MEETING WITH THE GODDESS

Notes from the First Symposium on Venus Science Enabled by Human Proximity

Keck Institute for Space Studies

Study Report prepared for the W. M. Keck Institute for Space Studies (KISS)

Team Leads: Noam Izenberg, Mallory Lefland, Alexander MacDonald

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Presentations from the Symposium can be found at the Keck Institute for Space Studies:
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Director: Prof. Tom Prince
Executive Director: Michele Judd
Editing and Formatting: Meg Rosenburg
Cover Image: Gordon Squires, Caltech/IPAC

Participants in the 2022 Symposium on Venus Science Enabled by Human Proximity

Keck Institute for Space Studies,
California Institute of Technology

Organizers

Noam Izenberg
Johns Hopkins University
Applied Physics Laboratory

Mallory Lefland
Jet Propulsion Laboratory
California Institute of Technology

Alexander MacDonald
NASA

Participants

Patricia Beauchamp
Jet Propulsion Laboratory
California Institute of Technology

Patrick Chai
NASA

Nick Cummings
SpaceX

Clark Esty
NASA

Matt Daniels
Office of Science & Technology Policy

Matt Duggan
Boeing

Dan Goods
Jet Propulsion Laboratory
California Institute of Technology

David Grinspoon
Planetary Science Institute

Jamie Landers
Lockheed Martin

Kirby Runyon
Johns Hopkins University
Applied Physics Laboratory

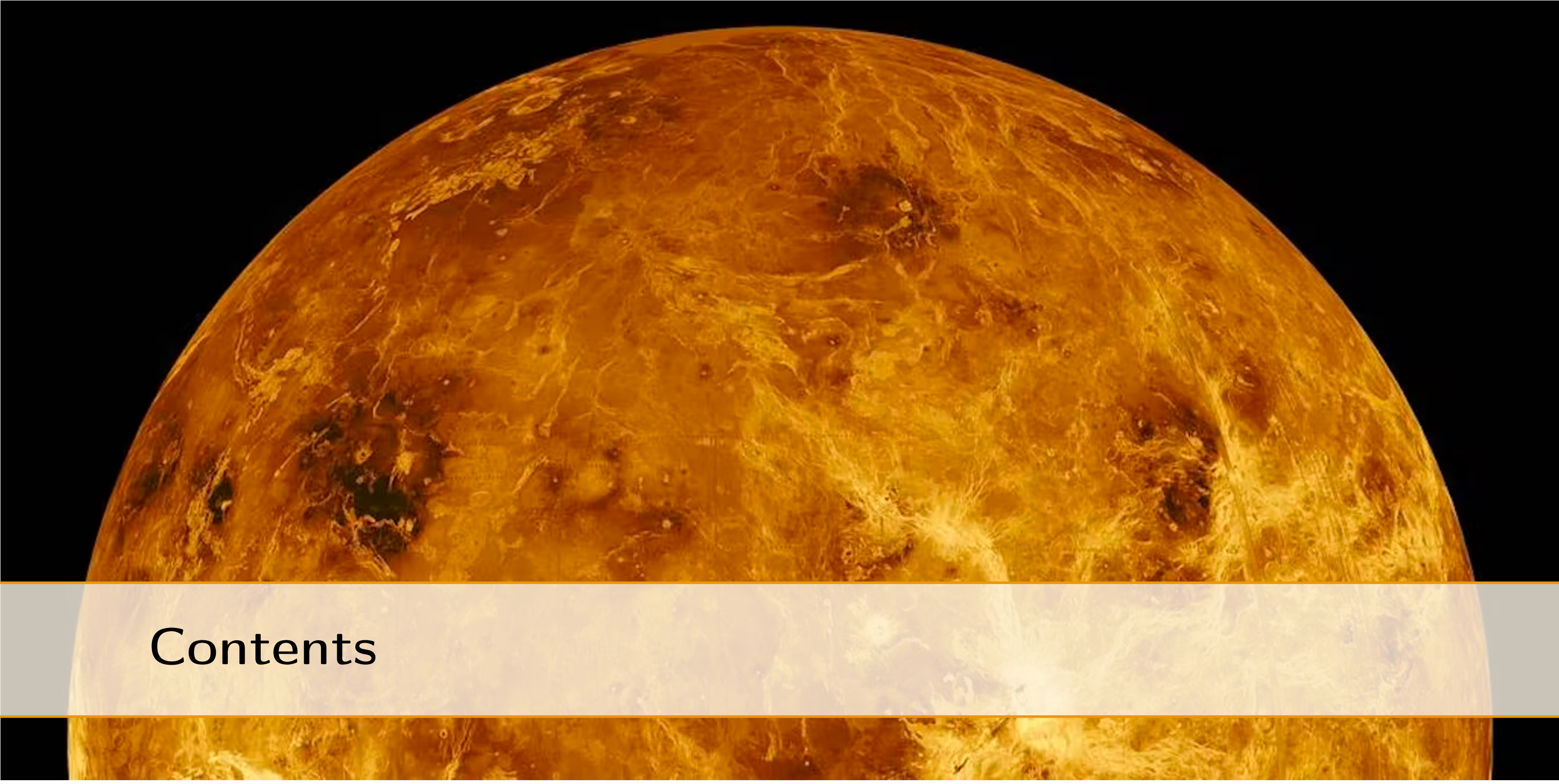
Mark Shelhamer
Johns Hopkins University

Ekaterina Tymofyeyeva
Jet Propulsion Laboratory
California Institute of Technology

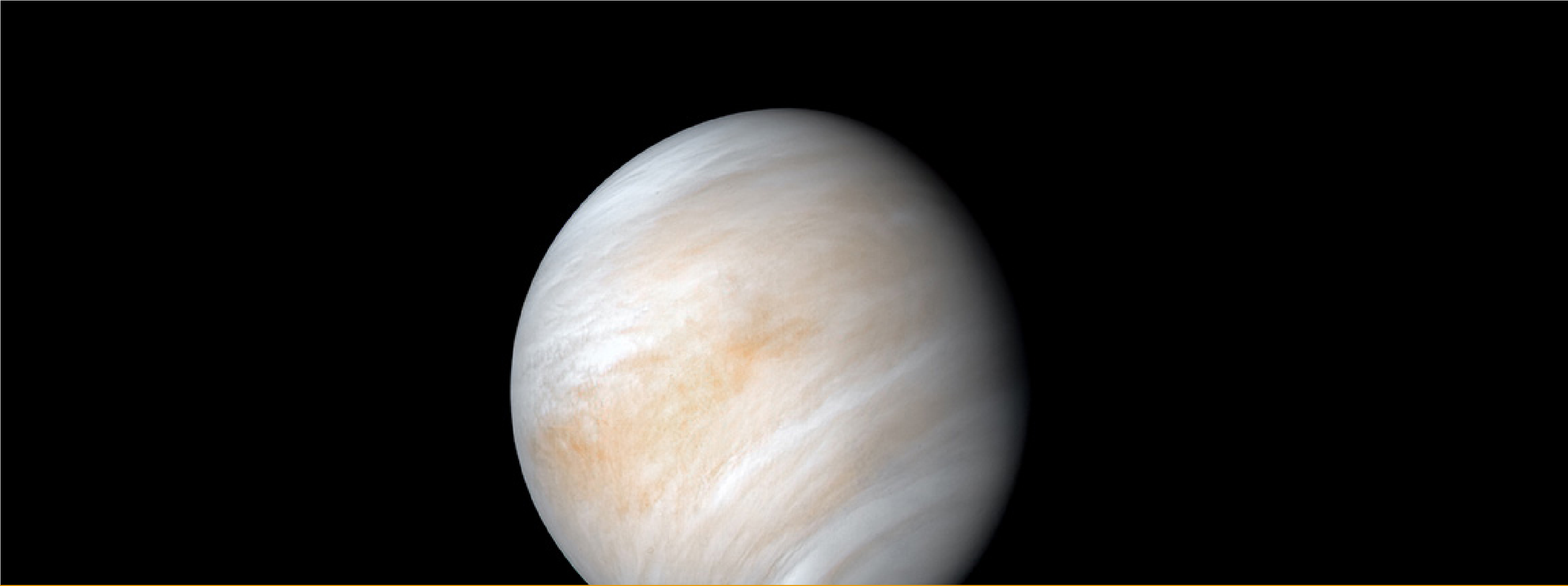
Mark Wallace
Jet Propulsion Laboratory
California Institute of Technology

Pete Worden
Breakthrough Foundation

Marcella Yant
Lockheed Martin



Contents



List of Figures

Overview

"It's been dark for 6 months. Void of sky, void of landscape, void of family and friends, being contained for what seems like forever with only points of light to ponder. The last thing I saw left me speechless, it was... profound... the thin blue line that was the atmosphere of my home world getting smaller, getting smaller, until it disappeared into the vast field of stars. Earth had never meant so much to me. My people, my land, my home, fragile in every sense of the word and seared into my memory banks as I and my crew approach the pale yellow dot. Venus, Earth's sister, who traveled a different path. One that left it inhospitable despite its similarities to home. What will our sister tell us about Earth, about ourselves, about the choices we have to make? What will being the first humans to ever see another planet up close do for those on this vessel and those waiting back home? We are 6 days out. It is dark, but the light is coming!"

—Imagined diary entry of an astronaut on a first human mission to Venus

In July of 2022, the Keck Institute for Space Studies (KISS) hosted a symposium entitled "Science Enabled by Human Proximity to Venus." Convened to explore the potential science that could be enabled by human mission fly-bys of Venus while en route to Mars, the symposium conversation expanded to encompass the policy and social rationales for a dedicated human mission to Venus, as well as a new concept for a potential human mission to Venus—The Venus Back-Flip.

This symposium summary, compiled by contributions from symposium participants listed at the beginning of this report, is the start of a broader discussion that is likely to become more and more relevant in the coming years as the multiple human space exploration capabilities under development provide potential opportunities to execute a human mission to Venus—whether en route to Mars or as a dedicated mission. This summary will outline some of the relevant options for Venus human fly-by and orbital missions, some of the new or enhanced science investigations that could be achieved in tandem with human fly-by or orbital missions, why integrating Venus into the overall Moon-to-Mars strategy may be valuable, how social and cultural activities might advance human missions to Venus, and why Venus may deserve its own journey of exploration independent of other destinations.

This report is a summary of the discussions, observations, and ideas that were generated at the symposium. The summary is written primarily for three types of audiences: human spaceflight mission and campaign planners, Venus scientists and technical innovators, and individuals interested in the social aspects of organizing to promote the human exploration of Venus.

The symposium revealed that Venus is a desirable human spaceflight destination in its own right. The compelling narrative of exploration combines planetary science at Venus, the search for life in its clouds, and an encounter with our sister planet that may shed light on our future climate.

Human missions to Venus are not part of the baseline exploration architecture of NASA or any other organization that participated in the symposium. Missions to Venus are not part of NASA's current Moon to Mars Objectives.

The thoughts and concepts expressed and explored at the symposium do not represent the positions of any participating organizations and are offered here in the spirit of open debate and discussion, which is encouraged by the Keck Institute for Space Studies.

