Space Physics at Venus: Exploring atmospheric dynamics, escape, and evolution

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Abstract:

Our understanding of ancient Venus and its evolution to the present day could be substantially advanced through future Space Physics investigations from orbit. We outline three high-priority strawman investigations, each possible for relative thrift with existing (or near-future) technology. ***1.)*** To understand the physical processes that facilitate Venusian atmospheric escape to space, so that we may extrapolate backwards through time; ***2.)*** To explore ancient Venus through the measurement of the escape rates of key species such as Deuterium, Noble elements, and Nitrogen; ***3.)*** To understand and quantify how energy and momentum is transferred from the solar wind, through the ionosphere, and into the atmosphere, so that we may reveal its impact to the dynamics of the atmosphere.

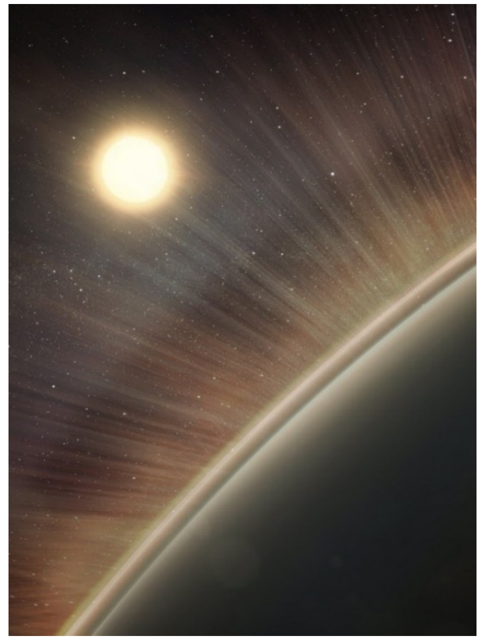


Figure 1: The clues to Ancient Venus lie waiting in the easily accessible upper

Introduction:

Of all planets so far discovered, Venus is the closest analog to Earth, with comparable surface gravity, and possibly previously orbiting within the habitable zone of its star where liquid water might theoretically exist at the surface (Way M. J., et al., 2016; Way & Del Genio, 2020). However, Venus is exceptionally dry, its atmospheres containing only 1.5×10^{-5} % of the total water at Earth (McElroy, Prather, & Rodriguez, 1982). The trace water remaining in the atmosphere is a hundred times richer in heavy water (HDO) than Earth, suggesting that Venus was once much wetter than today (Donahue, Hoffman, Hodges Jr, & Watson, 1982), although the ancient water budget has not otherwise been well constrained. More recent modelling (Way M. J., et al., 2016) has shown it is theoretically possible that ancient Venus may have been capable of retaining oceans of liquid water near the surface, with a climate extremely similar to Earths. Venus thus poses compelling science questions; How wet was early Venus? And how has its once water-rich atmosphere evolved since? How might water have been energized and lost to space? In broad terms, planetary atmospheres and water can be lost in two ways; down into the soil or mantle; or up into space.

At Mars, our understanding of the ancient water budget has come from a combination of geological investigation by landers and rovers (Squyres, et al., 2004), and from orbital space physics measurements by NASA’s Mars Atmosphere and Volatile EvolutioN (MAVEN) and ESA’s Mars Express (MEx) missions. MAVEN’s orbital measurements have conclusively demonstrated that loss of gas to space has been the dominant process responsible for changing the climate of Mars from an earlier wetter environment to the dry one today (Jakosky, et al., 2018) (Dong, et al., 2018).

At Venus, the crushing atmosphere makes near-surface geological investigations far more challenging, limiting their feasibility and scope. However, there is substantial progress that can still be made with Venus-orbiting satellites, missions which may be launched at a fraction of the cost of a Venusian lander. In this brief white paper, we will outline three compelling topics of scientific investigations that could be easily addressed from the orbit of Venus, using existing (or near-future) technology. Our intent is to A.) Show the importance of future plasma and fields measurements at Venus; and B.) Highlight how they may advance key goals identified by the community via the Venus Exploration Analysis Group (VEXAG).

Investigation 1.) How is the Venusian upper atmosphere ionized, accelerated, and lost in the current epoch?

