Future Exploration of Venus: International Coordination and Collaborations

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The International Venus Exploration Working Group was formed during the 2012 COSPAR General Assembly held in Mysore, India to foster international cooperation and collaboration for Venus exploration

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Introduction. The many scientific questions about Venus and its increasing relevance for understanding Earth are resulting in a growing interest in the further exploration of Venus. The Venus Exploration Analysis Group has compiled goals and objectives for understanding Venus[1] with input from the global Venus community through workshops and meetings. These goals require a prolonged, and multiple mission strategy with a program for astrobiology exploration of Venus that will be valuable for habitable exoplanets also as VEXAG advocates. Due to the thick highly acidic cloud cover and the high temperatures and pressures at the surface, Venus requires a multi-pronged approach to scientific exploration with orbiters, atmospheric platforms, descent probes, and surface stations or landers. Even a large flagship class mission will be unable to obtain all the required observations, so multiple missions are needed. Helbert, Dyar [1] argue that a long term Venus program is needed.

We suggest that challenges presented by the high cost of large missions and competition with other exploration targets can be overcome through international collaborations. Such collaborations can present challenges due to institutional or national policies in the allocation of budgets or resources and priorities. However, Cassini/Huygens was an exemplary collaboration between NASA and ESA for exploring Saturn and Titan; additionally two Mars collaboration are underway: ESA-Russia for TGO and NASA-ESA for Sample Return.[2]. Despite delays, the NASA-ESA collaboration for the exploration of the Jupiter system is now moving forward with launches of the JUICE and Europa Clipper missions later this decade. We expect that collaborations will continue and be valuable, if not essential, for advancing Venus science.

There is one mission under development for launch by the Indian Space Research Organization (ISRO) in 2025/2026, with multiple other missions under consideration in the not too distant future. Venera-D is under consideration by Roscosmos and NASA for launch in the 2029 – 2031 period[2]. In addition, EnVision is under consideration by ESA for launch in 2031 and is a collaboration with the US and Russia. Two Discovery class missions to Venus are in Phase A for NASA's Discovery-14 competition and awaiting selection in 2021. However, even if all three of these missions are successful, they will still leave unanswered questions about Venus, past and present habitability, and the evolution of its climate and surface-atmosphere interactions. The new discovery of phosphine in Venus' clouds raises the possibility of life there significantly [3]. These and other questions can be addressed by a series of small missions, which can be implemented internationally. Coordination and collaboration on such missions will vastly benefit the advancement of Venus science around the world. We describe an approach for enhanced science return.

History. Exploration of Venus began within five years after the dawn of the space age with Sputnik in 1957, with the launches of Venera-1 and Mariner 2 in 1961 and 1962 respectively. In this era of the cold war, the Soviet Union and the United States continued to explore Venus separately. The Soviet Union succeeded with Venera entry probes 4 through 8 until 1972, then with entry probes and more complex missions with orbiters and fly-by spacecraft supporting surface landers (Venera 9 through 14 and the VeGa balloon and lander missions). The US launched fewer missions – Mariner 5 (1965), Mariner 10 (1978) and the Pioneer Venus Orbiter and Mult-Probe missions (1978). The cold war freeze on interactions began to thaw around 1976 when the COSPAR general assembly was held in Philadelphia in the US independence bicentennial year. A few Soviet scientists participated in the Pioneer Venus mission and a few US scientists collaborated with Soviet scientists in the Venera mission data interpretation. Venera 15/16 radar

[1] https://www.lpi.usra.edu/vexag/reports/VEXAG_Venus_GOI_Current.pdf
[2] http://www.iki.rssi.ru/events/2019/Venera-DPhaseIIFinalReport.pdf

missions went further, involving some East German and Italian instrument contribution. The VeGa 1 and 2 missions (1985) to Venus and fly-by of comet Halley were a Soviet-French and US collaboration and set the stage for greater collaboration among international space agencies. The Magellan orbiter, launched by NASA in 1989 followed the earlier Venera 15 and 16 radars orbiters. They laid the foundation of much of what we know today about Venus geology – but is NASA's most recent Venus mission. The European Space Agency launched its first Venus mission - Venus Express – in 2005; it became the focal point for the international Venus community, including American, Russian and Japanese collaborators, for a variety of atmospheric, ionospheric and surface investigations. Japan's Akatsuki orbiter (2010 – present) has seen collaboration by JAXA with ISRO for reception of radio occultation data and with NASA for DSN support and a Participating Scientist Program.

