blue | | blue |
| | | Magnetism | I.A.MA | 3 | blue | yellow | | blue |
| | B. How does Venus elucidate pathways for planet evolution | Isotopes | I.B.IS | 1 | blue | | | blue |
| | | Lithosphere | I.B.LI | 1 | blue | yellow | | blue |
| | | Heat flow | I.B.HF | 2 | | | | |
| | | Core | I.B.CO | 2 | | | | |
| II Atmospheric Dynamics Composition | A. What drives global dynamics | Deep Dynamics | II.A.DD | 1 | blue | blue | yellow | green |
| | | Upper Dynamics | II.A.UD | 1 | | blue | | blue |
| | | Mesoscale Processes | II.A.MP | 2 | blue | blue | yellow | green |
| | B. What governs compositions and radiative balance? | Radiative Balance | II.B.RB | 1 | blue | blue | yellow | green |
| | | Interactions | II.B.IN | 1 | blue | blue | blue | green |
| | | Aerosols | II.B.AE | 2 | blue | yellow | blue | green |
| | | Unknown UV absorber | II.B.UA | 2 | blue | blue | yellow | green |
| | | Outgassing | II.B.OG | 3 | blue | blue | yellow | green |
| III Geologic history and processes | A. What geological processes shape the surface | Geologic history | III.A.GH | 1 | | | | |
| | | Geochemistry | III.A.GC | 1 | | yellow | yellow | yellow |
| | | Geologic Activity | III.A.GA | 2 | yellow | yellow | yellow | yellow |
| | | Crustal | III.A.CR | 2 | blue | yellow | | blue |
| | B. How do the atmosphere and surface interact | Local Weathering | III.B.LW | 1 | | yellow | blue | blue |
| | | Global Weathering | III.B.GW | 2 | yellow | blue | | blue |
| | | Chemical Interactions | III.B.CI | 3 | yellow | yellow | blue | blue |

| | |
|---|---|
| blue | Enables measurements that are vital alone or in combination to completing investigation - Assessment by VEXAG |
| yellow | Enables measurements that substantially address the investigation- Assessment by VEXAG |
| green | Enables the combination of measurements that address this investigation in a superior fashion - Assessment by VCGM team |

Note: Reproduced in part from VEXAG Strategic Plan p.GOI-30. Landers and entry probes have been removed from this version

The assessment of the science contribution of individual platforms aerobot, orbiter, sonde in Table 2 does not capture adequately the complementary nature of the measurements addressing the different investigations in Table 2 nor does it convey their synergism. For example, in the case of investigation II.B.RB Radiative Balance, both the aerobot and the orbiter are indicated as making measurements that are, alone, vital to completing the investigation. In this case, the measurements – one in situ and one remote from orbit – are clearly very different in nature. The ability of VCGM to make simultaneous, co-located, synergistic in situ and orbital measurements is what sets apart this multi-platform mission apart from missions in which the two platforms are sent to Venus at different times. To depict this advantage, in Table 2 we have provided a composite assessment of combined contemporaneous measurements by all three platforms. Where one of the measurements from an individual platform that was determined to be vital (blue), the combined measurements are also considered vital. Where two or more measurements are determined to be vital, the composite of the measurements is assessed to be superior (green) reflecting the complementarity of aerobot, orbiter and sonde vantage points. Out of the 23 VEXAG investigations, VCGM achieves superior or vital measurements for 16 topics (70%), and at least substantially addresses 20 (87%) of them. Superior measurements cover 7 (30%).

**VEXAG Technology Plan:** The VEXAG Technology Plan of 2019 (in [1]) includes an assessment of the maturity of aerobot, orbiter, cubesat and sonde technologies and instruments. Our selection of the mid-cloud aerobot for this mission reflects the judgement expressed there that this technology can be ready for flight in this decade. A VEXAG-sanctioned study [2] evaluated the science merit of a variety of aerial platforms, including the fixed altitude (super-pressure) and variable-altitude types. Indeed, considerations of complexities of various aerial vehicles - including mobile aircraft - led the aerial platform study team to conclude: "Variable-altitude (50 to 60 km altitude) balloons occupy the sweet spot. For a modest increase in size and complexity over the fixed balloon and accepting a moderate degree (vs. high degrees) of technology maturity, there is a significant gain in science."

