Solar Activity Variations of the Ionospheres of Venus and Mars:
Implications for Comparative Planetology

I. Overview

The aim of the proposed project is to characterize the effect of solar cycle variations on the ionospheres of Venus and Mars. This goal will be accomplished by analysis and interpretation of data from ESA's Venus Express spacecraft, NASA's Pioneer Venus Orbiter (PVO), Mars Global Surveyor (MGS), and Mars Atmosphere and Volatile EvolutioN (MAVEN) spacecraft. This goal is important because understanding how planets and their atmospheres respond to solar cycle variations is critical for understanding how atmospheres in our solar system have evolved since their formation. Venus and Mars both have carbon dioxide-dominated atmospheres and lack a global magnetic field, but differ in the magnitude of their surface gravity, atmospheric density, and incident solar radiation. Nevertheless, their ionospheres have similar compositions and structures. This project aims to fill a gap in our understanding of how the ionospheres of Venus and Mars react to changing solar activity; namely, how the electron density and ion composition change in the highly variable region above the ionospheric peak.

II. Background

Solar X-ray and extreme ultraviolet photons ionize atoms and molecules in a planet's upper atmosphere, generating a weakly charged plasma layer called the *ionosphere.* The typical vertical structure of the ionospheres of Venus and Mars is illustrated in Figure 1. Significant variations in ionospheric electron density with solar activity are apparent. Figure 1 also shows that the topside ionosphere of Venus responds much more strongly to changes in solar activity than does the topside ionosphere of Mars. This intriguing observation motivates this proposal.

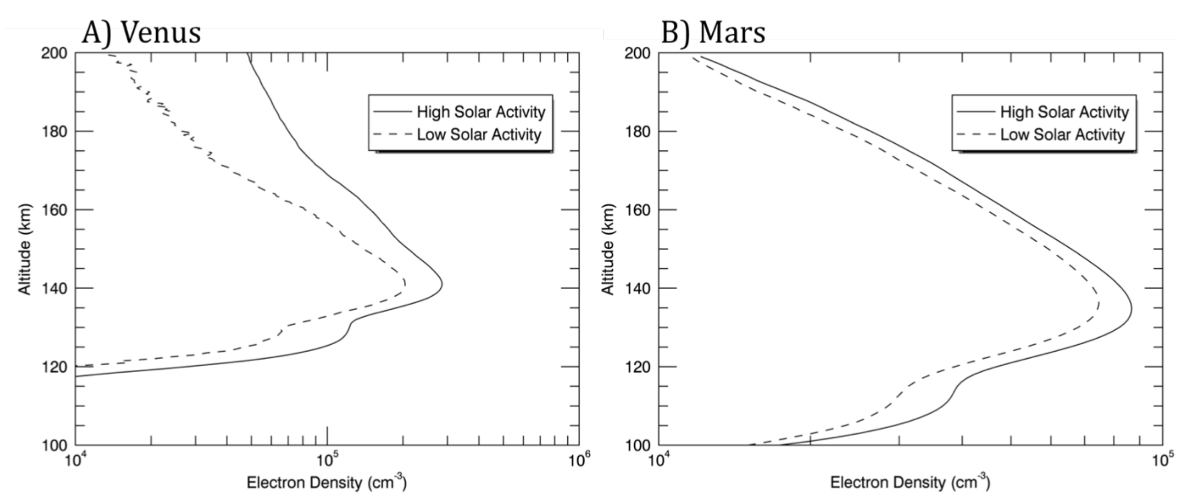

Figure 1. Average high and low solar activity electron density profiles for Venus (A) and Mars (B). Venus profiles are from Venus Express. Mars profiles are from Mars Global Surveyor. Both figures show measurements with solar zenith angles between 75 and 80 degrees. Density increases with solar activity are large and altitude dependent at Venus, but small and altitude independent at Mars. Note that the horizontal axis range differs between the two plots.

The common trend of increasing electron density with increasing solar activity is caused by changes in the Sun's ionizing flux over the 11-year solar cycle. The Sun's ionizing flux also undergoes changes over the lifetime of the Sun that have a substantial effect on planetary ionospheres. These ionospheric changes are significant because the ionosphere is a major reservoir from which atmospheric molecules are lost to space. Greater electron densities lead to greater loss to space, which in turn causes the planet's climate to change more rapidly. Hence, ionospheric variations with solar activity and with long-term solar changes have important implications for a planet's habitability over the course of solar system history.