With Earth-like gravity, the loss of "heavy" gaseous species (such as oxygen) to space is dominated by plasmas escaping from the ionosphere (as opposed to Mars, where the lower gravity opens up substantial avenues for the loss of neutral gas). The tail of Venus was comprehensively mapped by the European Space Agency's *Venus Express* (VEX) orbiter (2006-2014). VEX carried a skeletal space physics package; a magnetometer, and ion and electron spectrometers. These plasma instruments were the left-over flight-spares for a Mars Mission (not geared towards Venus). These instruments had several limitations; the ion measurements had poor temporal/spatial resolution, poor mass-resolution, and suffered from significant instrumental electronic artifacts; and the electron spectrometer had a very limited field of view, as well as an order of magnitude lower sensitivity than intended. In addition, it was not well calibrated at escape energies (10eV for O^+), and could not see below 10eV, and thus could not study how oxygen is accelerated beyond escape velocities. Nonetheless, VEX substantially advanced our understanding of atmospheric escape at Venus. Selected highlights include:

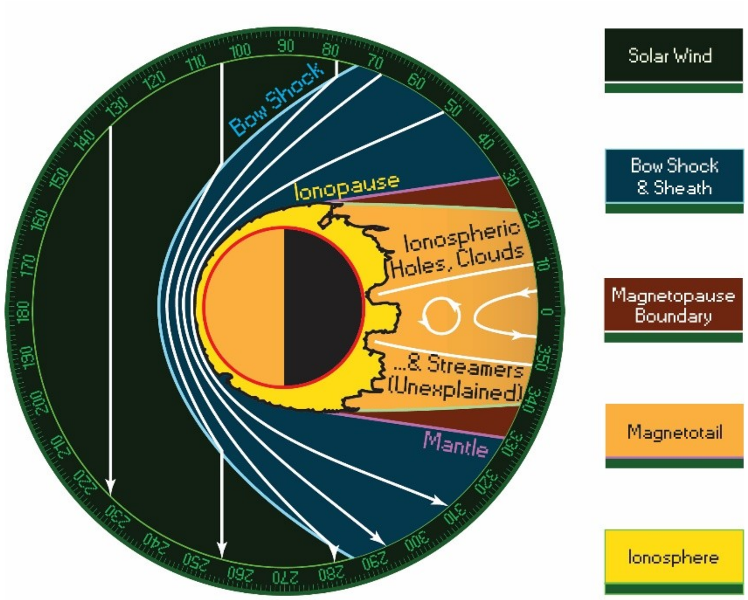


Figure 2: Schematic showing the loss of the Venusian atmosphere to space, and interacting with the thermosphere

- The Venusian plasma tail is effectively composed of highly ionized water: H^+ and O^+ (Barabash, et al., 2007). The stoichiometric ratio of this escape is close to 2:1 (though this changes with the solar cycle (Persson, et al., 2018)). Thus, Venus is still losing water through its tail. However, while loss rates have been mapped, and likely loss mechanisms identified, we do not know how Venus loses its atmosphere to space: which loss mechanisms dominate and when? How do they interconnect? How do they change with external drivers?

- Contrary to all expectations, loss rates appear to *decrease* as the sun gets more active in its solar cycle (Kollmann, et al., 2016) (Persson, et al., 2018). Overall loss rates today ($\sim10^{24}$ s^{-1}) are lower than at Earth, and comparable with Mars (Nilsson, et al., 2011; Lundin, et al., 2013; Brain, et al., 2015; Futaana, Wieser, Barabash, & Luhmann, 2017). However, due to the relatively poor spatial/temporal resolution of VEX's ion measurements, the dynamics of the Venusian tail is not fully understood, and thus the physical mechanisms through which atmospheric loss remains unsolved.

- The ionosphere of Venus generates an electrical field so powerful that any ionized oxygen caught in it would be accelerated to escape velocity (Collinson, et al., 2016). The strength of this "ambipolar" field defies explanation (Collinson, et al., 2019), but could only be measured very occasionally due to the limited payload of VEX. It is not clear if this is typical, at what altitudes this electric field operates, or why it is so strong.

