Unravelling the drivers of Venusian ionospheric structure, energy balance and evolution, through in-situ plasma measurements at Venus

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1. Executive summary

We recommend a multi-spacecraft dedicated plasma mission at Venus, capable of (1) sampling the entire induced magnetosphere, while (2) simultaneously measuring the upstream solar extreme ultraviolet (EUV) flux and solar wind. Such observations, obtained over a range of solar activity levels, would revolutionize our understanding of how the Venus time-dependent induced magnetosphere and ionosphere respond to solar EUV flux and solar wind variability, and would address several high priority VEXAG and planetary science goals.

The lack of a dipole magnetic field at Venus means that the solar wind interacts directly with the gravitationally bound conducting ionosphere, producing an induced magnetosphere that acts to slow down and deflect the solar wind around Venus. This interaction leads to a highly structured and dynamic plasma environment that responds strongly to changes in the solar EUV flux and the upstream solar wind conditions. Previous in-situ observations of the Venus plasma environment have provided information on the basic physical processes that dictate this interaction, however, limitations in instrument capabilities, solar cycle phase, and orbit coverage have left a plethora of questions unanswered. In particular, comprehensive (high time cadence and full distribution) plasma, neutral, magnetic and electric and field measurements, as well as simultaneous upstream solar wind monitors, are needed to fully characterize the state of Venus' magnetosphere, ionosphere and atmosphere, and the real-time response of these to variations in upstream solar wind conditions.

2. Scientific value:

Understanding the solar wind interaction with Venus under different solar activity conditions and determining the physical processes that facilitate energy transfer through the Venusian system and drive ionospheric variability, will provide information that is crucial to addressing the following high priority VEXAG goals:

1. **II.A.UD: Upper Dynamics:** In the upper atmosphere and thermosphere of Venus, characterize global dynamics and interactions between space weather and the ionosphere and magnetosphere.
2. **I.A.AL: Atmospheric Losses:** Quantify the processes by which the atmosphere of Venus loses mass to space, including interactions between magnetic fields and incident ions and electrons.
3. **I.B.IS: Isotopes:** Measure the isotopic ratios and abundances of D/H, noble gases, oxygen, nitrogen, and other elements in the atmosphere of Venus.
4. **I.A.MA: Magnetism:** Characterize the distribution of any remanent magnetism in the crust of Venus.

3. Introduction:

Venus is often considered Earth's twin due to its similar size, strength of gravity and thick atmosphere. Unlike Earth, however, Venus does not possess a significant dipole magnetic field. As a result, the gravitationally bound conducting ionosphere acts as the primary obstacle to slow and deflect the solar wind flow around the planet ^{1,2}. Because of this, the Venusian ionosphere responds strongly to changes in solar EUV flux and the solar wind (e.g. changes in solar wind pressure), leading to a highly variable plasma

environment ³. **The impinging solar wind interacts electrodynamically with the Venusian ionosphere, transferring some of the solar wind's energy into the ionosphere in the form of Poynting flux and particle precipitation.** The induced electric fields, waves, and ionospheric currents can heat and accelerate the electrically charged atmospheric ions, **but current in-situ observations are unable to resolve these important processes at Venus** that can directly influence ionospheric structure and energy balance.

Figure 1: A cartoon representation of the Venusian magnetosphere ⁴, highlighting solar wind energy input into the dayside upper ionosphere and the resulting topside variability. The highly structured night side ionosphere is also shown.

and the solar wind ⁴. The lack of a dipole field also influences atmospheric evolution, and recent observations of escaping H and O ions suggest that Venus has lost a considerable amount of atmosphere over its history via **non-thermal escape mechanisms** ⁶. **The solar wind is a primary candidate for driving this non-thermal escape but the lack of adequate observations mean that the specific ion energization mechanisms are not well constrained.**

This white paper outlines a scientific investigation that would be addressed via a Venus orbiter accompanied by a smaller solar EUV and solar wind monitor spacecraft, using existing technology. We are advocating for a future comprehensive Venus plasma mission, and will highlight how such a mission would advance key science goals identified by the Venus Exploration Analysis Group (VEXAG).