Venus and Mars have the most well-studied ionospheres aside from Earth's. Much of our knowledge of Venus's ionosphere comes from Pioneer Venus Orbiter (PVO) and Venus Express, which observed the ionosphere of Venus under a wide range of solar activity. More recently, the Mars Atmosphere and Volatile EvolutioN (MAVEN) spacecraft has observed the response of Mars's ionosphere to solar activity including solar flares and coronal mass ejections (e.g. Duru et al. 2017; Thiemann et al. 2018). The variations in electron density with solar activity seen in Figure 1 have not yet been fully characterized, nor has the underlying physical cause of the marked differences between Venus and Mars been fully explored. To date, comparative studies of the ionospheres of Venus and Mars have focused on the regions near or below the altitude of peak electron density (e.g. Girazian et al. 2015, Peter et al. 2014). This is insufficient because atmospheric loss occurs throughout the ionosphere, not only at the peak.

III. Objective

The goal of this project is to develop a thorough description of how the ionospheres of Venus and Mars respond to changes in solar activity. In particular, I propose to characterize how these ionospheres react to solar cycle variations at altitudes above the height of peak electron density, a region which has not yet been analyzed fully. I want to better understand how the topside electron density at Venus and Mars responds to changes in solar activity (Task 1). I also aim to understand the underlying physical causes behind the markedly different ionospheric responses shown in Figure 1. I will accomplish this by characterizing the changes in the ion composition (Task 2) with solar activity at both planets. A comparison of the results at Venus and Mars will inform our understanding of which behaviors are common to terrestrial planet ionospheres as a whole and which are unique to each planet.

IV. Data

This work will employ measurements of ionospheric electron density, ion composition, and solar activity to characterize the response of Venus's and Mars's dayside ionospheres to changes in the incident solar flux. Specifically, this work will make use of radio occultations from Venus Express, MAVEN, and MGS, in situ data from PVO, in situ data from MAVEN, and ground-based solar $F_{10.7}$ measurements. The data used by the project are listed in Table 1 below.

To date, my preliminary work on the ionosphere of Venus has made use of PVO in situ data as well as PVO and Venera 15/16 radio occultations. Due to the similarities between PVO and MAVEN in situ data, as well as between PVO, Venera, MAVEN, VEX, and MGS radio occultations, I will be well-prepared to apply the techniques and programs I have used in previous investigations of Venus's ionosphere to analyze Mars. I can draw upon my advisor, MAVEN team member Dr. Paul Withers, as well as members of my research group, to smooth my transition from Venus to Mars.

Data Type	Venus Source		Mars Source	
Electron Density (>100 km)	Venus Express (VEX) radio occultations[1]		Mars Global Surveyor (MGS) and MAVEN radio occultations[2]	
Ion Density (>150 km)	PVO Orbiter Retarding Potential Analyzer (ORPA)[2]		MAVEN Neutral Gas & Ion Mass Spectrometer (NGIMS)[2]	
Solar Activity[3]	Ground-based solar $F_{10.7}$			
Approximate $F_{10.7}$ Range[3]	VEX	60 – 230 s.f.u.	MGS	60 – 280 s.f.u.
	PVO	130 – 310 s.f.u.	MAVEN	60 – 250 s.f.u.
Dates (Solar Cycle)	VEX	2006 – 2014 (23 – 24)	MGS	1997 – 2006 (23)
	PVO	1978 – 1992 (21 – 22)	MAVEN	2014 – present (24)

Table 1. Summary of data to be used.
[1] Available through Dr. Withers' role as VEX Co-I (Girazian, Withers et al. 2015)
[2] NASA's Planetary Data System (pds-ppi.igpp.ucla.edu, see references)
[3] $F_{10.7}$ measured at 1 AU from ngdc.noaa.gov; 1 s.f.u. = 10^{-22} W m^{-2} Hz^{-1}

V. Proposed Work and Timeline

Task 1: Characterization and Comparison of Electron Density at Venus and Mars *(Year 1)*

Many studies have observed an increase in the peak electron density with increasing solar activity on both Venus and Mars (e.g. Kliore & Mullen 1989, Girazian & Withers 2013). According to simple photochemical theory, the peak electron density, N_e, should vary with solar flux, F, as $N_e \propto F^k$, where $k = 0.5$. While the peak density at both Venus and Mars responds to solar activity as predicted by photochemical theory (see Figure 2), past studies have not addressed how the electron density at other altitudes behaves over the course of the solar cycle. I aim to answer fundamental questions about the ionospheres of Venus and Mars: Does the electron density depend more or less strongly on solar activity with increasing altitude? How do the responses of Venus's and Mars's ionospheres to solar activity differ? My selected method of answering these questions is to determine and interpret the value of k as a function of altitude.