Aerobots able to descend to ~ 47 km altitude near 100C just below the cloud base and acquire near-infrared images from that vantage point require further technology development and are more suited to earlier in the subsequent decade. Accordingly, our VCGM measurements that require access to below the clouds would be implemented with ***deployable sondes of limited lifetime***. A companion white paper [30] describes a sub-cloud aerobot mission that focuses specifically on acquiring near infrared nighttime surface images, including the coronae and tesserae, and identifies the new technologies that will be needed to get there in the 2033-2042 timeframe.

## RATIONALE FOR A STUDY OF THE VCGM MISSION CONCEPT

One multiplatform concept, The Venus Flagship Mission (VFM) has been studied under the Planetary Mission Concept Studies program [31]. The VCGM, described here, would involve a subset of the platforms included in VFM. It does NOT include:

- A Venus Lander capable of landing safely in the tessera, surviving on the surface for five hours and conducting a comprehensive set of geochemical investigations with remote sensing and ingestions of samples.
- A Long-Duration Landed capability involving advanced electronics and power technology capable of surviving on the surface for up to 60 days and measuring temperature pressure and wind speed.
- A capable orbital imaging radar needed to characterize the surface of Venus to ensure a safe and scientifically productive Venus landed mission.
- Two additional orbiters needed for a comprehensive investigation of Venus loss rates.

The baseline VCGM mission concept includes a Variable Altitude Mid-Cloud aerobot, which is part of VFM, but for VCGM the operational requirements on this vehicle have been limited to enable an aerobot of much smaller mass than for VFM. Correspondingly, the VCGM orbiter, which neither needs to support an imaging radar nor access a tight circular orbit can be simplified. Operating by analogy with previous orbiter (VESAT, [32]) and balloon (VALOR, [15]) concepts developed by the lead author for the Discovery program, a baseline VCGM concept with an aerobot and an orbiter should be feasible within the New Frontiers cost envelope. Whether additional capabilities such as sondes and CubeSats could be accommodated is less clear and would require a detailed study to define the trade space. Conducting such a study under the auspices of the Decadal Survey could not only clarify these options but would also provide the community needed experience in assessing the cost and risk of Venus missions with new types of observational platform.

**SUMMARY:** A large segment of the Venus community has advocated broadening the set of missions eligible for proposal to the New Frontiers program to permit a broader set of science objectives by including platforms such as aerobots and orbiters. This white paper has described such a mission and demonstrated the breadth of science that it can address in terms of the comprehensive science framework of Goals, Objectives and Investigations developed by VEXAG. While analogy with previous mission concepts involving balloons and orbiters provides confidence that the VCGM mission concept of an aerobot and an orbiter could fit within the New Frontiers cost cap, a study could buttress the case for this. In addition, the study could clarify the additional science contributions of sondes and CubeSats and clarify whether there would be sufficient margins for the primary platforms orbiter and aerobot to allow the addition of such auxiliary platforms.