4. Overarching science question:

We propose a dedicated plasma orbiter mission at Venus to address the following science question:

How does the lack of a Venusian magnetic field influence magnetospheric and ionospheric structure, dynamics and evolution?

Such an investigation would include **determining which physical processes drive the solar wind interaction with Venus, how these processes change with solar activity, how these processes facilitate electrodynamic energy transfer to the upper ionosphere, and consequently, how these processes drive ionospheric structure, dynamics, energy balance and evolution.** The following subsections provide more detail on a sample of more specific, high priority focus points.

4.1 Why didn't Pioneer Venus Orbiter and Venus EXpress achieve these goals?

Pioneer Venus Orbiter (PVO) provided the first long term dataset of the Venusian plasma environment, including measurements of the bulk plasma quantities (thermal ion and electron densities and temperatures, ion composition, and 3D magnetic field). These have formed the cornerstone of our understanding of the basic components of the Venus-solar wind interaction^{4,7,8}. However, these plasma measurements were designed to measure cold (<1 eV) thermal plasma, and as such, **observations of full ion and electron distributions were not made. The prime mission, in which periapsis sampled the dayside ionosphere, occurred only during active solar times (and not solar minimum). These limitations precluded the study of the full ranges of kinetic physical processes and ion acceleration mechanisms, which play a key role in the interaction between the solar wind and unmagnetized planets via wave-particle interactions^{2,9}.**

The Venus EXpress (VEX) mission has provided the most recent in-situ plasma observations at Venus, however, the ion instrument package was the flight spare for Mars Express (MEX). Subsequently, measurements were limited in several key aspects necessary for accurately measuring low (<10 eV) energy ions. Additionally, the primary ionospheric ions (O^+ and O_2^+) could not be distinguished. As a result, **MEX could not accurately track ion energization processes in the ionosphere.** Additionally, the high spacecraft periapsis speed (9.7 km/s) and the 192 second cadence of the ion measurements mean that **VEX could only resolve ionospheric features larger than ~half the planetary radius**, precluding study of any of the finer scale features and structure identified by PVO.

PVO and VEX were single spacecraft missions in long elliptical orbits that **led to significant gaps in spatial coverage of the Venusian ionosphere and induced magnetosphere. Simultaneous measurements of the upstream solar wind and magnetosphere were unobtainable, limiting studies of the system response to changes in the solar wind.**

5. High priority science topics:

5.1 Foreshock structures and wave generation upstream of Venus

The foreshock is a region magnetically connected to and upstream of the bow shock that can be a source of low frequency, large amplitude wave generation via kinetic processes^{10,11,12}. A host of transient structures and low frequency wave modes have been observed in the Venusian foreshock^{13,14,15} that can penetrate the bow shock^{16,17} and propagate planetward^{18,19}. **A lack of high time cadence, full ion distribution observations prevents any detailed study of these processes, particularly with relevance to their formation in the foreshock region and impact on the upper ionosphere.**

Figure 2: Simulations of the Venusian foreshock predict low frequency, large amplitude magnetic and density structures to form under certain solar wind conditions¹⁸, but their effects on the upper ionosphere are not yet known.

In contrast, at Mars, comprehensive observations have shown that similar interactions can impart significant energy to the Martian ionosphere^{20,21,22}. A full understanding of foreshock phenomena at Venus requires coordinated, simultaneous multi-point measurements in the foreshock and upstream pristine solar wind.

5.2 Energy deposition and energy balance in the dayside upper ionosphere

Electron and ion temperatures are important in determining ionospheric structure through photochemical reactions that control local heating, cooling and transport rates²³. Modeling of the Venusian ionosphere has demonstrated that topside heat fluxes are required to obtain the elevated temperature profiles that match observations, and wave-particle interactions as a result of the Venus-solar wind interaction have been cited as a likely facilitator of this heating^{24,25}. Evidence for such wave-energy deposition has been observed by PVO with the electric field detector²⁶, however, **a lack of accompanying full ion and electron distributions at relatively high time cadences have precluded a full understanding of energy transfer from the upstream solar wind to the Venusian ionosphere via wave-particle interactions**^{27,9}.