I will accomplish this task by analyzing electron densities from Venus Express, Mars Global Surveyor, and

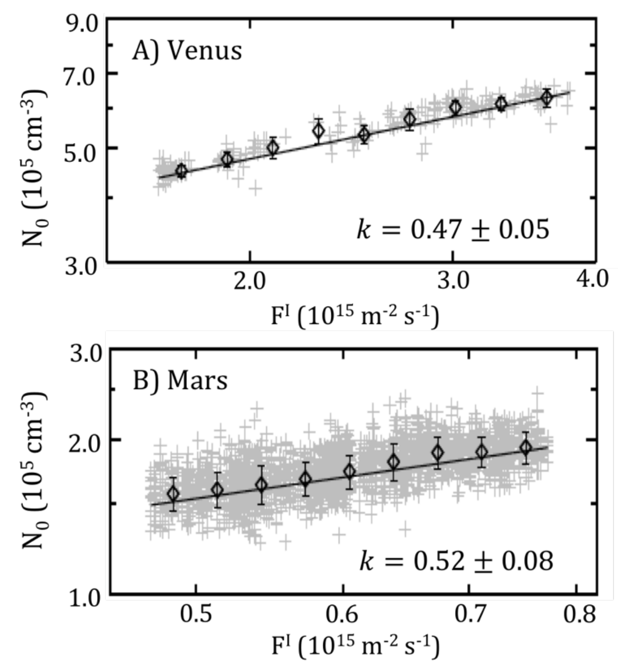

Figure 2. Peak electron densities in the ionospheres of Venus (A) and Mars (B) as a function of solar activity. The gray crosses indicate peak density measurements, corrected to the subsolar point, gleaned from individual VEX and Mars Global Surveyor profiles, while the black diamonds show the average for each bin with the 1-σ uncertainty. Adapted from Girazian (2016).

MAVEN radio occultations to determine how k changes as a function of altitude on each planet. Although the solar cycles sampled by the three spacecraft are different, considerable overlap exists in the solar activity levels for which data exist, as shown in Table 1. This task will allow us to quantify and compare the responses of the ionospheres of Venus and Mars to changing solar activity. This will illuminate the impact that different planetary parameters have on ionospheric behavior as well as increase our understanding of how the Sun affects terrestrial planets as a whole.

First, I will resample the observed electron densities onto a 1-km altitude grid and assign a $F_{10.7}$ value to each observation. $F_{10.7}$ is proposed as the nominal solar activity indicator; others will be investigated over the course of this project (http://lasp.colorado.edu/lisird/). Then, I will select solar zenith angle bins of appropriate size and select electron density and $F_{10.7}$ values within that bin for each altitude level. Next, I will fit the dependence of electron density on solar activity using the relation $N_e \propto F^k$, obtaining fit values, a goodness-of-fit metric, and uncertainties in the fit values. Figure 3 shows how the best-fit exponent k varies with altitude at one solar zenith angle in Venus's ionosphere.

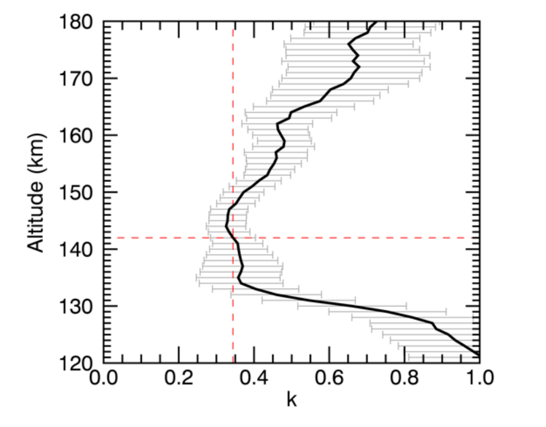

Figure 3. The response of electron density to changing solar activity as a function of altitude in the dayside ionosphere of Venus at a solar zenith angle of 30°. The red dashed lines indicate the average altitude of peak ionospheric density and the best-fit exponent k at that altitude. The response of ionospheric electron density to changes in solar activity is clearly at a minimum near the ionospheric peak and increases with increasing altitude above the peak. The large values of k at low altitudes, which are not the focus of this proposal, are caused by the hardening of the solar spectrum.