1. Mission Architecture Options

There is a long-enduring cultural interest in the planet Venus, with the result that humans have been thinking about expeditions there for over a century and designing missions to Venus for decades. For the foreseeable future, the most feasible human missions to Venus will be missions that fly-by or orbit the planet. The near-term impossibility of landing humans on the surface makes any human mission to Venus architecturally simpler than many human missions to Mars, which often focus on surface landings and activities. For the purposes of this summary, all references to human missions to Venus are to missions that fly-by, double fly-by, or orbit Venus. The relative design simplicity of human missions to Venus is what makes them particularly appealing as a stepping stone into the solar system in the foreseeable future.

As with any major space exploration achievement, there is a potential signaling value to be claimed by anyone who accomplishes a first human mission to Venus. The combination of the intrinsic motivation of individuals and the potential signaling value for nation states or individuals suggests that once it is possible and practicable to achieve, someone will try to achieve it. Since a mission to Venus could be non-trivially simpler than a mission to Mars, a mission to Venus could be less expensive and become achievable sooner than a mission to Mars.

One reason for the relative simplicity is proximity to Earth. Venus gets closer to Earth than any other planet, and is on average significantly closer to Earth than is Mars to Earth (see Figure 1.1).

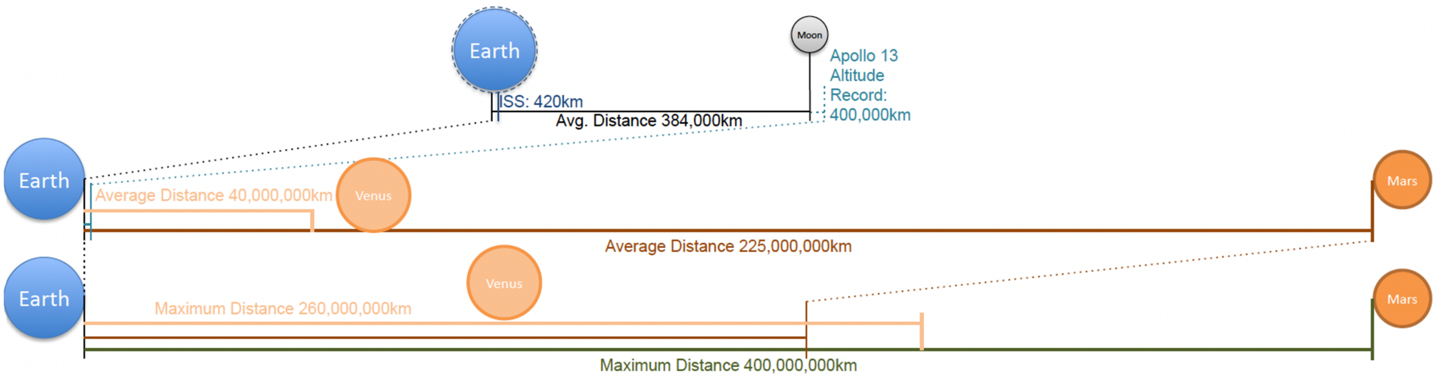


Figure 1.1: Planetary proximity: Earth–Moon System, Venus, and Mars

One consequence of this proximity is that human missions to Venus can be of significantly shorter duration, which can greatly mitigate the risks of long-duration human spaceflight and allow for a stepwise testing and development of human health and performance systems and capabilities in deep space as we begin to venture beyond the Earth–Moon system.

1.1 Architecture Drivers

Initially, the symposium conversation centered around what science a crew might perform while flying by Venus on a mission destined for Mars. In discussing the merits of various experiments, the concept of using Venus as a dedicated, long-duration interplanetary human spaceflight proving ground arose and became an additional focus. While unique, human-enabled science is a prime motivation; the ability to reduce the risk of a human mission to Mars is an equally strong, if not stronger, argument in favor of a dedicated mission to Venus. Rather than only leveraging a Venus fly-by in getting to or from Mars, a standalone Venus mission presented merit on its own. Consequently, several different Venus mission types were discussed and preliminarily investigated: a Venus fly-by, a double Venus fly-by, and a Venus orbital mission. Ideally, the Venus mission would be a proving ground for long missions deeper into the solar system while performing key science to advance our knowledge of our sister planet. Given the concerns associated with maintaining propellant and engines for a long period, the single and double fly-by classes provide the unique opportunity of having the main departure burn be the only significant maneuver. Delving deeper, the double fly-by, and specifically utilizing a "backflip" trajectory, offer a substantial increase in the duration of time spent in the vicinity of Venus.

The recent reintroduction of Venus into the human spaceflight trade space began, however, with the potential for a human fly-by of Venus en route to Mars, and so we will discuss this case first.

1.2 Earth–Mars–Venus–Earth Mission

Over much of the previous two decades, NASA's first human Mars mission was intended to be a "conjunction-class" mission with a ~300–500-day stay at Mars. Recently, this transitioned toward designing an "opposition-class" mission. The NASA Administrator's speech at the 2019 International Astronautical Congress indicated that NASA was considering opposition-class human missions to Mars—where, at launch, Mars and Earth are close to each other in their orbits—that would include a Venus fly-by as part of an overall two-year mission. In 2022, the NASA Moon to Mars objective definition group released a video describing a notional human short-stay mission architecture, with opposition-class missions including Venus fly-by opportunities still in the trade space (Figure 1.2 and Table 1.1). While this approach provides a roughly 50-day stay in the Mars vicinity, the opposition-class mission cuts down the overall mission duration. One component of enabling these shorter Mars missions—other than adopting nuclear propulsion—is adding a Venus fly-by on either the outbound or return leg of the trajectory.

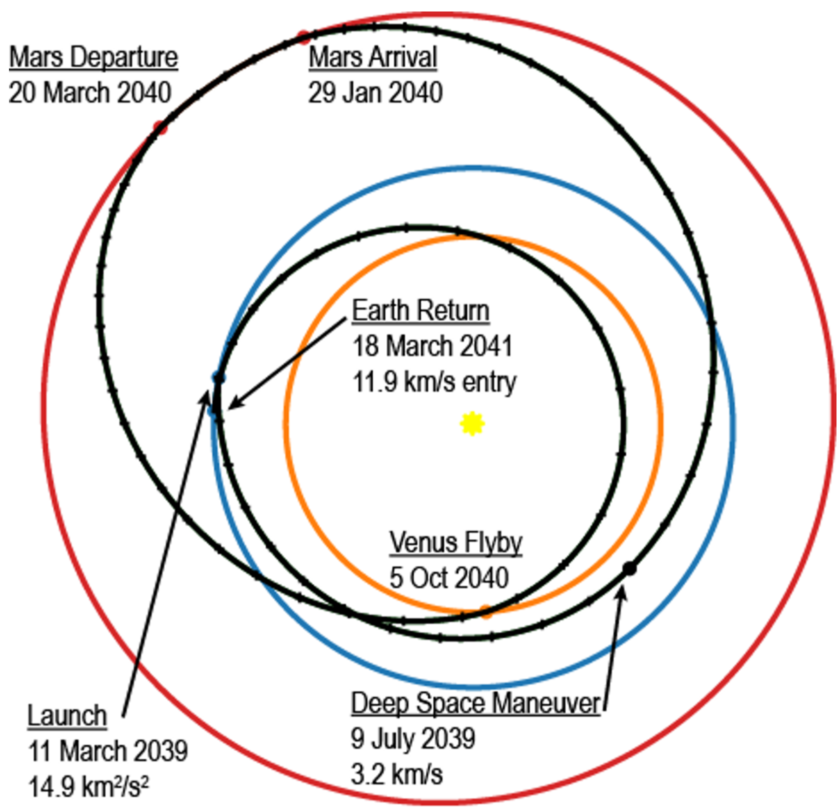


Figure 1.2: Earth–Mars–Venus–Mars mission example trajectory

Earth Departure	11 Mar 2039
3.2-km/s Deep Space Maneuver	9 Jul 2039
Mars Arrival	29 Jan 2040
Mars Departure	20 Mar 2040
Venus Fly-by	5 Oct 2040
Earth Arrival	18 Mar 2041
Outbound	324 days
Stay	51 days
Inbound	363 days
Total	738 days
Mission ΔV (excluding Earth Departure)	8154 m/s

Table 1.1: Earth–Mars–Venus–Mars Mission Example Parameters

While this yields shorter overall mission durations, there is a high amount of interplanetary travel time for a relatively short duration spent in the Mars vicinity. Additionally, this architecture presents a significant jump in our longest human spaceflight experience, going from 437 days (record set on MIR in 1994–95) to approximately 2.5–3 years.

Assessing this class of trajectories spurred conversation on Venus as both an interplanetary destination and a human deep space duration stepping stone. The shorter duration of a Venus-only fly-by mission could fit into a broader long term architecture of human missions to Mars by providing a significant step in understanding and reducing the risk of long-term human presence in deep space (beyond cis-lunar), while providing a significant science target, and with similar environmental risks (from radiation to thermal) and challenges as a mission to Mars.

1.3 Venus Fly-By

The simplest dedicated human mission would be a Venus fly-by. Multiple studies have discovered trajectories with a total flight time around one year.[1] This simplified mission presents an opportunity to be the first interplanetary mission, increase the flight duration record, and gain valuable human health and performance knowledge, all while on a free-return trajectory. Any mission outside of the Earth–Moon system, including to Venus, will test

[1] Foster and Daniels, "Mission opportunities for human exploration of nearby planetary bodies," AIAA SPACE 2010 Conference & Exposition, `https://arc.aiaa.org/doi/10.2514/6.2010-8609`

our readiness for long-duration deep space human spaceflight, in particular long-duration spacecraft operations, as well as crew psychology and health.[2] As part of an integrated strategy toward a first mission to Mars, a dedicated mission to Venus has the potential to be a productive and beneficial mission that could expand our human spaceflight operations knowledge in a stepwise manner starting at and around the Moon, continuing to Venus, and then at Mars. This would allow for more precise and intentional risk reduction efforts to expand our knowledge base around several key areas.