Future science actions required:

1a.) Understand how Venus loses its atmosphere:

i.) Measure and understand the origin of physical forces that drive atmospheric acceleration and loss

ii.) Map and understand electrical fields at Venus, including the abnormally high ambipolar electric potential. (Collinson, et al., 2016)

iii.) Understand the bulk plasma losses, such as the mysterious "ionospheric clouds", "holes" and "streamers" reported by NASA's *Pioneer Venus Orbiter* (PVO), detached from the atmosphere and apparently escaping down the tail. (Brace, Theis, Mayr, Curtis, & Luhmann, 1982; Collinson, et al., 2014)

1b.) Model how Venus' loss rates may have changed over time due to changing solar luminosity and activity through the eons, and its impact on atmospheric evolution

i.) Understand how loss rates change with external drivers

ii.) Extrapolate back in time based on how these drivers have evolved over the lifetime of the solar system (as has been done at Mars)

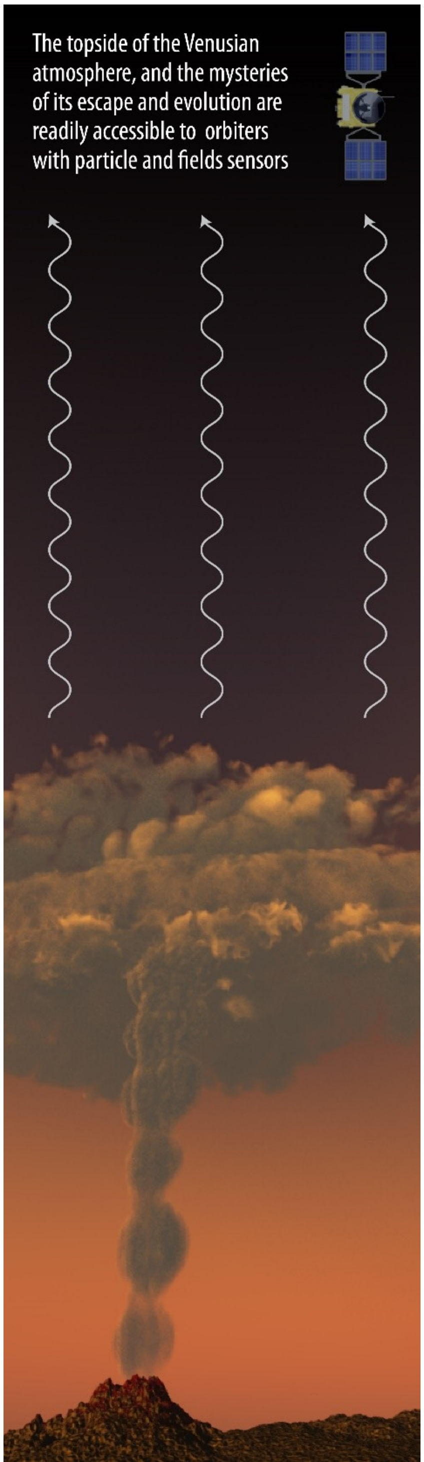
1c.) Study how escape is moderated by external drivers (space weather, solar illumination, etc)

i.) How does increased solar EUV decrease ion escape rates (Kollmann, et al., 2016), despite increasing the total energy input and producing photo-ions at a higher rate?

ii.) How much more energy is transferred from the solar wind to the ionosphere during extreme space weather events such as Coronal Mass Ejections, and quantify the effect on the atmospheric ion escape rate?

iii.) Determine which upstream drivers limits the escape rate.

How does this connect to VEXAG community goals?



This investigation directly addresses VEXAG goal 1.A.AL: *"Quantify the processes by which the atmosphere of Venus loses mass to space, including interactions between magnetic fields and incident ions and electrons."*

Investigation 2.) How has the Venusian atmosphere evolved?

A long-established goal for Venusian exploration has been the need to measure the isotopic ratios of key atmospheric species. The ratio of deuterium and hydrogen informs us about the ancient water budget, and the ratio of noble gasses may inform us about the evolution of the Venusian atmosphere. However, to date, no plans have been made to measure the relative loss rates of these species.

One of the most intriguing observations by NASA's *Pioneer Venus Orbiter* (PVO, 1978-1992) is the suggestion that the dominant mass 2 species in the ionosphere of Venus may be Deuterium (Hartle & Taylor, Jr., Identification of deuterium ions in the ionosphere of Venus, 1983). If true, this provides numerous comparable potential escape pathways for both Deuterium and Hydrogen. This would have significant implications for our calculations of the ancient water budget (Hartle & Grebowsky, Planetary loss from light ion escape on Venus, 1995). However, this Deuterium ion dominance has yet to be proven, and the loss rate of Deuterium with respect to Hydrogen is unknown. Thus, investigating both these questions is key to unlocking the story of water evolution on Venus.

