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Characterization of the lower layer in the dayside Venus ionosphere and comparisons with Mars

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ABSTRACT

The influence of solar zenith angle (SZA) and solar irradiance has been well characterized for the V2 layer in the Venus ionosphere, but not the V1 layer, where previous efforts were limited by data scarcity and incomplete SZA coverage. Here we use more than 200 radio occultation profiles from Venus Express with good SZA coverage to characterize how the V1 peak altitude, peak density, and morphology respond to changes in SZA and solar activity. The V1 and V2 peak altitudes vary little with SZA, and both peak electron densities vary with SZA in an approximately Chapman-like manner. These results imply that the thermal structures of the atmosphere and ionosphere between ~125 km and ~140 km vary little with SZA. As solar activity increases, the ratio of the V1 to V2 peak density increases, and the V1 morphology changes more than the V2 morphology. These results are due to the soft X-ray flux increasing relative to the EUV flux as solar activity increases. We compare the behavior of the V1 layer to the analogous M1 layer at Mars, and find that their peak altitudes respond differently to changes in SZA and solar activity. The V1 peak density also increases more with solar activity than the M1 peak density. These distinct behaviors arise from differences in their underlying neutral atmospheres.

1. Introduction

Characterization of the Venus ionosphere is essential for understanding how the planet is influenced by the Sun. The ionosphere is formed by the attenuation of ionizing solar radiation, and characterization of its vertical structure, namely the dependence of electron density on altitude, provides a foundation for more detailed studies of chemistry, dynamics, and energetics. Perhaps the simplest question that can be asked about the ionosphere is "how much plasma is there and where is it located?" This motivates our investigation of the major features in the Venus ionosphere.

Comparisons between planetary ionospheres are also fruitful; identifying trends that are unique to one planet helps to distinguish universal physical processes from those that are influenced by planet-specific conditions. Comparisons between the Venus and Mars ionospheres are especially enlightening because their upper atmospheres are strikingly similar.

In this work, we characterize how the lower layer in the dayside Venus ionosphere is influenced by solar zenith angle (SZA) and solar activity. We provide quantitative results that can be tested by numerical models and discuss their implications for the Venus neutral atmosphere and electron temperature between ~125 km and ~140 km. We also use our results to compare the ionospheres of Venus and Mars and discuss their similarities and differences.

1.1. The vertical structure of the Venus ionosphere

Comprehensive reviews of the Venus ionosphere can be found in Hunten et al. (1983), Mahajan and Kar (1988), Bougher et al. (1989), and Brace and Kliore (1991). Constraints on the vertical structure have primarily come from radio occultation experiments, including those on the Pioneer Venus Orbiter (PVO) and Venus Express (Kliore et al., 1967; Fjeldbo et al., 1975; Ivanov-Kholodnyi et al., 1977, 1979; Savich et al., 1982; Gavrik and Samoznaev, 1987; Brace and Kliore, 1991; Pätzold et al., 2007, 2009; Peter et al., 2014). Constraints on ionospheric composition and energetics have primarily come from PVO in situ data during its low altitude

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periapses between 1978 and 1980 (Bauer et al., 1977; Brace et al., 1983; Hunten et al., 1983; Bougher et al., 1989).

The dayside Venus ionosphere has two layers: the V2 layer at ~140 km, where electron densities are the largest, and the V1 layer at ~125 km. We have adopted the nomenclature of Rishbeth and Mendillo (2004) and Pätzold et al. (2007), other studies (e.g., Fox, 2007) have referred to the V1 and V2 layers as the E and F1 layers, respectively. Since the periapsis of PVO rarely dropped below ~150 km, the properties of the V1 and V2 layers are not constrained by in situ measurements.

At altitudes around the V1 and V2 layers, transport processes are unimportant and the ionosphere is in photochemical equilibrium (Schunk and Nagy, 2009). The ion composition is primarily ${O_2}^+$ with lesser amounts of ${CO_2}^+$, O^+, and other trace species. The dominant loss process is dissociative recombination of ${O_2}^+$ with an electron ($O_2^+ + e^- \rightarrow O + O$). The rate of this reaction is proportional to $T_e^{-0.7}$ (Schunk and Nagy, 2009), where T_e is the electron temperature, and so higher electron temperatures lead to larger electron densities.

Photoionization in the V1 and V2 layers is driven by photons from different parts of the solar spectrum. Extreme ultraviolet (EUV) photons in the range ~15–90 nm, where the ionization cross-section of CO_2 is relatively uniform, are absorbed in the V2 layer (Schunk and Nagy, 2009). More energetic soft X-ray photons in the range ~1–15 nm, where the ionization cross-section of CO_2 varies strongly with wavelength, are absorbed in the V1 layer (Schunk and Nagy, 2009). Plasma in the V1 and V2 layers is also produced by electron impact ionization, whereby energetic photoelectrons ionize neutral molecules as they thermalize. Since the ionizing photons absorbed in the V1 layer are more energetic than those absorbed in the V2 layer, the ratio of the electron impact ionization rate to the photoionization rate is predicted to be ~7 in the V1 layer, but only ~0.4 in the V2 layer (Fox, 2007).