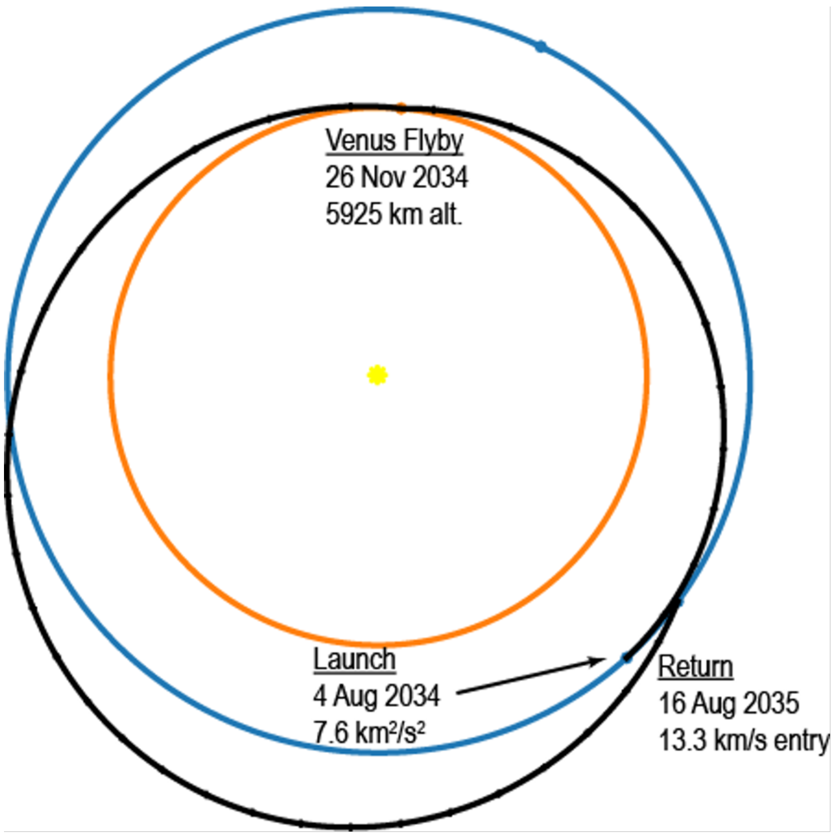


Figure 1.3: Venus fly-by mission example trajectory

[2]MacDonald, A., "Towards an Interplanetary Spaceship: The Potential Role of Long-Duration Deep Space Habitation and Transportation in the Evolution and Organization of Human Spaceflight and Space Exploration" AIAA Space 2017, Session: Low Earth Orbit and Cislunar Habitation https://arc.aiaa.org/doi/10.2514/6.2017-5100

Earth Departure	4 Aug 2034
Venus Fly-by	26 Nov 2034
Earth Return	16 Aug 2035
Outbound	114 days
Near Venus (1 light-minute)	72 days
Inbound	263 days
Total	377 days
Mission ΔV (excluding Earth Departure)	0 m/s

Table 1.2: Venus Fly-by Mission Example Parameters

An example trajectory has a launch date of 4 August 2034 (Figure 1.3 and Table 1.2). After the Earth departure maneuver, the crew would be on a free-return trajectory, only needing to clean up any launch dispersions and account for some potential small trajectory corrections throughout the mission. The Venus fly-by would occur on 26 November 2034, 114 days after launch. This would give the crew roughly 72 days in the vicinity (defined as being within a light-minute of one-way light-time, or ~18 million km) to perform key scientific studies. Earth return occurs on 16 August 2034, for a total flight time of 337 days. For a direct entry, the entry velocity would be 13.24 km/s. This approach would eliminate concerns with having to relight the engines after hundreds of days for a critical maneuver. Should relighting the engines prove not to be a significant concern, a propulsive capture or aero-capture and subsequent rendezvous and return via capsule is an alternative return strategy. A second alternative involving carrying a return capsule and deploying it from the parent spacecraft on approach for a direct entry could also be considered. The main interplanetary craft could then be recovered via ground-commanded propulsive capture/aero-capture or simply disposed of. This kind of trade is present in every human-class deep space mission architecture and is not a discriminator.

1.4 Venus Orbital Mission

While Venus fly-by mission architectures represent the simplest option for a first interplanetary mission, the limited duration in the proximity of Venus reduces the amount and types of scientific activities that can be enabled. An orbital mission to Venus has the potential to increase the science return from the mission by allowing for longer time in the proximity of Venus and greater utilization of telerobotic capabilities for everything from drone and rover teleoperation to, potentially, atmospheric robotic sample capture and return to the human vehicle. Although a Venus orbital mission is significantly more complex and challenging than a Venus fly-by on a free-return trajectory, Venus orbital missions nonetheless are of lesser duration and lower total ΔV than comparable orbital missions to Mars (Figure 1.4 and Table 1.3).

Although there is often public and community expectation that a first mission to Mars would go to the Martian surface, the complexity of such a mission means that a first mission to Mars may instead be an orbital mission that may visit the moons of Mars (Phobos and Deimos) first. In such a case, as a Venus orbital mission is a less challenging mission than a comparable Mars orbital mission, it may be that there would be demonstration, testing, and strategic value in conducting a Venus orbital mission prior to a Mars orbital mission.

We do need to recognize that energetically, a Venus orbital mission is challenging, and may make it less of an appealing architecture. Achieving Venus orbit requires significant ΔV, and breaking orbit to go home requires another major propulsive maneuver. The ΔV budgets below require that the periapsis and plane of the orbit about Venus be aligned with both the inbound (from Earth) and outbound (to Earth) trajectories. This is possible, but may push the solution off the optimistic ΔV assumptions consistent with these budgets.

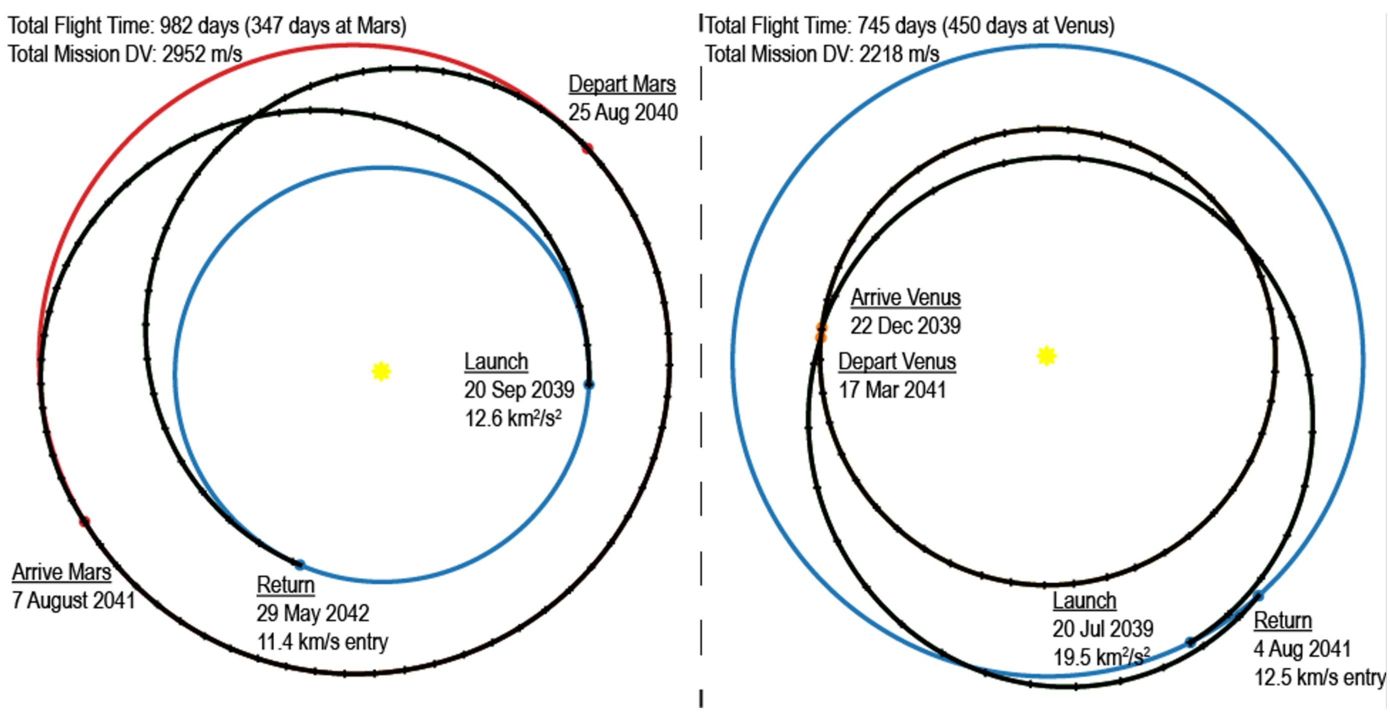


Figure 1.4: Comparison of Mars orbital and Venus orbital example trajectories

	Mars	Venus
Earth Departure	20 Sep 2039	20 Jul 2039
Arrival	25 Aug 2040	22 Dec 2039
Departure	7 Aug 2041	17 Mar 2041
Earth Return	29 May 2042	4 Aug 2041
Outbound	340 days	155 days
Stay	347 days	450 days
Inbound	296 days	140 days
Total	982 days	745 days
Mission ΔV (excluding Earth Departure)	2338 m/s	1310 m/s

Table 1.3: Earth and Venus Orbital Mission Example Parameters

1.5 Venus "Back-Flip" Double Fly-By

The workshop discussion, along with subsequent trajectory work by Mark Wallace, possibly revealed an appealing new mission option that combines the simplicity of a fly-by mission with a longer amount of time in the vicinity of Venus to enable teleoperated Venus science: a trajectory called a Venus "back-flip," which provides two fly-bys of Venus (Figure 1.5). Back-flip trajectories have been known for some time and used in satellite tour designs, such as the Cassini mission to Saturn, where they are often known as "Pi Transfers."[3] To the knowledge of the workshop participants, they have not previously been considered for human interplanetary missions. Such a mission profile includes flying by Venus on a trajectory that would see the spacecraft go below (or above) the ecliptic by 0.1 au—presenting another potential 'first' as the first human mission significantly outside of the ecliptic with a new 'view' on the solar system.

Preliminary studies have discovered free-return trajectories with a total flight time of 566 days with 176 days within a light-minute of Venus. During the 111-day interval between the two Venus fly-bys the spacecraft would remain over a pole, enabling continuous lower-latency teleoperation. Thus, this presents an opportunity to be the first human interplanetary mission, set a new flight duration record, present longer time for science teleoperation, and gain valuable human health and performance knowledge for deep space all while on a free-return trajectory.

[3] https://www.nasa.gov/content/cassini-spacecraft-uses-pi-transfer-to-navigate-path-around-saturn

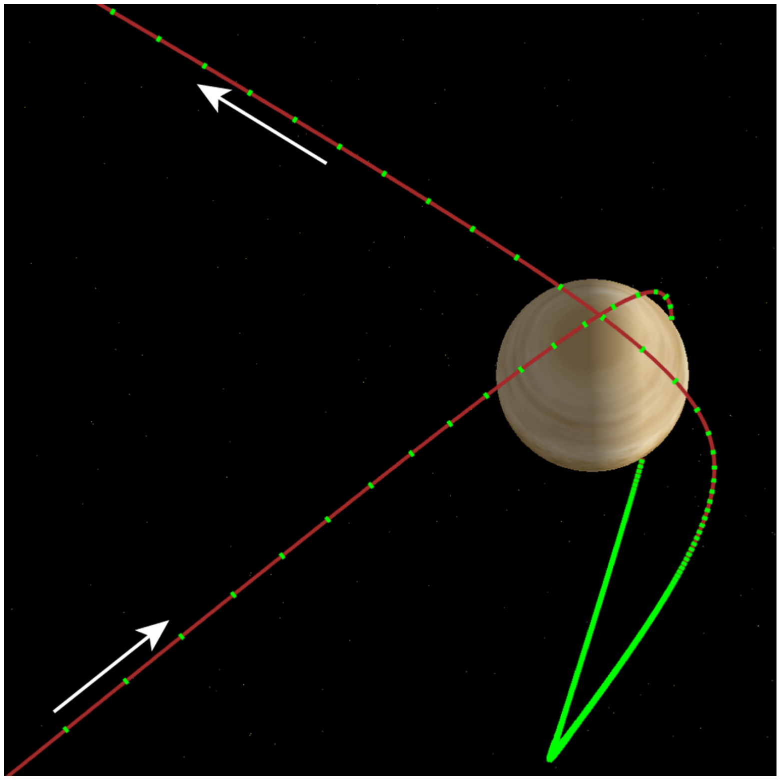


Figure 1.5: Venus back-flip double fly-by trajectory from the perspective of Venus (long duration over Southern hemisphere)