Venus Exploration Planning. In 2005, NASA established the Venus Exploration Analysis Group (VEXAG) to identify scientific priorities and opportunities for the exploration of Venus. From the outset, VEXAG has endeavored to involve the international community of scientists in carrying out its charter. In Nov 2019, VEXAG updated its scientific goals for the exploration of Venus and developed a new Roadmap and Technology plan. VEXAG identified three goals for the near and long-term exploration of Venus:

Goal #1. Understand Venus' early evolution and potential habitability to constrain the evolution of Venus-sized exoplanets

Goal #2. Understand atmospheric composition and dynamics on Venus, and

Goal #3. Understand the geologic history preserved on the surface of Venus and the present-day couplings between the surface and atmosphere.

These goals are associated with measurement objectives that can be addressed by specific investigations. The investigations are diverse and require detailed observations at the surface, within the atmosphere and within the magnetosphere. Thus, a single mission will not be able to accomplish them all and a number of missions and different platforms are required. Several mission architectures have been identified by VEXAG and described in its "Roadmap for Venus Exploration" document[3]. The Roadmap provides a framework for exploration, identifying missions and platforms that can be matured within a time frame of the next two decades but does not prescribe specific missions or priorities.

The science goals established by VEXAG are similar to the science drivers for missions considered by other space agencies. There are thus many common aspects to mission science objectives, architecture and mission elements, as described below. The commonality of science goals and instruments provide many opportunities for international collaborations at all levels. Continued collaboration among scientists and engineers as well as coordination among the space agencies of their missions to Venus will be valuable in the overall science return from the collected observations.

Mission Elements. The future exploration of Venus will requires a number of different types of scientific platforms deployed as mission elements: orbiters, descent probes, fixed and mobile landers, aerial platforms, dropsondes and skimmers. They may be used singly or in combination to carry out missions.

Venus Orbiters. Two type of orbits have been used for spacecraft around Venus: polar and equatorial with periods ranging from a few hours (Magellan) to about eleven days (Akatsuki) and eccentricities from ~ 0.4

[3] https://www.lpi.usra.edu/vexag/reports/VEXAG_Venus_Roadmap_Current.pdf

to 0.85. The short period, low eccentricity orbits are suited for global radar mapping (Magellan, Venera 15 and Venera 16). Eccentric, polar orbits have been generally favored due to orbit insertion energy considerations, but equatorial orbits provide a better global coverage as shown by Akatsuki. Orbital eccentricities and periods can be chosen to meet the desired science and programmatic considerations. Short period orbits present more radio occultation opportunities but face thermal and orbit keeping challenges, while long-period orbits (e.g. Akatsuki orbiter) provide long observing periods with slowly changing face angles.

Cubesats. Small satellites (*cubesats) such as* Marco 1 and Marco 2 [4] demonstrated the utility of cubesats at Mars and it is expected that cubesats will also be considered for Venus applications. Cubesats can enhance larger missions but they present lifetime and communication limitations. They can be deployed by a Venus orbiter mission either during its insertion into orbit or at a later time. With the inclusion of an Ultra Stable Oscillator (USO), cubesats may also be useful in increasing the thermal profile coverage of the atmosphere by the radio occultation technique.

Lagrange Point Orbiters (LPO): Lagrange point orbiters (LPO) around L1 and L2 locations of the Sun-Venus system are very appealing for monitoring Venus continuously over a narrow range of low (L1) and high (L2) phase angles and provide continuous relay capability for surface and atmospheric platforms [5, 6]; they have been considered for Russia's Venera-D mission[4]. Various scientific missions have been launched into Lagrange point orbits of the Sun-Earth system [7, 8]. The Lagrange or libration point orbits, as they are sometimes called, provide favorable vantage points for continuous observations of Venus. The orbits are inherently unstable, and require periodic but very low-cost station-keeping manoeuvres. The ACE mission is an example of a long-life mission, launched in 1998; it is expected to operate until 2026. LPOs can be deployed along with a larger main mission or independently as secondary payloads.

Due to the continuous observing capability and slow rotation rate of Venus, LPOs are visible for radio communications from both the day (L1) and night side (L2) of Venus continuously allowing reliable communications from any atmospheric or surface landers/stations, albeit at a somewhat lower rate due to the greater range. Venus orbiters can also provide periodic communications capabilities with such stations as determined by their orbits. A suitably designed orbit, such as a small-amplitude Lissajous orbit, around the L2 point, located on the Sun-Venus line at about 1 million km from Venus (away from the Sun direction), provides an opportunity to not only treat [9] but also observe Venus as an exoplanet, i.e., in transit across the solar disk. Japan's Institute of Space and Astronautical Science (ISAS) is developing Akatsuki-2, a follow-on mission to Akatsuki consisting of orbiters around L1 and L2 to be proposed to JAXA in 2021 to monitor the climate of Venus [10] as suggested by [6].