For both Venus and Mars, I will obtain best-fit exponents k for all solar zenith angles and altitudes from 100 km to the photochemical/transport boundary at 180 km (Kim et al. 1989; Morgan et al. 2008). In order to interpret the results, I will use my advisor's existing photochemical models of the ionospheres of Venus (Girazian 2016) and Mars (Fallows, Withers, and Matta 2015). By varying the model inputs, I will test four hypotheses for what determines how the ionospheres of Venus and Mars respond to changing solar activity: the overall expansion of the neutral atmosphere (i.e. the varying altitude of a fixed pressure level), changing neutral composition at a fixed pressure level, changing importance of minor ions, and changes in the electron temperature. This task will pinpoint which factors control how the ionospheres of Venus and Mars change with changing solar activity and why the two planets' ionospheres react differently to changes in solar activity (Figure 1).

Task 2: Characterization & Comparison of Ionospheric Composition at Venus & Mars *(Year 2)*

The ionospheric chemical composition represents a dynamic equilibrium between ionization by solar photons, chemical reactions between species, and recombination, with the recombination rates moderated by the electron temperature. Ionospheric models, such as the Venus model depicted in Figure 4, predict compositional shifts tied to changes in solar activity at both

Venus and Mars. Figure 4 shows that at topside altitudes, the total ion density increases with solar activity at all altitudes, but the relative amounts of the most abundant ions change as a function of altitude. Analogous Mars models predict similar changes (e.g. Fox et al. 1996). Compositional variations with solar activity changes have been observed at both Venus and Mars (e.g. Grebowsky et al. 1993; Thiemann et al. 2018), but have not been fully analyzed.

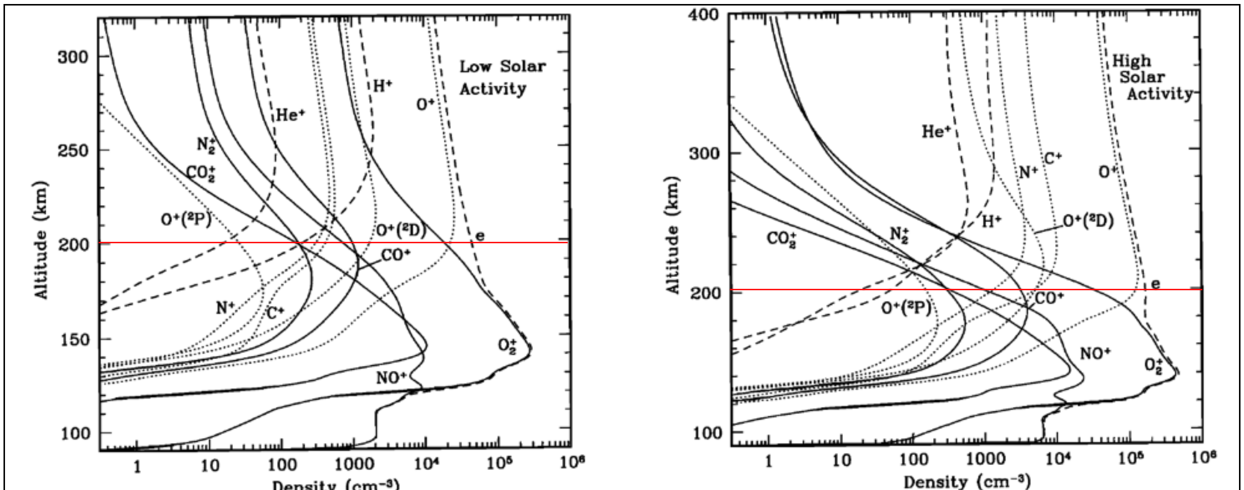

Figure 4. Modeled ion and electron density of the Venus ionosphere during periods of low (left) and high (right) solar activity. In the high solar activity case, the electron density (rightmost dashed line) is larger at all altitudes, but the relative amounts of the most abundant ions change with altitude. For example, the O^+/O_2^+ ratio at 200 km (red line) is ~1 at low solar activity and ~6 at high solar activity. At higher altitudes, this effect becomes even more pronounced. Note that the vertical scale increases in the second plot (Fox & Sung 2001).