In addition, while the escape rates of the major (most common) species (H^+, He^+, O^+) were extensively mapped by Venus Express, we know nothing about the escape rates of other important species. For example, the atmosphere of Venus contains four times as much nitrogen as Earth, but we do not know its escape rate, and thus cannot constrain the potential for an ancient Venusian biosphere. In addition, the possibility exists that noble gas species are lost to space, which would be very impactful for any calculations of atmospheric evolution. For example, Xenon is quite easily ionized.

Future science actions required:

2a.) Measure the relative rates of escaping Deuterium/Hydrogen; constrain the ancient water budget

2b.) Measure the absolute escape rate of all water group (W+) species

2c.) Measure the escape rate of noble group ions to support our understanding of atmospheric evolution

2d.) Measure the nitrogen escape rate from Venus and constrain the ancient Venusian biosphere.

This investigation addresses and supports VEXAG goal 1.B.IS: *“Measure the isotopic ratios and abundances of D/H, noble gases, oxygen, nitrogen, and other elements in the atmosphere of Venus.”*

Figure 3: The history of Venus may be explored from orbit with existing or near

Investigation 3.) How does the ionosphere drive the dynamics in the upper thermosphere?

A tantalizing discovery of the ESA *Venus Express* mission is that the solar wind imparts momentum to oxygen ions in the Venusian ionosphere, driving a global “zonal” wind (i.e. around the planet) of ions in the ionosphere . Below 500km, the mass flux of this wind of

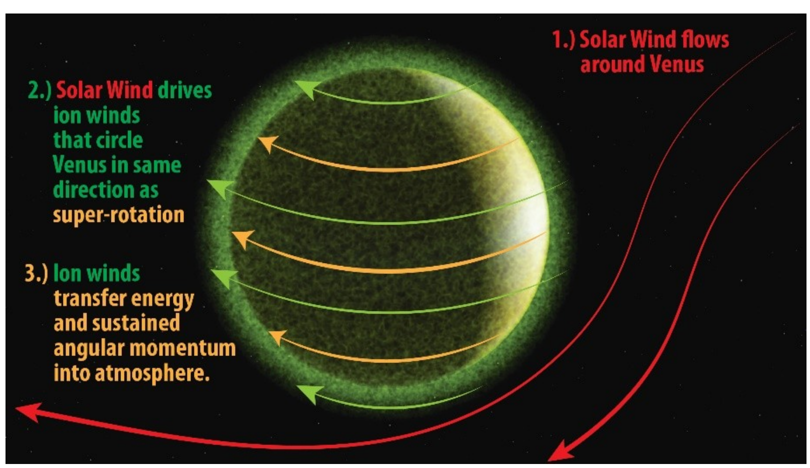


Figure 4: How do the solar wind, ionospheric winds, and neutral winds couple together?

oxygen ions dramatically drops, implying that the energy is being lost into the top of the thermosphere through drag and friction. This raises a key question; what is the cumulative effect of this global ion wind on the thermosphere? Since this was a constant effect observed over multiple years, on a long-term basis, it has been suggested that energy and momentum transfer reaches the lower atmosphere (Lundin, et al., 2011). This raises the possibility of a that the dynamics of at least the upper atmosphere may be impacted in part due to a global “flywheel” effect driven by long-term coupling between the solar wind, ionosphere, thermosphere, and atmosphere.

What is thus required is to map, measure, and understand ion and neutral winds in the upper atmosphere of Venus; where they flow, how strong they are, and what drives them. A prime region of exploration is the “exobase transition region” at around 200km altitude, where ionospheric plasma stops being coupled to the neutral atmosphere through collisions, and may escape to space. The technology to do this has existed since NASA’s Dynamics Explorer mission (1981-1983), which simultaneously mapped neutral and ion winds in Earths’ thermosphere. Thus, key science actions for future Venusian exploration include:

3a.) Map neutral and ion winds across the Venusian exobase (ala Dynamics Explorer)

3b.) Measure and map the global exchange of energy and momentum between the Venusian ionosphere and thermosphere

How does this connect to VEXAG community goals?

> This investigation directly addresses VEXAG goal 2.A.UD: *“In the upper atmosphere and thermosphere of Venus, characterize global dynamics and interactions between space weather and the ionosphere and magnetosphere.”*

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