Earth Departure	7 Aug 2034
Venus Fly-by 1	18 Nov 2034
Venus Fly-by 2	9 Mar 2035
Earth Return	24 Feb 2036
Outbound	102 days
Near Venus (1 light-minute)	176 days
Inbound	352 days
Total	565 days
Mission ΔV (excluding Earth Departure)	0 m/s

Table 1.4: Earth–Mars–Venus–Mars Mission Example Parameters

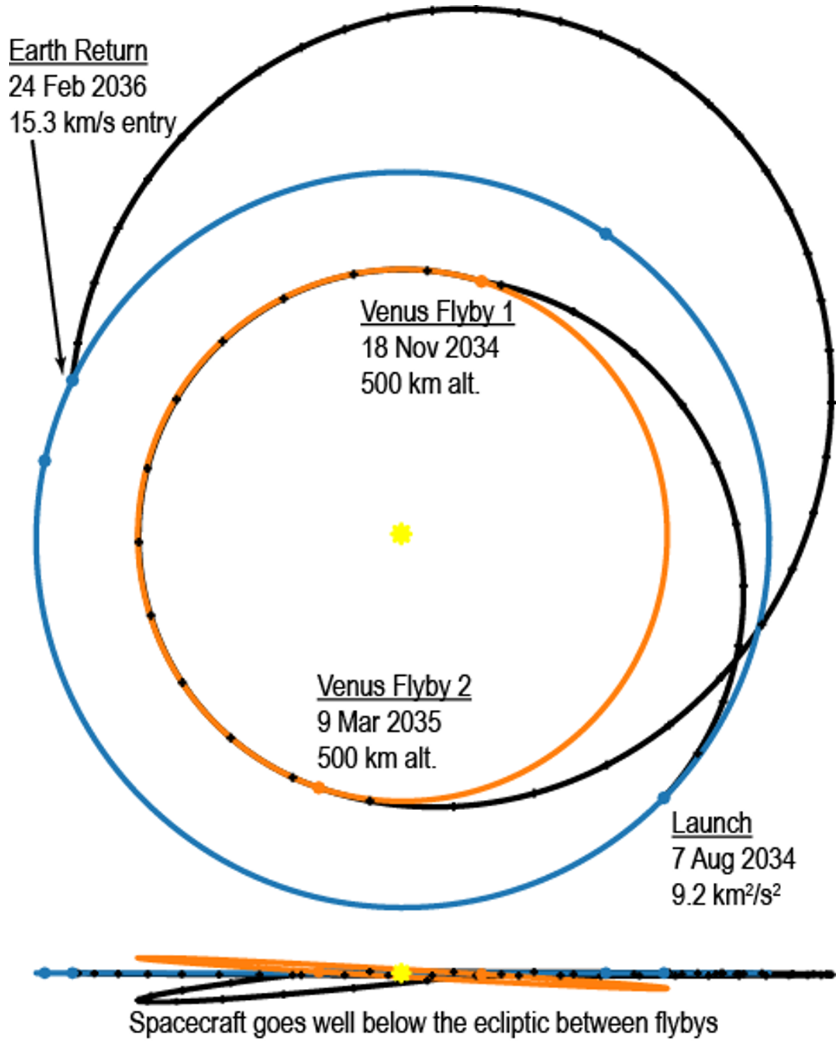


Figure 1.6: Venus back-flip double fly-by example mission trajectory

A preliminary trajectory has been found with a launch date of 7 August 2034 (Table 1.4 and Figure 1.6). After the Earth departure maneuver, the crew will be on a free-return trajectory, only needing to clean up any launch dispersions and account for some potential small trajectory corrections throughout the mission. The first Venus fly-by would occur on 18 November 2034 and the second would occur on 9 March 2035. Both occur at an altitude of 500 km. This would give the crew roughly 177 days in the vicinity to perform key scientific studies. Of these, 111 days are between the fly-bys, with a continuous view of the southern hemisphere. Following the second fly-by, the crew would return to Earth on 24 February 2036 with a ballistic entry velocity of 15.3 km/s.

This velocity is relatively large, but adding a moderate deep space maneuver after the second Venus encounter can significantly reduce it at the cost of some additional flight time. Converting one or the other Venus fly-by into a powered fly-by may also improve the solution. It should be emphasized that while these specific trajectories are the result of high-fidelity simulations they are not necessarily the most-optimal. They have only been very briefly studied, being the result of a few days' work. Further analysis may find trajectories with shorter flight times with lower Earth-return velocities. An Earth-Venus opportunity occurs every 19 months (compared to 26 months for Earth-Mars), and each opportunity varies relatively dramatically in terms of the departure and arrival energies. Further, which hemisphere is available for a backflip varies with the opportunity, depending on where Venus is in its orbit at the first encounter.

Finally, this class of mission should be amenable to an in-flight descope to a single fly-by. Instead of targeting the first fly-by to set up the backflip, the flight team could instead choose to target the fly-by to come home. This offers a more robust abort capability than most other interplanetary trajectories. As such, a backflip-class trajectory has some crew-safety benefits that other mission classes may not possess.

The most simple possible back-of-the-envelope analysis suggests that a vehicle conducting a Venus Backflip Mission would have about 80% of the total GCR environment exposure of the very best-case Mars conjunction class mission analyzed by NASA's Strategic Analysis Cycle 2021 (which includes NEP propulsion and other assumptions about the Earth-departure system).

2. Venus Science Enabled by Human Missions

The merit of having a human presence on a scientific mission to Venus is the ability of humans to perform exploratory studies focused on serendipitous observations and real-time decision-making (Figure 2.1). A robotic planetary mission is meticulously designed long before launch, and is required to have a predefined set of targets and objectives, without any detailed prior information about in-situ conditions and opportunities. This is particularly true for short duration missions dictated by the harsh near-surface environment of Venus (in contrast to bodies where landers or rovers can operate for many months). A robotic mission either requires significant longevity or high cadence and throughput to perform multiple in-depth analyses. This drives multiple requirements—including technical complexity (selection systems, intelligence, or high-rate throughput) total power (cooling and operations), and mass to ensure scientific return. In contrast, a human mission would not be prescriptive with a predefined set of targets, but rather based on an iterative approach, where the human crew would have the prerogative to make spontaneous decisions in real time. This can allow for a more efficient and creative observation plan, where an in-depth study can only be performed on a small number of targets, which would first be classified as "promising" by the human crew. This approach has been called "flexicution"—referring to the flexible execution of a scientific study.

To give a hypothetical example of the contrast between a robotic and a human-driven mission, we can consider a search for evidence of volcanic activity on Venus. A robotic mission may have to be pre-planned to make repeat observations of multiple candidate Venusian volcanoes over a period of time, then send a large volume of data back to Earth to be analyzed by a science team for evidence of activity. On the other hand, a human crew can utilize IR telescope data, targeted radar emissivity images, or flyover drone footage to do real-time

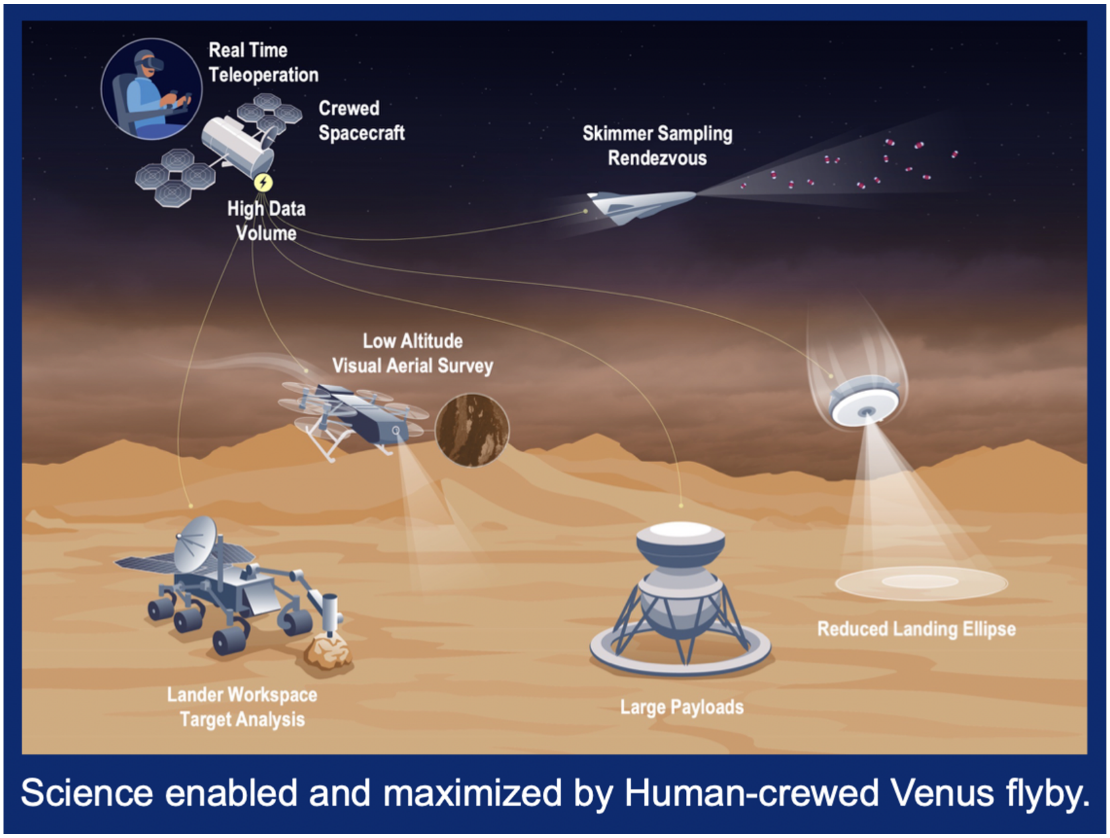


Figure 2.1: Examples of science investigations enabled by human proximity at Venus[a]

[a]Izenberg, N. R., McNutt Jr, R. L., Runyon, K. D., Byrne, P. K., & MacDonald, A. (2021). Venus Exploration in the New Human Spaceflight Age. Acta Astronautica, 180, 100-104. Image Credit: Johns Hopkins APL/Caleb Heidel

analysis of a volcano, and based on their expertise can quickly decide whether the volcano looks as though it is erupting, or has erupted in recent times, and whether it merits a more in-depth study, in addition to sending the data back for in-depth analysis at home. Similarly, in the search for evidence of active tectonics, a human crew can identify areas of interest after cursory observations of potentially active faults. In these scenarios, fewer resources would be spent studying targets that are not classified as "promising" by the human experts.

Most spaceflight research involving humans is highly programmatic and rigorously planned and scheduled. Astronauts on the ISS are on a timeline that specifies activities with a resolution of five minutes. There is often limited flexibility to deviate from planned procedures in order to pursue unexpected findings and results—a hallmark of a great deal of basic science in terrestrial laboratories. Apollo astronauts commented that they would like to have had a schedule for lunar-surface operations that specified overall goals, with the details of planning and execution left to their discretion in real time. This allocates decision-making capability to the crew on site, who are arguably in the best position to make immediate decisions. This also increases crew autonomy, which generally enhances the sense of agency and improves psychological outlook. Communication delay will impose a measure of crew autonomy anyway, wanted or not.