I will use data from PVO's retarding potential analyzer, ORPA, and MAVEN's mass spectrometer, NGIMS, to investigate how the chemical composition of the ionospheres of Venus and Mars changes with solar activity. Although these missions were active during different solar cycles, there is broad overlap in the solar activity levels captured, as Table 1 shows. This investigation will be restricted to a narrower altitude range than Task 1 due to limitations of the data; PVO and MAVEN measured ion densities down to ~150 km.

Similar to Task 1, I will first assign $F_{10.7}$ values to each observation and collect the data in altitude and solar zenith angle bins. For each bin, I will then determine the dependence of the density of each ion species on solar activity, obtaining fit values, a goodness-of-fit metric, and uncertainties in the fit values. I will compare the dependence of each ion species to the overall behavior of the electron density to assess which ion species react more, less, or equally strongly to changing solar activity. I will also establish how the relative abundance of each species changes with solar activity by computing ion density ratios (e.g. O^+/O_2^+, Σ(minor ions)/O_2^+).

Using the photochemical models from Task 1, I will test four competing hypotheses for the cause of compositional variations with solar activity: the overall expansion of the neutral atmosphere (i.e. the varying altitude of a fixed pressure level), changing neutral composition at a fixed pressure level, changing importance of minor ions, and changes in the electron temperature. This task will determine the relative importance of these effects, as well as quantify how 1) the density of individual ion species and 2) the bulk chemical composition of the ionospheres of Venus and Mars change with solar activity.

VI. Summary

The proposed work will expand our knowledge of the workings of terrestrial planet ionospheres beyond the well-constrained region near the ionospheric peak. In particular, we will learn how ionospheric electron and ion densities at Venus and Mars vary with solar activity. This will provide constraints for future studies of how the climates of Venus and Mars have changed over the course of solar system history, which will contribute to a key goal of the MAVEN mission. The timeline for the proposed work is summarized in Table 2.

Time Period	Research	Communication of Results
YEAR 1	**Complete Task 1**	Publish paper on Task 1; Present results at AGU
YEAR 2	**Complete Task 2**	Publish paper on Task 2; Present results at DPS

Table 2. Expected timeline of award period.

VII. Importance to NASA

This work will directly contribute to the goals of NASA's Planetary Science Division, particularly the Solar System Workings program goal of "understanding the atmospheric, climatological, dynamical, geologic, physical, and chemical processes occurring within the Solar System."[1] This project will also answer in part one of the major science questions of NASA's Living With a Star program: "How do Earth, the planets, and the heliosphere respond [to our variable Sun]?"[2] This project will directly benefit these objectives because understanding the structure, composition, and variation of planetary ionospheres is critical for understanding the physical processes that create and maintain them.

VIII. Expected Impact and Potential Setbacks

This work will provide a thorough description of how the electron density and chemical composition in the ionospheres of Venus and Mars change with solar activity. Because an increase in ionospheric electron density leads to greater atmospheric loss to space, this project will provide constraints for future studies of how solar activity affects the loss and escape of terrestrial planet atmospheres. This will lead to a better understanding of star-planet interactions and the evolution of the habitability of planets in our solar system. Understanding how our Sun affects the atmospheres of planets in our solar system will lend insight to how other stars impact their planets. Comparing Venus and Mars will especially inform future studies of exoplanets that, like Venus and Mars, lack global magnetic fields.

This research plan is robust against foreseeable challenges. One potential setback is that the orbits of Venus Express, PVO, MGS, and MAVEN could precess too quickly to allow for observation of a sufficient range of solar activity at a given SZA. However, the Venus Express radio occultations show clear solar activity variations despite spanning a wide range of SZA (Figure 2a), as do the PVO in situ data. Additionally, MAVEN's orbit precesses sufficiently slowly that it crosses only a small range of SZA during a 27-day solar rotation period, over which time solar irradiance varies appreciably. If necessary, I will reduce the scope from all dayside solar zenith angles to focus on a handful of narrow solar zenith angle ranges where solar activity variations are sufficient. I expect that these setbacks would have only a minor effect on the expected results.

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[1] https://nspires.nasaprs.com

[2] https://science.nasa.gov/about-us/smd-programs/living-with-a-star

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