5.3 Nightside ionospheric structure and variability

The Venusian nightside ionosphere **is solar cycle dependent and characterized by highly dynamic, small scale density, temperature and magnetic field structures**^{28,29,30}. The temporal and spatial variability of these structures is thought to be linked to variations in the solar wind and ionospheric-thermospheric coupling, but much is still unknown about **the depth to which these features penetrate the nightside ionosphere, how they form, and how the solar EUV flux and solar wind controls their spatial and temporal variability**^{31,30,32}. High time cadence in-situ plasma observations spanning the full range of nightside latitudes and local times are required to solve these mysteries.

5.4 Exosphere - solar wind interaction

Venus represents a unique laboratory for understanding the desiccation and oxidation of Earth-sized planets via H escape. Based on its Deuterium/Hydrogen (D/H) ratio, the overwhelming majority of Venus' primordial H inventory has been lost to space⁵. Thermal H at Venus cannot escape in significant quantities because the planet's thermosphere is relatively cool and its gravity strong. Instead, H loss at Venus is the result of a superthermal H population created via ion-neutral interactions^{33,34}.

Figure 3: Detection of hot hydrogen in the atmosphere of Venus, from³³. A slope change in the brightness profile of Lyman alpha (121.6 nm) sunlight scattered by hydrogen is best explained as the combination of cold thermal hydrogen tightly bound to the planet, along with a nonthermal population produced by ionospheric charge exchange that dominates at larger distances.

Despite the clear detection of these hot escaping neutrals and extensive modeling of the processes that create them on the basis of PVO data ³⁴, **substantial questions remain about how this population is produced and its absolute contribution to H loss.** Near coincident (in time) measurements of escaping exospheric H, the ionospheric source region, and solar conditions are required to resolve these questions ³⁵.

5.5 Electric currents in the Venusian ionosphere

Diamagnetic currents driven in the conducting upper ionosphere are crucial in standing off the solar wind, producing a magnetic barrier just above the ionosphere that can be strong enough to withstand the solar wind dynamic pressure ³⁶. The strength and direction of these currents are dependent upon the magnitude and direction of the interplanetary magnetic field (IMF) carried by the solar wind. **The relationship between these currents and the solar EUV flux and solar wind IMF have not been investigated at Venus due to the lack of coincident ionospheric and upstream measurements.** Additionally, ionospheric currents can be driven by interactions between the ionospheric plasma and the neutral atmosphere ³⁷. These currents can, in turn, impact the upper atmospheric dynamics through Joule heating. Vector magnetic field measurements can be used to determine these electric currents ^{38,39,40}, and **understanding their behavior will provide understanding of how the solar wind interacts with and drives electrodynamic processes within the near-space environment and upper atmosphere of Venus and other non-magnetized bodies.**

5.6 Magnetic topology and its importance at Venus

Venus does not possess strong crustal magnetism and as a result, magnetic topology (which defines whether the local magnetic field connects to the atmosphere or solar wind) is an essential aspect of the Venus-solar wind interaction. This topology denotes how low in altitude the solar wind magnetic field penetrates into the Venus ionosphere, and **plays an important role in understanding energy deposition and ion escape.** At Mars, different magnetic topologies have been found to facilitate different ion acceleration mechanisms ^{41,42,43,44}, **and such information is not known, but necessary at Venus, to understand the non-thermal escape processes that drive atmospheric ion escape.** Magnetic topology is also key for characterizing energetic electron precipitation, a source of ionization, thermal plasma heating, and auroral emission ^{45,46}. Knowledge of magnetic topology, combined with full electron distributions and real time upstream solar wind conditions, are required to fully characterize magnetic topology and its variation, as well as its impact on ionospheric structure and energy balance. Full electron distribution and 3D magnetic field measurements are required to achieve this understanding.