**References: 1.** VEXAG (2019), Venus Strategic Documents; https://www.lpi.usra.edu /vexag/reports/ Combined _VEXAG_Strategic_Documents_Current.pdf **2**. Cutts, J. A. et al. (2018). Summary report. JPL D-102569. **3**. Sebastien Lebonnois (2017). Presented at Venera-D Venus Modellng Workshop, IKI, October 5-7, 2017, http://venerad.cosmos.ru/fileadmin/user_upload/documents/Workshop2017_ Proceedings .pdf. **4**. Baines, K. H., et al. (2018) https://www.hou.usra.edu/meetings/vexag2018/ pdf/8031.pdf. **5.** Limaye, S. S., et al. (2018). *Astrobiology* 18: 1-18. DOI: 10.1089/ast.2017.1783. **6.** Schulze-Makuch, D., et al. (2004) *Astrobiology* 4:11–18. **7.** Baines, K. H., et al. (2013). Tn *Comparative Climatology of Terrestrial Planets* (S. J. Mackwell, A. A. Simon-Miller, J. W. Harder, and M. A. Bullock, Ed). University of Arizona Press, Pp. 137-160. **8.** Banfield, D., et al. (2004). In: Proc. Int. Workshop 'Planetary Probe Atmospheric Entry and Descent Trajectory Analysis and Science', Lisbon, Portugal, 6–9 October 2003 (ESA Publication SP-544, February 2004). **9.** Renard, J-B., et al. (2016). Atmos. Meas. Tech., 9, 1721–1742 doi:10.5194/amt-9. **10.** Aslam, S., et al. (2015). N*EPSC Abstracts*, Vol 10. EPSC2015-388. **11.** Grimm, R. E., et al. (2012). *Icarus*, *217*(2), 462–473. **12**. O'Rourke, J. et al. (2019). *Geophys. Res. Lett.*46, 5768-5777. **13.** O'Rourke, J.G., et al.(2018). *Earth Plan. Sci. Lett.* 502, 46–56. **14.** KISS: Keck Inst. for Space Studies, Venus Seismology Study Team (2015), Keck Institute for Space Studies, Pasadena, Calif., April 2015, http://resolver.caltech.edu/ CaltechAUTHORS: 20150727-150921873**. 15.** Baines et al. (2009). Long-duration exploration of Venus with a high-altitude balloon: The VALOR Discovery mission. Abstract, Low-Cost Planetary Mission Conf., Laurel, MD. **16.** Cheung, K.-M. et al. (2019). Single-satellite real-time 3D positioning of balloon at Venus/ Titan. IAC abstract. **17.** Helbert, J., et al. (2018). SPIE Proc. Vol. 10765, *Infrared Remote Sensing. and Instrument.* XXVI., 107650D., https://doi-org.ezproxy.library.wisc.edu/10.1117/12.2320112. **18**. Piccioni, G.et al., (2004). VIRTIS. in SP-1295. **19**. Marcq, E. et al. (2008). *JGR* 113, E00B07. **20.** Garcia, R., et al. (2005). *GRL.* 32, L16205.doi:10.1029/2005GL023558 **21.** Gray, C. L. (2015). PhD dissertation, New Mexico State University. **22.** Gray, C. L. et al. (2014). *Icarus* 233, p. 342347. **23**. Kleinboehl et al. (2019). https://www.cps-jp.org/~akatsuki/pub/venus2019/abstracts/ IVC2019_05-3_Kleinboehl_abstract.pdf**. 24.** Waite, J. H., Jr., et al. (2004). *Space Sci. Rev*. 114, 113–231. **25**. Vergados, P., et al. (2018). AGU Fall Meeting 2018, December 10-14, Washington, DC., 2018, Poster number P41F-3795. **26.** Hunter, G. W., et al. (2007). Microsystems, space qualified electronics, and mobile sensor platforms for harsh environment applications and planetary exploration. Presented at Fifth International Planetary Probe Workshop, Bordeaux, FR, June 25-29, 2007. **27.** Petculescu, A., et al. (2006). *J. Acoustical Society America* 120, 1779-1782. doi: 10.1121/1.2336758. **28**. Lebonnois, S. and Schubert, G. (2017). *Nature Geosci*. 10, 473-479. DOI: 10.1038/NGEO2971. **29**. Izenberg, N.R. et al. (2020) The Venus Strategic Plan. White paper submitted to the Planetary Decadal Survey 2023-2032. **30**. Cutts, J. A. et al. (2020). Venus Corona and Tessera Explorer (VeCaTEx). White paper submitted to the Planetary Decadal Survey 2023-2032. **31.** Gilmore, M. (2020) The Venus Flagship Mission, a Planetary Mission Concept Study. Delivered July 27, 2020. **32.** Baines et al. (1995). VESAT: The Venus Environmental Satellite Discovery Mission. *Acta Astronautica* 35, 417-425.