Entry Probes/Landers. From Venera 4, the first instrumented probe to enter the atmosphere of Venus, to the VeGa 1 and VeGa 2 landers, the challenge has been survival and operations in the high temperature environment. Pioneer probes and the Venera/VeGa landers operated for about an hour. The proposed Venera-D lander is designed to operate for about three hours. The challenges for long duration operations are electrical power and electronics operations as the internal temperatures rise above + 50° C. The Venus Flagship Mission Study [11] includes a lander that would target the tessera, a region of great scientific

[4] http://www.iki.rssi.ru/events/2019/Venera-DPhaseIIFinalReport.pdf

importance but complex mountainous terrain that will require precision landing and hazard avoidance for success.

The surface operating challenges faced by Venus lander missions make them strong candidates for collaboration. By leveraging advances across the globe more science can be achieved as more opportunities are createdbe. For example, advances in high temperature electronics and batteries will enable much longer observations on the Venus surface, potentially as long as four months. A small duration surface station, that can be deployed independently or by a lander, is under development [12]. This design actually builds on the ongoing development of the Venus lander called Long-lived In-situ Solar System Explorer (LLISSE) which has been baselined on the Venera-D joint mission concept study by ROSCOSMOS and NASA.

Surface mobility. The experience of the Mars rovers since Pathfinder has shown the value of mobility on the surface. However, the extreme environment and lack of high-resolution topography information makes designing a surface platform with mobility a difficult prospect. The Venus Flagship Mission lander [9A] increases the range of access by the use of laser sensing systems that can extend the effective reach of the lander. Concepts for going beyond this include purely mechanical concepts such as the Automaton Rover for Extreme Environments (AREE), but their scientific potential needs to be investigated[5].

Aerial Platforms. The VeGa 1 and VeGa 2 balloon missions [13] demonstrated the ability of constant-level balloons carrying instrumented gondolas to make *in situ* atmospheric measurements and transmit data directly to Earth for 48 hours. The flight of the balloons was tracked by Very Long Base Line Interferometry (VLBI) using an international network of 20 radio telescopes [14]. The Venus Aerial Platform Study conducted by NASA considered a variety of concepts including aircraft and semi buoyant vehicles[15] but identified variable altitude balloons (aerobots) as the next step in aerial exploration, including vehicles that can reach the cloud base and image the surface of Venus in the near infrared [14}. Other innovative concepts such as low mass distributed sensor platforms have also been investigated but not yet developed [16]. Dynamic soaring by fixed wing aircraft is being investigated for sustained *in situ* experiments in Venus' clouds (Elston et al., 2020). For aerial platforms, support and collaboration with orbital platforms is vital, not just for data relay and context remote sensing, but also for position and attitude determination.

Dropsondes. In the terrestrial atmosphere, small, instrumented dropsondes are used often to acquire *in situ* measurements for certain applications such tropical cyclones. Such devices have been proposed for deployment from aerial platforms in the Venus atmosphere to provide some critical measurements.of atmospheric chemistry, cloud aerosols and biogenic signatures compiled by VEXAG.

Atmospheric Skimmers. For measuring some of the atmospheric properties, a small instrumented device that can skim through the atmosphere is an interesting possibility. A small satellite to measure the noble gas isotopic ratios has been explored for the Venus atmosphere [17, 18].

Sample Return Missions. Many of the questions about the Venus atmosphere and surface/interior can be answered if atmospheric and surface samples could be returned and analyzed in a laboratory on Earth.

[5] https://www.nasa.gov/directorates/spacetech/niac/2017_Phase_I_Phase_II/Automaton_Rover_Extreme_Environments/

Return of atmospheric samples seems feasible but return of surface samples presents formidable technical challenges[6] and so far, there have been only some conceptual studies performed.

Fly-by Opportunities. Spacecraft going towards Mercury or beyond Earth's orbit often rely on gravity assist fly-bys to reach their target. Mariner 10, Cassini, Galileo, MESSENGER, and BepiColombo are examples of planetary spacecraft that observed Venus during their fly-by encounters. The Venus Earth Gravity Assist Science Opportunities (VEGASO) study[7] considered the upcoming fly-bys of Venus by the Parker Solar Probe, Solar Orbiter and BepiColombo missions. Coordination between NASA/ESA (solar missions) and jointly with JAXA (BepiColombo) has enabled useful Venus observations.

Future Mission Scenarios. Currently, there are missions to Venus which are finalists in both ESA and NASA competed programs for future missions: the VERITAS orbiter and DAVINCI Plus probe missions (Discovery/NASA), and the EnVision orbiter (ESA); decisions on these are expected by mid-2021. Beyond that, ISRO has a Venus orbiter in development for a mid-2020s launch, and Venera-D is under continued development by Roscosmos and NASA. At the same time, a separate Venus flagship mission study has been completed for the decadal survey. Both of these missions are expected to have many of the elements described above and likely invite international contributions. Potentially, non-state actors may also send spacecraft to Venus, with Rocket Lab and Breakthrough Foundation announcing their plans to send an entry probe of 50 kg entry mass to Venus in the mid-2020s.