In addition to the value of crew being in the loop on science observations, human missions also present two additional opportunities that can increase the science return: significantly increased comms capabilities and the opportunity to carry multiple ride-along payloads that can be sent down to explore the Venusian atmosphere and surface (whether teleoperated or not). High data and communications bandwidths are often required for crewed missions, including for mission operations, personal communications home, and for public engagement purposes. The communications capabilities involved are often significantly in excess of what attends robotic missions alone, providing for opportunities to design payloads and investigations that can take advantage of this. Similarly, the high mass of human mission vehicles means that additional ride-along science payloads can accompany the mission for relatively marginal additional costs. This may enable multiple robotic probes to accompany a human-class mission to Venus, whereas it is currently a challenge to fund a single robotic probe into the Venus atmosphere or to the surface.

Below are examples of the driving questions of the next phase of Venus science that will be enabled by currently planned and funded robotic missions to Venus, as well as new types of science investigations that could be enabled by human proximity to Venus.

2.1 The Next Robotic Era of Venus Science: After V3NUS

The missions comprising V3NUS—VERITAS,[1] DAVINCI,[2] and EnVision[3]—will provide fundamental data on the atmospheric chemistry, global crust, and active surface processes. However, the data sets will be ambiguous about the geochemistry, mineralogy, and specific rock types which are crucial to understanding ancient aqueous activity and habitability. In order to make these types of measurements, observations below the cloud deck are needed. These observations would be best performed utilizing a rover or low-altitude aerial platform. Due to the short-lived (few hours) nature of geochemical instruments in the Venus surface environment, having a human making real-time decisions on the sample selection for analysis would provide the greatest science return. Radiogenic element (U, K, and Th) measurements could be made using Gamma Ray Spectroscopy (GRS) and abundances of common rock-forming elements (Na, Mg, Al, Si, Ca, K, Ti, Mn, Fe) can be provided by X-ray Fluorescence (XRF) or Laser-Induced Breakdown Spectroscopy (LIBS). The mineralogy and rock type could

[1] Venus Emissivity, Radio Science, InSAR, Topography, And Spectroscopy, `https://www.jpl.nasa.gov/missions/veritas`

[2] Deep Atmosphere Venus Investigation of Noble gases, Chemistry, and Imaging, `https://ssed.gsfc.nasa.gov/davinci/mission`

[3] `https://www.esa.int/Science_Exploration/Space_Science/EnVision_factsheet`

be determined using infrared spectroscopy in the near and/or mid-infrared. This platform, with human-in-the-loop selectivity, would provide more mature chemical analysis and could conclusively answer important Venus questions, including: What is the surface made of? Is continental crust present? What are the differences between the blocky and smooth terrain? How did the tesserae form? Further, by answering these questions, we can determine whether Venus ever had an ocean (and for how long), or if it ever had a period of plate tectonics. We will be able to more completely understand the divergent paths of Earth and Venus, and how the two ostensibly similar planets have become so different.

The clouds and atmosphere are known to be highly variable spatially and temporally. None of the currently planned Venus missions have the capability to explore the atmosphere in a sustained or piloted way. If an aerial platform like a gondola or balloon is implemented, complementary data to DAVINCI can be provided on a more global scale. A Tunable Laser Spectrometer (TLS) and Neutral Mass Spectrometer (NMS) can be used to measure abundances of light isotopes, noble gases, and trace species. The structure and particle size of the clouds can be measured using a Nephelometer and a Net Flux Radiometer can investigate the upwelling and downwelling visible infrared radiation, providing information on the atmospheric circulation on Venus. Additionally, radio tracking can be used to understand wind velocity and circulation patterns. The Venus Express and Akatsuki missions have shown that the clouds are highly variable in space and time. Having humans in the loop can allow for more specific targeting of unique cloud features below the homopause. This platform could answer questions like: What is the structure and circulation of the deep atmosphere? What drives the super-rotation in the upper cloud layer? What are the chemical cycles operating in and below the clouds? What drives variability in the cloud layers? What are the unknown ultraviolet absorbers that largely dominate the energy budget of the upper clouds? What explains the observations of anomalous and seemingly solid components of the large cloud particles? The next robotic missions to Venus will explore these questions and provide data and observations that future missions, including human missions, could follow up on and explore further.

2.2 The Human Proximity Era of Venus Science: Surface investigations from ROVs

Perhaps the greatest scientific advantage of astronaut proximity to Venus is for near-real-time and rapid control of robotic vehicles over and on Venus; and for responding in real time to serendipitous discoveries or other changes. Thus, while the crew will have a scientific plan to execute, they will be flexible in how they execute it. This "flexecution" approach to field science has been ratified by the Apollo lunar surface expeditions and numerous analog field geology exercises.[4]

Given the wide variety of terrains revealed by Magellan's relatively low-resolution global mapping, and the wide range of surface ages, including probably zero age actively forming volcanic terrains, it is likely that some of the surface terrains of highest science and exploration value will be extremely complex and varied. The exploration of such environments will be greatly facilitated by human-in-the-loop decisions enabling surface exploration with remote vehicles operated by astronauts working from near-Venus space.

Having humans within a light-minute to a light-second or less from Venus would enable a fast-driving rover to cover many geologic units in a short time, thus maximizing scientific productivity at Venus' harsh mean surface temperature of ~464°C. Advances in high-temperature power sources and electronics could enable a ~week long surface survival of such a robotic asset.[5] By driving many times faster than the Mars rovers with a human directing the speed and direction of travel, coupled with near-real-time audio, image and video uplink, and teleoperated sample selection and handling, geologic surveys would be efficient. The rover would only need to stop for geochemical analysis, such as from laser-induced breakdown spectroscopy (LIBS), Raman spectroscopy, or x-ray diffraction (XRD); multispectral stereo imaging would occur during the fast-paced drive, allowing for geomorphometric, topographic, and compositional mapping from the resulting dataset. Astronauts would respond almost immediately to serendipitous discoveries and adjust the rover's actions accordingly. However, wheeled, driveable rovers are only one class of remotely operated vehicle possible for Venus. Near-surface, or variable altitude aerial vehicles that float like balloons or fly like airplanes or fan-driven drones are others.

Attractive exploration targets for such expeditions will include:

- Sites of active volcanism, including possible real-time observation and monitoring of lava flows and vents.
- Signs of past water on the surface. This could include morphological evidence such as shorelines or sedimentary/erosional structures or mineralogical and isotopic evidence.
- Evidence of past life, which may have evolved during a previous oceanic phase of planetary evolution. This may include bioindicator isotopic anomalies or even fossils.

[4]Young, K., Hurtado Jr, J. M., Bleacher, J. E., Garry, W. B., Bleisath, S., Buffington, J., & Rice Jr, J. W. (2013). Tools and technologies needed for conducting planetary field geology while on EVA: Insights from the 2010 Desert RATS geologist crewmembers. Acta Astronautica, 90(2), 332-343.

[5]Greer, C. (2021). Chemical Combustion Power Systems for Extreme Environment Planetary Landers. PhD Dissertation, The Pennsylvania State University.

2.3 The Human Proximity Era of Venus Science: Directed Aircraft

Advances in aerial drone technology featuring advanced autonomy allow amateur pilots to easily and precisely direct such aircraft to desired locations at desired speeds. In other words, the person tells the robot where to go, and the aerobot figures out which control surfaces it needs to use to get there. With such drone autonomy coupled with Venus' dense atmosphere and Earth-like gravity, our sister planet has created a hospitable environment for aircraft to fly its skies.

A solar-powered uncrewed semi-autonomous aircraft ideally pairs astronauts-in-the-loop with compelling science objectives. Recharging batteries via solar power above the clouds at 70+ km altitude, the aircraft could then fly into the clouds and use in situ instrumentation to study cloud/aerosol composition, even looking for habitability and biosignatures.

For example a human teleoperator with up to a few seconds time delay could actively guide an atmospheric vehicle through the hazes and clouds. Given that the lower clouds, where the "mode 3" particles, of particular interest for both geological/volcanological processes and potential biology, are highly variable, it would be valuable to guide instrumented vehicles toward the more dense areas.

An interesting use case would be for a Venus airplane to fly into the planet's night side, both within and below the cloud deck. Surface emissivity measurements in the far-optical to near-infrared could constrain silicate mineralogies as well as map any volcanic hotspots. Within the clouds, questions could be addressed related to diurnal temperature variations' effects on potential cloud habitability and haze photochemistry.

2.4 The Human Proximity Era of Venus Science: Teleoperated Rover on Maxwell Montes

Venus' Maxwell Montes looms 11 km above the planetary datum and is the highest point on the planet. At this elevation, the temperature is over 100°C cooler—about 377°C—and at 45 bars of pressure, about half that of datum.[6] As the coolest and lowest-pressure region on the surface of Venus, Maxwell Montes is an ideal location for a long-lived (i.e., ~1 week) rover to explore. Additionally, the summit of Maxwell features a geologic contact between two geologic units—volcanic edifice material and tessera terrain.[7] This geologic wonderland

[6] McGill, G.E., Stofan, E.R., Smrekar, S.E., (2010) Venus Tectonics. In Planetary Tectonics. (2010). United Kingdom: Cambridge University Press; Seiff, A., Kirk, D. B., Young, R. E., Blanchard, R. C., Findlay, J. T., Kelly, G. M., & Sommer, S. C. (1980). Measurements of thermal structure and thermal contrasts in the atmosphere of Venus and related dynamical observations: Results from the four Pioneer Venus probes. Journal of Geophysical Research: Space Physics, 85(A13), 7903-7933.

[7] Bruegge, RW Vorder, J. W. Head, and D. B. Campbell. "Orogeny and large-scale strike-slip faulting on Venus: Tectonic evolution of Maxwell Montes." Journal of Geophysical Research: Solid Earth 95.B6 (1990): 8357-8381.

exhibits the least hostile surface pressure/temperature conditions on the planet and is thus ideal from both an operational and scientific perspective to address questions related to Venus' history of volcanism, tectonic deformation, heat flux, the plausibility of past oceans, and the continental nature of the tessera. This type of exciting mission opportunity is representative of the scale of ambitious, adventurous endeavors that human missions could help enable with increased communications bandwidth, significant mass delivery capabilities, and humans in the loop.

2.5 The Human Proximity Era of Venus Science: Exploring Possible Venus Life Processes

Historically, Venus was believed to be a likely abode for life. Its extensive cloud cover was viewed as evidence for an extensive ocean. With space probe and other data in the 1960s, the extremely high surface temperature and pressure seemed to preclude Earth-type life. However, the recognition of atmospheric zones with approximate Earth-surface equivalent temperature and pressure implies at least a physical environment where Earth-life might survive—although the extreme acidity of the sulfuric acid cloud droplets at this level is a challenge for life as we know it. The presence of significant ultraviolet absorption from an unknown chemical constituent near this atmospheric zone has led some astrobiologists to propose a plausible life process to explain this absorption. The possible detection of the gas phosphene, which can be produced abiogenically, but also as a byproduct of biological processes, has triggered both criticism and renewed interest.[8] In 2022, a privately funded study suggested a series of missions to characterize the temperate levels of the Venusian atmosphere and determine whether life processes might be present.[9] The first of such missions is defined and scheduled for a May 2023 launch.[10] The third mission proposed in that series includes a Venus atmospheric sample return.[11]

Humans in the vicinity of Venus could have a significant role in the search for life in the Venusian atmosphere. If there are robotic systems in the Venusian atmosphere or on the surface, astronauts can redirect these systems in real time to respond to unexpected barriers and opportunities. For example, a human teleoperator with up to a few seconds time delay could retarget an atmospheric vehicle to focus on interesting atmospheric formations more likely to hold life or life-relevant conditions or materials.