5.7 Global simulations of the Venus-solar wind interaction

Single point measurements from individual spacecraft cannot span the entire Venusian induced magnetosphere at all times simultaneously, and global simulations are used to “fill in the gaps”. Additionally, various physical processes can be “switched off” in these simulations, making them powerful tools for investigating which physical processes act

in specific regions and conditions. Increasing computing power has enabled much more accurate and high fidelity descriptions of plasma processes in global hybrid, magnetohydrodynamic (MHD), and fully kinetic simulations of the Venusian induced magnetosphere ^{19,47}. In particular, **large and small-scale plasma wave phenomena are resolved in modern global simulations, and these waves can drive ionospheric structure, energy deposition and atmospheric escape** ^{19,48}. To ensure accurate results, these simulations **must be constrained with observations** throughout the simulation domain, and the previously discussed limitations with PVO and VEX data preclude this to a high degree. Of particular importance are **high cadence mass resolved observations of ions and neutrals, and the magnetic field, which are needed to parameterize conditions at the inner ionospheric boundary within these global simulations** ^{49,47}.

6. Recommended investigation outline

We recommend an investigation consisting of multiple spacecraft: at least one Venus orbiter and a small upstream solar EUV and solar wind monitor. This combination enables simultaneous observations of the solar EUV flux, upstream solar wind, and downstream magnetospheric and ionospheric responses, all of which are vital to understanding the Venus-solar wind interaction. Our recommendation, outlined in Table 1, is informed upon the experience and success of the recent MAVEN mission at Mars, which has revolutionized our understanding of the Martian plasma environment due to its dedicated plasma instrument package and elliptically precessing orbit ⁵⁰. Based on our experience with MAVEN and SIMPLEX smallsat development, we estimate such an investigation would be well under the Discovery cost cap, in the \$200M - \$350M range.

7. Broader impact

A dedicated plasma mission to Venus, with carefully selected orbital coverage and an upstream solar EUV and solar wind monitor, would revolutionize our understanding of the Venusian induced magnetosphere and beyond. Intercomparison of plasma observations at Venus, Earth and Mars can yield new insight into how planetary systems in general interact with stellar winds. While Venus and Earth possess similar sized gravity fields, Venus does not possess a dipole field. Mars, on the other hand, possesses only localized strong crustal field remnants but has a significantly smaller gravity field than Earth and Venus. Thus, intercomparison of these three bodies further informs us as to how planet size, gravity field and magnetization state affect the planet-solar wind interaction. It is known that atmospheric escape rates, for example, vary differently upon EUV and solar wind properties, depending on whether Earth ^{51,52}, Mars ^{53,54} or Venus ^{55,56} is being considered.

A dedicated solar EUV flux and solar wind monitor at Venus would also be of great benefit to the heliophysics community, and would enable studies of the solar wind and the evolution of solar wind transient features (such as coronal mass ejections) as they propagate through the heliosphere.

Instrument	Measurement	Spacecraft	Mass [kg]	Power [W]
Ion (electron) electrostatic analyzers	Full ion (electron) distributions, (including ion mass)	VOB, SWM	3.5 (2.0)	4.2 (1.5)
Fluxgate magnetometer	3D magnetic field	VOB, SWM	1.3	5.0
Langmuir Probe	Thermal electron density and temperature	VOB	0.5	1.5
Electric field probes	Electric field power spectrum	VOB	12.0	0.3
Neutral mass spectrometer	Neutral atmospheric densities	VOB	13.0	40.0
EUV irradiance monitor	Solar EUV energy input	SWM	1.1	0.7
Ultraviolet spectrograph	Neutral H coronal densities	SWM	25.0	25.0

Table 1: Top level information on the recommended instrument suites to be carried by the Venus orbiter(s) (VOB) and solar wind monitor (SWM) (see Section 6).

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