For many scientific objectives, there are benefits to having multiple platforms operating at the same time in orbit, in the atmosphere and, on the surface. The orbiters can be cubesats (~ 10 kg), small (~ 100 kg) to medium (~ 500 kg) in size, or larger spacecraft for flagship class missions. They need to share some communications commonalities among themselves to be able to handle radio science and relay capabilities for in situ platforms and locate them. This concept is described in a companion white paper on a Venus Observing System [19]. We can envision scenarios in which such a constellation comes about through top-down agreement between national agencies. However, it is also possible that it could emerge incrementally in a bottoms-up fashion driven by collaborations among scientists and engineers. Either way, developing a shared vision of the scientific goals and technical strategies will be essential to get the maximum benefit from this combination of missions.

Telecommunications Interoperability. One of the major challenges facing atmospheric and long-term measurements from the surface of Venus is the transmission and collection of data. The Pioneer Venus Multiprobe mission used direct-to-Earth communications, which imposed two constraints – all the platforms had to be visible from Earth stations during the transmission, and the data rates were low (64 bps or lower) because of limitations on power, mass and range. Such a situation also occurs for Mars platforms but it has been solved by communication relay capability provided by the orbiters and data storage on the platforms. Neither of these options are available at present for Venus and hence missions have to rely on the carrier spacecraft or an orbiter (if it is part of the mission) to relay the data. Telecommunications interoperability between platforms developed by different agencies will be vital and future orbiters should be equipped with relay systems as they are for Mars [20]. A first question to be decided on is the frequency of inter-spacecraft links. The Venus lower atmosphere becomes strongly absorbing as frequency rises past 4

[6] https://www.lpi.usra.edu/vexag/reports/VEXAG_Venus_Roadmap_Current.pdf
[7] https://www.lpi.usra.edu/vexag/reports/VEGASO-04-24-15.pdf

GHz, so data relay from the surface should be at lower-frequency UHF or S bands. Cloud-level aerial platforms, operating above >98% of the atmosphere, could use higher-frequency X- band, which could allow for higher data relay rates but would reduce interoperability with surface assets. International agencies should commit to the adoption of a standard communication protocol, such as the Prox-1 protocol used for Mars.

Orbiters at both L1 and L2 locations and lower altitude would be able to provide either continuous or high rate communications contact with Venus atmospheric and surface platforms, in addition to performing their own science observations such as monitoring global cloud cover reflectivity (day-side) and opacity (night-side) for radiative balance and climate studies. Studies of atmospheric escape and global thermal structure via orbiter-orbiter radio occultations for global atmospheric thermal structure with Venus orbiters would also be enabled.

The Way Forward. Venus is an attractive target for exploration because of its proximity to Earth, which makes it accessible with a modest budget as well as presenting major scientific and technical challenges to the established space faring nations because of its extreme environment in the lower atmosphere and acidic cloud layer. The scientific motivations for understanding Venus continue to expand as we learn more about the planet, including understanding its origin and evolution, what brought about its extreme climate, past and present habitability and its role as a prototypical exoplanet. The scientific talent for addressing these questions is international with much of the scientific expertise about Venus now residing outside the United States, a consequence of the ESA and JAXA missions of the last two decades. International cooperation and collaboration in mission elements and instrument will lead to more opportunites for global scientists and space agencies and will benefit Venus exploration immensely.

Engage International Agencies. The International Space Exploration Coordination Group (ISECG)[8], comprised of its 23 members, was established to help coordinate human and robotic space exploration focused on Solar System destinations where humans may one day live and work. Understanding how Venus' climate evolved to its current extreme state, its past and present habitability and value of Venus for investigating habitable exoplanets, are all critical goals that trace to the ISECG purpose [21, 22]. NASA and other space agencies would benefit by coordinating a collaborative forum to bring about more effective cooperation and develop a joint program for Venus exploration. The structure of such a program could be tailored to the specific programmatic strategies of each agency, and in this way avoid redundancy and maximize science return. Models for such a program include the Mars program, which has been structured around a series of directed missions, and the Ocean Worlds Program, which has a defined set of scientific goals and objectives, but is implemented through competitive programs like Discovery, New Frontiers, as well as Flagship missions. Through such a Venus Program, synergistic optimization could be identified and implemented to maximize the efficacy to benefit the exploration of our neighbor planet. We urge the Decadal Survey to recommend that the IAECG include Venus as a target for exploration and thereby continue to foster international collaboration. Telecommunications interoperability should be a high priority item in the discussions.

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[8] https://www.globalspaceexploration.org/wordpress/

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