[8] Greaves, J.S., Richards, A.M.S., Bains, W. et al. Phosphine gas in the cloud decks of Venus. Nat Astron 5, 655–664 (2021)

[9] https://doi.org/10.48550/arXiv.2112.05153

[10] French R, Mandy C, Hunter R, Mosleh E, Sinclair D, Beck P, Seager S, Petkowski JJ, Carr CE, Grinspoon DH, Baumgardner D, on behalf of the Rocket Lab Venus Team. Rocket Lab Mission to Venus. Aerospace. 2022; 9(8):445.

[11] https://venuscloudlife.com/venus-life-finder-mission-study/

Should atmospheric samples be collected and a rendezvous made with a human-proximate mission, the crew could perform sophisticated laboratory experiments to determine the presence of or amenability to life processes. This would better enable more detailed analyses when the samples are returned to Earth. On the unlikely, but possible, chance that the samples prove pathogenic, the spacecraft can be optimally quarantined. Finally, for a backflip mission configuration that would include two fly-bys of Venus, samples could be collected in both fly-bys, with the results from the first used to better target collection and robotic exploration for the second.

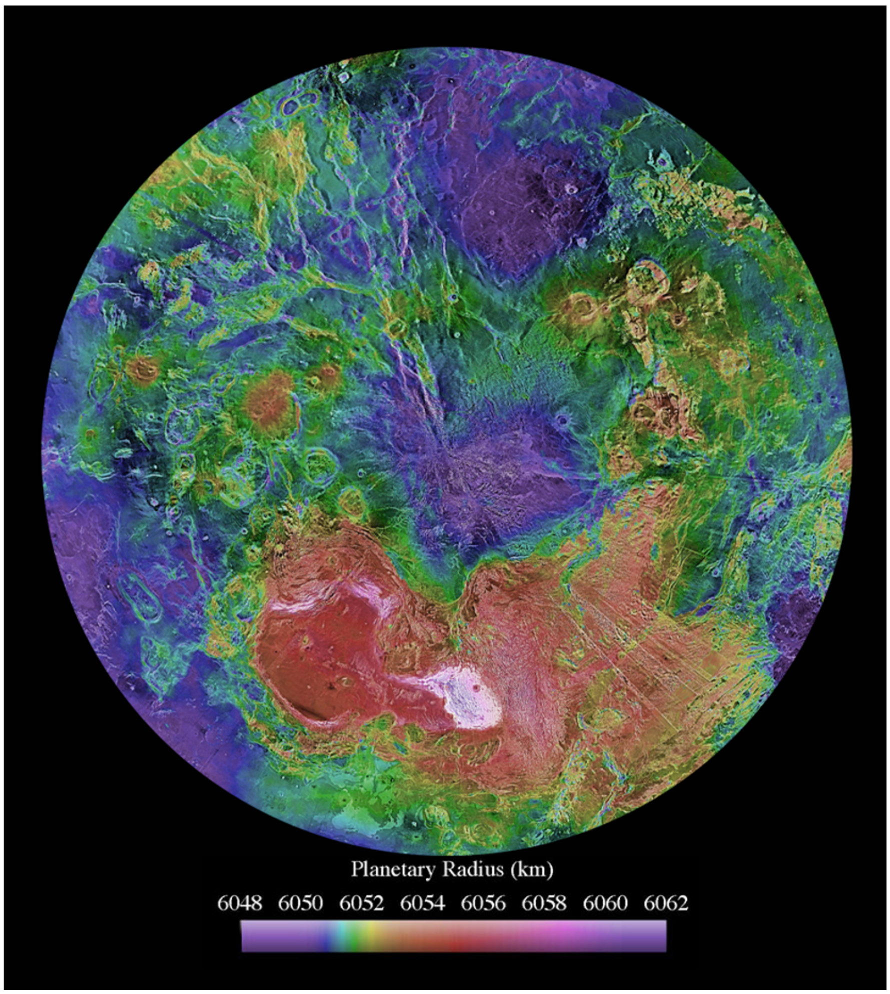
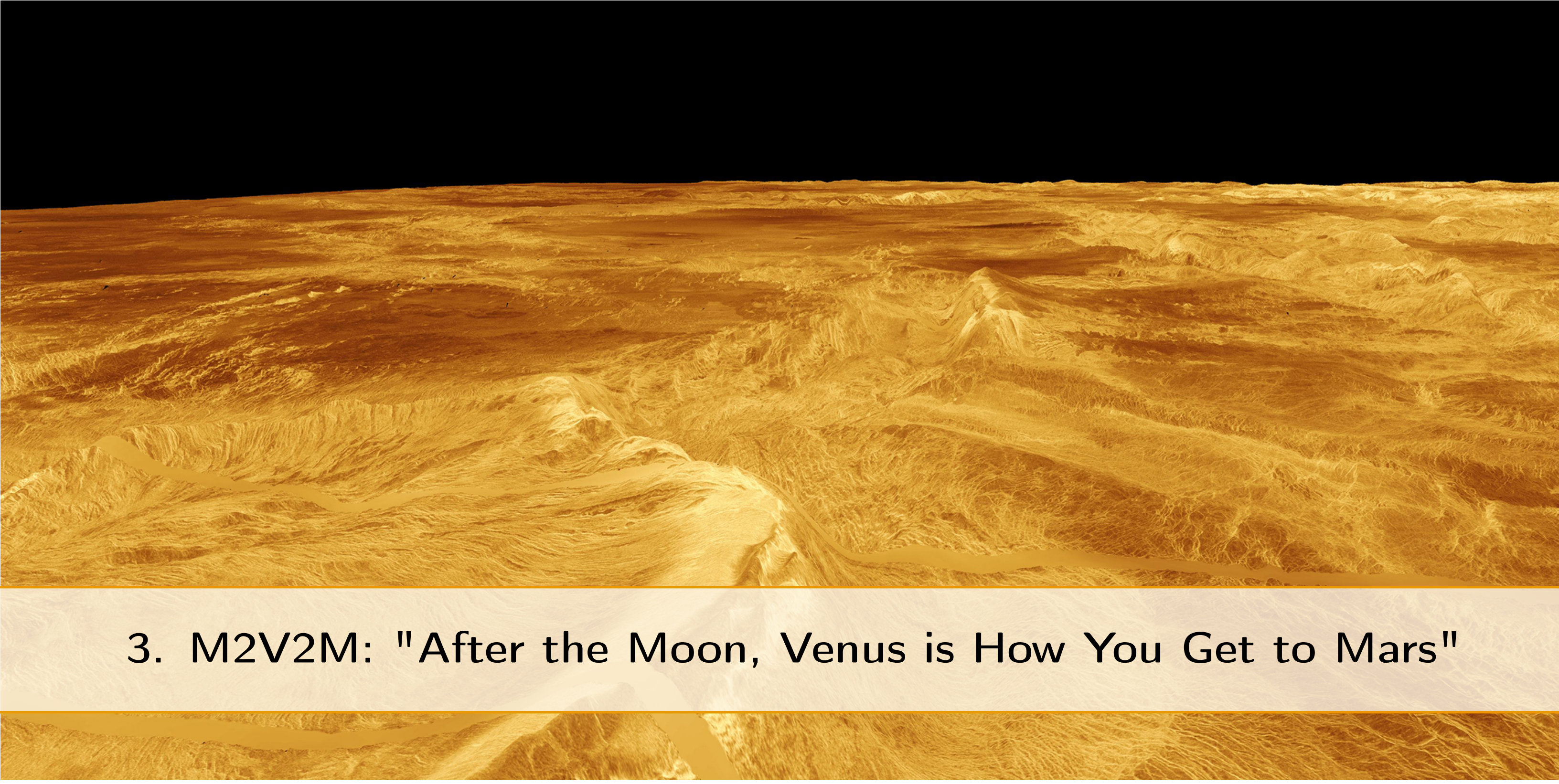


Figure 2.2: Partial North Polar view of Venus radar-derived topography from Magellan, (USGS 1994 map). A "North Polar Back-flip" concept would have Maxwell Montes (white, lower center) and Ishtar Terra (red around Maxwell) remain in line of sight under the clouds below the spacecraft between planetary fly-bys.

2.6 Venus as an Exploration Target

Beyond but closely related to the science value of human Venus exploration is the exploration value. Like the "Terra Incognito" signs on maps of old, Venus is "Venera Incognito," a vast, almost completely unexplored world of great variety, mystery, and beauty, with an area of unknown lands several times the land area of Earth. Given what we do know, based on incomplete, low-resolution orbital data and the returns from a few scattered Soviet surface landing sites, there is every reason to believe that Venus will be a land—or rather a multitude of lands—of enchantment. In many ways it is the most Earth-like and Earth-relevant world we will ever get to explore up close. Given that there appears to be a range of surface ages, from over 1 billion years old to zero age (active, still forming, volcanic terrain), and an intriguing mix of familiar and alien geographies and landscapes (for example, a wide range of types and ages of volcanic landforms and steep canyons dominated by chemical, rather than physical erosion), there is every reason to believe that Venus will be an endless wonderland of beguiling and mysterious vistas and formations. With teleoperated exploration, the public—perhaps following along at home with their own VR enabled headsets—can come along for the ride and join in the discovery and the fascination.



3. M2V2M: "After the Moon, Venus is How You Get to Mars"

A primary argument for a human mission to Venus discussed at the symposium was based not on an argument for science per se, but rather on the feasibility and desirability of the Venus mission in comparison to more ambitious missions, such as to Mars. With lower ΔV requirements and more frequent launch windows, Venus can be easier to reach than Mars, depending on mission design. Missions to Venus would have value demonstrating integrated exploration capabilities and developing human health and performance measures and mitigations on interplanetary missions leading up to and along with missions to Mars. Beyond the existing "Moon-to-Mars" programmatic paradigm, symposium participants suggested that it may be worth discussing a broader "Moon-to-Venus-to-Mars" (M2V2M)—or a "Moon-to-Venus-and-Mars"—strategy.

3.1 Historical Context

Although the particular framing of "Moon-to-Venus-to-Mars" or "Moon-to-Venus-and-Mars" may be novel, the general concept is in fact over 50 years year old. In the 1960s and early 1970s, NASA considered human Venus missions to be potentially appropriate missions in between human missions to the Moon and human missions to Mars. At that time, NASA conducted a number of design studies, most notably the EMPIRE ("Early Manned Planetary–Interplanetary Roundtrip Expeditions") and UMPIRE ("Unfavorable Manned Planetary–Interplanetary Roundtrip Expeditions") studies. Even since, it has been clear that Venus fly-bys can reduce the overall energy requirements for opposition-class missions to Mars, and that Venus-only fly-by missions have independent merit in terms of gaining systems-level confidence and demonstrating human-machine teaming and feasibility.

Perhaps most notably, Edward Willis at NASA's Lewis (now Glenn) Research Center wrote a technical memorandum entitled 'Manned Venus Orbiting Mission' in 1967 and concluded that 'a Venus mission can be accomplished using Apollo level technology' and argued for its inclusion as part of the Apollo Applications Program, which ultimately resulted in Skylab.[1] In the years immediately preceding and after Apollo—when NASA engineers were acutely focused on implementation practicalities of human planetary missions—Venus was recognized as providing by far the easiest first planetary human spaceflight mission opportunity.

3.2 Venus Shakedown Cruise

More recently, in addition to the potential inclusion of a Venus fly-by on the way to or from Mars during an opposition-class short-stay first human Mars mission, a number of engineers and mission designers have argued for the potential value of including a 'shakedown cruise' for the Mars Transit Hab and associated systems, including propulsion, prior to a first human Mars surface mission. Separating the two missions (fly-by/orbital vs. surface landing) also allows separate destination planets. Engineers and mission designers have considered Venus as a potentially viable destination for such a shakedown cruise given similarities in mission complexity for both Venus and Mars, with a Venus fly-by mission being slightly less complex and shorter in duration than a Mars fly-by. No decision has been made on any potential shakedown cruise, and, given the priority of Artemis lunar missions and the Mars Mission Analog missions planned at the Moon, it may be some time until a decision is taken. It may nonetheless be worthwhile for NASA and private sector mission planners and engineers to consider the opportunities and challenges that a human shakedown cruise to Venus represents.

Separating the first human flight to a planet and the first human landing on Mars significantly lowers mission risk and complexity. Some see it as politically and popularly untenable to have a first human Mars mission that does not land—in other words, if humans are going to Mars, the public will want them to land. Although some see the practical inability for humans to land on Venus as a drawback to any human Venus mission, in fact, symposium participants argued it is the opposite: it provides the opportunity to practice a human circumplanetary mission without the political risk of not landing. Due to the technical infeasibility of landing humans on Venus, a planned Venus mission would avoid the potential mission creep that a Mars mission faces to include a surface landing on the first visit when it may be technically and operationally premature to do so. This makes planning and designing such a mission potentially simpler and cheaper while still maintaining high public engagement and interest.

3.3 Human Health and Performance Aspects of a Human Mission to Venus

A human Venus shakedown cruise is a unique opportunity to conduct human health and performance research for the first time in deep space, and to support a crew on a shorter

[1] Manned Venus Orbiting Mission, NASA TM X-52311, E. Willis, 1967.

interplanetary mission than would be the case with a mission to Mars. It is thus in many ways an ideal Mars mission analog—more so in some ways than Mars analog missions on Earth, ISS, or even Earth's moon. This mission analogy is especially true with regard to radiation and distance from Earth.[2] The longer duration in weightlessness and exposure to deep-space radiation allow for the investigation of synergistic effects.[3] Distance from Earth brings with it the need for a great deal of crew autonomy, including the need for onboard clinical decision support.[4] A great deal of information on human health and capabilities can be obtained by monitoring performance on tasks that spaceflight crews undertake for other reasons—such as science observations of Venus. The consistency and degree of precision in taking a measurement, the time it takes to carry out a routine task, and errors in performance can all provide information that can, with the right mathematical models and a database of nominal performance built up over several repetitions, indicate latent medical or psychological issues. Thus, these performance indicators are not only important to Venus science return, but they also supply information for understanding the myriad connections between human health and performance across a wide range of physiological, psychological, and cognitive domains.

Without landing and surface operations, a human Venus mission could potentially focus more fully on the psychological, health, and performance aspects of a crew on a first interplanetary mission, such as:[5]

- Psychological impacts of a 1–1.5-year absence with substantial (~4–30 minutes) communications delay with Earth;
- Self-reported crew stress as a function of mission elapsed time;
- Effect of crew stress (both subjective and objective measures) on cognitive response in tests and real operations;
- Changes in crew microbiome during the mission;
- Changes in crew immune response to standardized challenges such as vaccines;
- Effects of galactic cosmic rays and solar particle events on crew health.

[2] `https://www.nasa.gov/hrp/5-hazards-of-human-spaceflight`; and `https://humanresearchroadmap.nasa.gov/tasks/task.aspx?i=1799`

[3] Tan S, Pei W, Huang H, Zhou G, Hu W. Additive effects of simulated microgravity and ionizing radiation in cell death, induction of ROS and expression of RAC2 in human bronchial epithelial cells. npj Microgravity. 2020 Nov 5;6(1):1-6.

[4] Garcia-Gomez JM. Basic principles and concept design of a real-time clinical decision support system for managing medical emergencies on missions to Mars. arXiv preprint arXiv:2010.07029. 2020 Sep 29.

[5] `https://humanresearchroadmap.nasa.gov/explore/`

There is further benefit to using a human Venus fly-by as a Mars analog mission. The effort is not merely a cataloging of spaceflight effects and identification of correlations with health and performance. What is needed for these types of ambitious human missions is an integrative approach—one that investigates the relationships and interconnections between physiological systems, between physiology and cognition, and between body systems and spacecraft systems.[6][7] This is especially important to spaceflight, where multiple simultaneous adaptive processes take place in response to multiple stressors, and the investigation of one body system at a time is not only scientifically shortsighted but potentially medically dangerous.

While the crew on any mission to Venus will potentially have greater exposure to solar particle events (SPEs) than on a Mars mission, SPE risks can be mitigated by a "storm shelter" capable of supporting the entire crew for several days. Such a storm shelter would most likely be required for a human Mars mission whether or not it includes a Venus fly-by. In addition, the shorter durations of Venus missions reduces exposure to Galactic Cosmic Ray (GCR) radiation, which is sometimes considered to present one of the highest medical risks for deep-space missions. A Venus mission thus is also ideal for testing various SPE risk mitigations while exposing the crew to less GCR radiation overall than they would receive on a Mars mission.

Overall, the potential reduction in risk of a human mission to Venus relative to a human mission to Mars, combined with the potential to utilize the mission to focus on human health and performance research and mitigations testing, presents a strong argument for its inclusion as part of an overall Moon-to-Mars strategy. A human Venus mission can last roughly half as long as a human Mars mission, while still subjecting the crew to similar environments. Thus, such a human Venus mission affords the ability to close knowledge gaps and buttress confidence in technology, concept of operations, and human adaptability before setting out on a Mars expedition. Symposium participants argued that it would be from confidence gained in a crewed Venus fly-by mission that we would have the confidence to send humans to Mars.

[6] White RJ, Averner M. Humans in space. Nature. 2001 Feb;409(6823):1115-8.

[7] Shelhamer M. A call for research to assess and promote functional resilience in astronaut crews. Journal of Applied Physiology. 2016 Feb 15;120(4):471-2.

4. Social Organizing to Promote Human Missions to Venus

Discussions at the symposium also returned repeatedly to questions related to the broader potential for private society activities that could promote human exploration to Venus—and Venus science in general—in similar ways that have been seen to be effective in promoting the exploration of the Moon and Mars. The national and international narrative of spaceflight thus far has predominantly been focused on exploring locations with surfaces where we can live and work for long durations—in some conceptions, destinations where we can begin again and grow a society on a new world. In order to develop and raise the social, political, and financial capital needed to embark on the first steps to becoming a multi-planet species, however, there is also value in a broader demonstration of the potential future capabilities of spaceflight beyond the standard proposed missions to the Moon and Mars. Additionally, a multi-planet species strategy also includes the continued habitation of Earth, and we stand to benefit from an encounter with Venus to help us better understand our mother planet. There are valuable scientific discoveries to be made from our sister planet, Venus, that can aid us not only in the exploration of other worlds but with addressing some of Earth's most vexing problems today. Venus has the potential to be added as a viable destination on the international exploration roadmap, but to do so will ultimately require a groundswell of support from the scientific, educational, and space agency communities, along with non-profit and industry partners.

How could the potential of crewed Venus missions be communicated to these multiple communities? Discussions at the symposium often returned to the theme of engaging and exciting the public. Discussions also centered on engaging industry in tandem with space agency managers and policy makers to explore the advantages of human missions to Venus and the opportunities that they present.

The symposium participants also discussed the value of a potential umbrella support community or organization, notionally called a Venus Cooperative—or even 'The Venus Cooperative' (TVC). A Venus Cooperative could begin with a core group of motivated individuals—much in the same way as the Mars Society began with a handful of dedicated visionaries—with the express purpose of promoting the goals of human spaceflight to Venus on its own merit and as an essential stepping stone in the grand journey of human exploration of the solar system. Within a Venus Cooperative there could also be two focal groups—organizations or sub-organizations—simultaneously supporting Venus exploration efforts.

One organization or sub-organization could focus on engaging scientific interest and human spaceflight planning efforts, with a goal to advance Venus exploration architectures, understand gaps in technologies, communicate risk mitigation plans, and enthuse the broader community of scientists and engineers. This could include those in focused fields such as: planetary geologists, aerospace engineers, human spaceflight technologists, spaceflight psychologists, planetary climate change researchers, and more. Proposed names for such an organization or sub-organization include the Venus Exploration Society (VES), which would invoke exploration organizations of old, such as the National Geographic Society, and Science for Venus Exploration (SVE), which invokes the collective and cooperative nature of myriad, informed individuals working together with the goal of increasing human knowledge through missions to Venus.

A second organization or sub-organization could focus on highlighting the broad cultural appeal of the planet Venus and the unique nature of Venus missions, including inherent associations with peaceful cooperation. Human missions to Venus would be focused not on conquering or claiming new lands, but rather on the gathering of knowledge related to our beautiful sister planet, and the sharing of that experience with others. This organization or sub-organization could be a collective that engages artists, philosophers, entertainment industry experts, and content creators to ignite a passion and understanding of a potential future that includes human proximity to Venus. At the symposium, names for this organization or sub-organization were proposed that emphasized the more playful nature of this aspect of promoting Venus exploration, including, most popularly at the symposium, the 'Venusian Benevolent Society' (VBS).

Whatever organizations may or may not emerge, through websites, interviews, articles, white papers, podcasts, and social media presence, a Venus Cooperative—a potentially more formal version of the current, informal 'Venus Underground' that worked to convene the symposium—could serve as an advocacy hub for the goals of human space exploration at Venus, including its technical challenges, scientific benefits, unique appeals, and national signaling potential. A Venus Collective could begin as a volunteer membership organization focused on informing and growing the community, with the potential to grow into a self-supporting organization through merchandising, ticketed events, nonprofit fundraising, and other engagement and support. Since the color of Venus is a pale yellow and white, it was proposed at the symposium that the symbol of the community could be a pale yellow ribbon shaped like a Mobius strip with a length of white denoting the Venusian clouds.

Community outreach of this kind could not only benefit the exploration of Venus, but it could also enable people to become more intimately familiar with our solar system and why human exploration is beneficial overall. Workshop participants noted that engaging social media influencers, athletes, musicians, artists, and scientists with a wide range of followers brings more attention to human spaceflight—and that Venus, given its uniqueness, has the potential to engage new people and new audiences. Science in planetary exploration can sometimes be confusing to those not currently in the field and content could be created that could connect our scientists with the community and figures they admire to build a swell of enthusiasm around our sister planet, Venus. Along with social media outreach, engagement with the entertainment industry could develop documentaries, science fiction narratives, and multi-platform entertainment depicting Venus as a common connection between us all, such as with the imagined diary entry at the opening of this paper.

In order to advance the concept of a Venus Cooperative, the symposium participants discussed the potential to celebrate the next 'Venus Proximity Day' on August 13th, 2023—when Venus is closest to Earth at inferior conjunction—as a public engagement event with an associated technical workshop. Pete Worden of the Breakthrough Foundation proposed to host the event in Luxembourg, possibly at and around the Menhir of Beisenerbierg.

Additional potential avenues related to the development of a Venus Cooperative include linking up with the science and technology communities represented by the Venus Exploration Analysis Group (VEXAG) and the public engagement of the LPI/VEXAG Venus Initiative regarding Venus science and exploration. A new Venus Cooperative would likely best focus on the additional facets of human exploration and its motivations from science and outside of science.

4.1 Audiences

As with all types of science and exploration communications, there are unique opportunities and challenges related to engaging with different audiences around human missions to Venus. Below is a list of some of the engagement opportunities that were discussed at the symposium:

> *Primary and secondary education:* video and board games ('Aphrodite Trail'); academic packages (Journey to the Solar System, Journey to Venus, Venus in History and Literature); education for elementary, high school, and college students, including scholarships and museum displays.

College and graduate programs: engaging professors, departments in science and engineering (planetary, atmospheres, aerospace, systems), and human factors (long duration human ventures), and most importantly students; study programs, scholarships, research proposals and grants, including tie-ins to climate change and how our 'sister planet' diverged in its evolution; utilizing the confluence of robotic missions to Venus in 2028/2029 to create NASA/ESA/JAXA-based college and early-career engagement initiatives.

Professionals in technical and nontechnical fields: engaging human spaceflight mission designers and Mars advocates; stressing the risk reduction and broad program benefits, including the crucial need for an intermediate deep space mission 'shakedown cruise' before spending over 2 years going to Mars.

General public: articles and interviews stressing the human adventure and the logical potential of taking multiple steps at multiple locations out into the solar system; creating a YouTube channel; creating 'Venus Benevolent Society' podcasts; Venus-themed Ted Talks; a 'Lonely Planet'-style guide to Venus; tie-ins to far future ideas, such as cloud-level floating research stations (such as described in the HAVOC concept of habitable airships) to fire the imagination and expand horizons; encouragement and amplification of Venus-related science fiction narratives to support public engagement (e.g., Venus narrative in The Expanse, George R.R. Martin's Old Venus edited collection, etc.).

4.2 Venus as a Brand and Associated Themes

The symposium also considered important themes that are relevant for dedicated human missions to Venus independent of the additional value that such missions would have as a stepping stone to Mars. We can think about the 'Venus brand,' a planet not well understood but one that offers potentially a glimpse into the past and signs of what we may need to change about Earth and our own human actions for a better future. In Western mythology, Venus is the goddess of love and without love we wouldn't have romance, beauty, and art. She calls to us not for conquest but to show us her secrets and to guide us to a better future. In many Mesoamerican origin stories, Venus is a male warrior, a protector of humanity and defender against its enemies. A 'Venus brand' could synthesize ideas from many cultures. As part of the development of a 'Venus brand,' a number of themes were discussed, including:

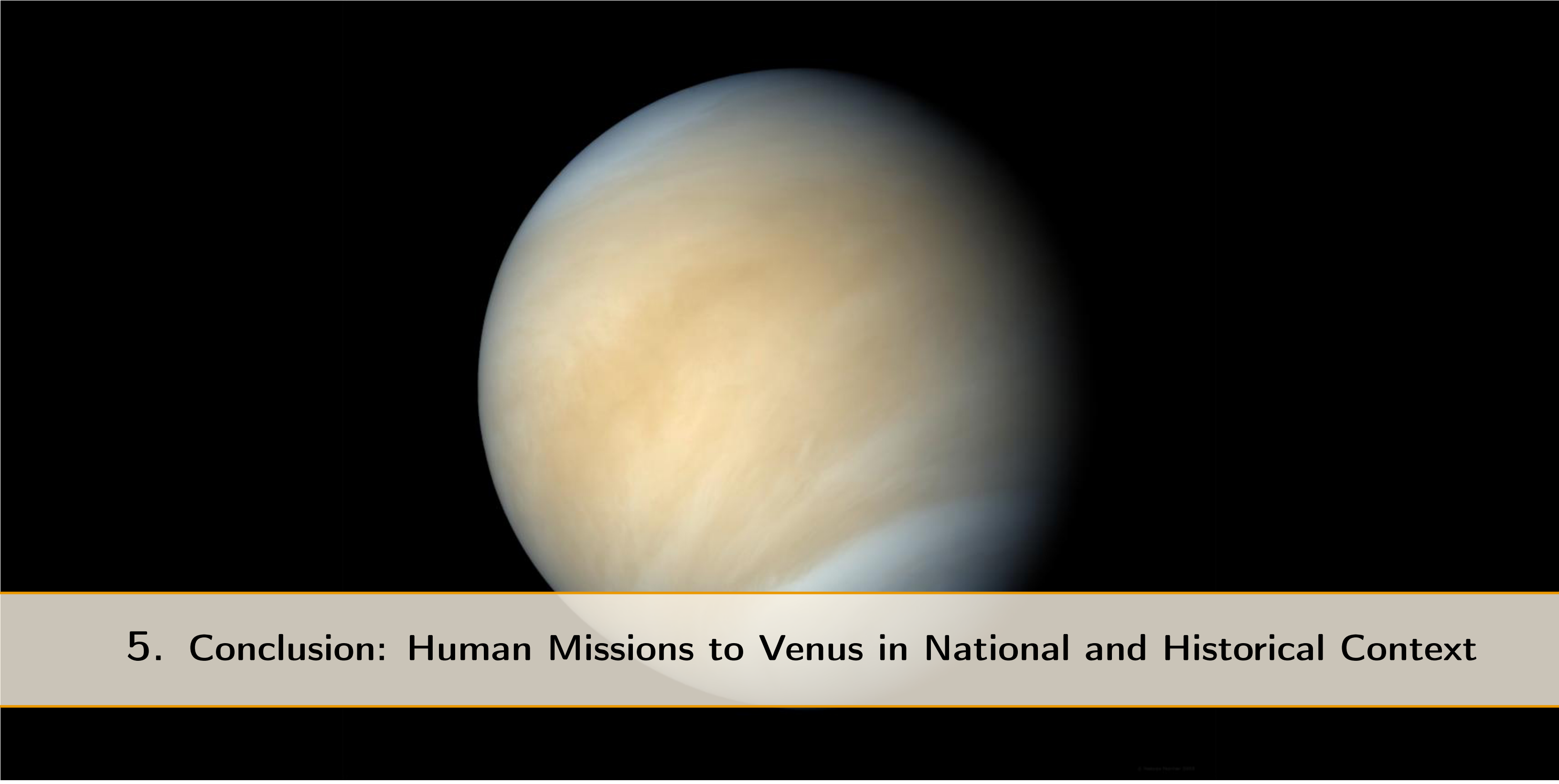
Sister Planet: Venus is the brightest planet in the night sky, has been associated with various gods and goddesses in a wide variety of cultures throughout human history, and is understood in popular culture as our sister planet. This can help create human connections to a distant world and create ties to a planet we have barely begun to understand. *"It's time to go visit our sister."*

Planetary Climate Change: Venus is believed to have potentially once been habitable, with liquid water on its surface. Today, however, its surface is inhospitable to life as we know it—the result of an extreme runaway greenhouse effect. The latter term itself originated in a scientific paper referencing Venus, before it was later applied to the potential future here on Earth that may result much sooner than we'd like due to anthropogenic climate change. As the world encounters our changing climate, it could potentially be important—even transformative—for us to encounter close-up a world made hostile to human life as we know it by climate change. *"What vital lessons about climate change on Earth-like planets are waiting for us on Venus?"*

Humans as a Multi-planet Species: Human expansion into the solar system is too easily reduced to just two places—the Moon and Mars—in popular culture and even space agency planning narratives. This limits the scope and scale of imagining what a human expansion into the solar system can look like. Venus has the potential to show some of the exciting 'non-linear' and unexpected aspects of what a truly multi-planet exploratory experience would look like. *"There are more planets in the Heavens to explore, Horatio, than are dreamt of in linear Moon-to-Mars planning."*

Cosmic Paradigm Shift: A first interplanetary mission has the potential for a new perspective shift, different from either the 'overview effect' or 'earthrise.' A first mission through the dark, outside of the Earth–Moon system, will be a new human experience and the crew will come back with new perspectives. In the case of the Venus back-flip double fly-by, in addition to two encounters with the planet Venus there would also be a first journey outside of the ecliptic, which may present a new perspective on humanity in the solar system. *"For the first time, we see another planet up close with our own eyes, alien and yet so similar, and see ourselves anew."*

Hero's Journey: In common world myths there is the idea of the hero's journey—an individual's quest into unknown lands and a return, changed, to benefit and change their home. In Joseph Campbell's description, one of the core phases is the 'Meeting with the Goddess' where the hero, after surviving trials on the journey, experiences a love—romantic, familial, or divine—through which they gain wisdom and strength. *"In humanity's mythic quest in the cosmos, a meeting with Venus—a 'Meeting with the Goddess' if there ever was one—has the potential to change everything."*



5. Conclusion: Human Missions to Venus in National and Historical Context

The oldest known human literature describes a Sumerian ruler who leaves his kingdom to go on adventures in pursuit of eternal life; the king doesn't find eternal life, but returns wiser with better ways of thinking about the relationship between humans and the cosmos. Grand adventures and their retelling, it turns out, are a substantial way to influence current and future human societies.

One of the greatest modern examples of the "hero's journey" is the Apollo 8 Mission, which circumnavigated the Moon and captured the first images of Earth taken by humans from the Moon. Photographs from Apollo 8 showed Earth from a new vantage point and helped to prompt the environmental movement in the United States. Apollo 8 was also a stepping-stone mission, which demonstrated the technology and operations for subsequent missions, most significantly of all the Apollo 11 Moon landing.

Apollo 8 also exemplifies one of the purposes of our space program: to attract allies and partners to want to work with us. This principle was first described in American space policy in what is now called the Webb–McNamara memo,[1] which helped set the foundation for the Apollo program. The memo describes "prestige" as an end for U.S. space activities, but we can be more precise about what this means in the context of national policy for a democracy. Prestige is a way to affect the bets of the rest of the world—are they going to bet on us (and our system of government), or an authoritarian competitor? Getting other nations to bet on

[1] James E. Webb, NASA Administrator, and Robert S. McNamara, Secretary of Defense, to the Vice President on May 8, 1961, with attached: "Recommendations for our National Space Program: Changes, Policies, and Goals." `https://history.nasa.gov/SP-4407/ETUv1.pdf`

us, and to see their aspirations as resonant with our endeavors, is the strategic end of such activities.

The Webb-McNamara memo also says something about the engineering approaches necessary to pursue this end: we need to actually achieve things, not just generally be making improvements. It recognizes that we tend to seek perfection in our big aerospace systems, and that we need to instead create mechanisms to insist on measurable achievement. Certain space missions can meet this criterion better than other mission types: missions that offer unambiguous achievement, that are amenable to translation into clear engineering goals, and that are achievable on short enough timescales to ensure measurable intermediate progress and excite public anticipation of personally witnessing the mission.

Crewed expeditions to Venus are a modern analog to Apollo 8, but on the scale of the inner solar system. There are several positive attributes of crewed missions to Venus: they are achievable in the foreseeable future; advance human expansion into the solar system by fostering capabilities relevant for Mars and beyond; and can advance planetary science and new searches for life.

We want an audacious human spaceflight program. But it is not sufficient to be audacious in word only, we must also demand achievements. The first crewed expedition into the solar system will be awe-inspiring around the world—and is therefore of the highest value to American strategic interests. Crewed expeditions to Venus may present one of the best ways of achieving this blending of national interest and scientific exploration.