1.2. Prior studies of the V1 layer

The properties of the dayside V2 layer have been explored in many previous studies, especially the dependence of the peak altitude and peak density on SZA and solar activity (Ivanov-Kholodnyi et al., 1979; Cravens et al., 1981; Savich, 1981; Breus et al., 1985; Gavrik and Samoznaev, 1987; Kliore and Mullen, 1989; Peter et al., 2014). By contrast, the V1 layer has not been studied in great detail. Ivanov-Kholodnyi et al. (1979) analyzed 13 electron density profiles from Venera 9/10 and asserted that the SZA dependence of the V1 peak electron density is Chapman-like. Savich (1981) analyzed 29 profiles from Mariner 5/10, Venera 9/10, and PVO and asserted that V1 peak altitude and peak density depend on SZA in a similar manner to the V2 peak altitude and peak density. Breus et al. (1985) analyzed 27 profiles from Venera 9/10 and PVO and showed graphs of the dependence of peak density and peak altitude on SZA for both the V1 and V2 layers. They concluded that the V1 peak density depended on SZA in a Chapman-like manner with a subsolar peak density of 2×10^{11} m^{-3} and that the V1 peak altitude was insensitive to SZA. Gavrik and Samoznaev (1987) analyzed 86 profiles from Venera 9/10 and 15/16 and confirmed these results. They also showed that the V1 peak density increases with the $F_{10.7}$ solar index ($F_{10.7}$), but did not provide a fit to the data.

These prior observational studies are limited; they were based on a relatively small number of electron density profiles that are particularly sparse at SZAs <50° and the effects of solar activity have scarcely been addressed. Additionally, few modeling studies of the dayside V1 layer exist. Fox (2007) used a numerical model to study the V1 layer at SZAs >60° for moderately high solar activities consistent with the irradiance at the beginning of the PVO mission. They fit the V1 and V2 peak densities to $[\cos(\mathrm{SZA})]^k$, and stated that $k=0.35$ for the V1 layer and $k=0.39$ for the V2 layer. However, analysis of their tabulated peak densities suggests that these powers were inadvertently transposed and that the predicted V1 peak density is actually proportional to $[\cos(\mathrm{SZA})]^{0.39}$. Fox (2007) also predicted that the V1 peak altitude increases from 125 km at SZA=60° to 129.5 km at SZA=85°.

1.3. Differences between the V1 and V2 layers

The main difference between the V1 and V2 layers is that the V1 layer is produced by the soft X-ray irradiance but the V2 layer is produced by the EUV irradiance. Although solar flares are expected to influence the V1 layer on short timescales, we do not investigate that here, instead, we focus on how the long-term trend in the solar soft X-ray irradiance influences the V1 layer. As solar activity increases, the number of soft X-ray photons increases relative to the number of EUV photons (Lean, 1991; Woods, 2008). This hardening of the solar spectrum will cause the V1 and V2 layers to respond differently to changes in solar activity.

Another difference is that the assumptions of Chapman theory are violated more strongly in the V1 layer than in the V2 layer. This is because changes in the ionization cross-section of carbon dioxide are much more pronounced at soft X-ray wavelengths than at EUV wavelengths (Fox, 2007; Schunk and Nagy, 2009). The assumptions of idealized Chapman theory represent a substantial simplification over the true complexity of any ionosphere and Venus is no exception. However, the predictions of Chapman theory serve as a benchmark against which we can evaluate its behavior. Predictions that are satisfied, predictions that fail, and the ways in which they fail are valuable constraints on numerical models that attempt to accurately describe the physical processes at work in the ionosphere (Fox and Yeager, 2006; Fox, 2007; Fox and Weber, 2012; Wedlund et al., 2011; Peter et al., 2014).

1.4. Objectives

In this work, we characterize the dependence of the V1 peak altitude and peak density on SZA and solar activity and compare against a simultaneous characterization of the V2 layer (Sections 3.2–3.5). Since SZA variations of the peak altitudes and peak densities are controlled by the neutral atmosphere and the electron temperature, comparisons of the two layers can reveal how these properties behave at these altitudes. We also characterize how the peak density and the morphology of the V1 layer respond to changes in solar activity (Sections 3.6–3.8). Lastly, we compare our Venus results to similar work at Mars so that we can begin to distinguish processes that are planet-specific from those that are more universal (Section 4).

2. Data

This study uses ionospheric data, electron density profiles from the VeRa radio science experiment on Venus Express, and solar activity data, the $E_{10.7}$ solar index. Here we introduce these datasets.

2.1. Electron density profiles

The Venus Express spacecraft (VEX) launched on 9 November 2005 and entered Venus orbit on 11 April 2006. The scientific payload of VEX includes the Venus Express Radio Science Experiment (VeRa) (Häusler et al., 2006; Pätzold et al., 2007), which can perform radio occultation studies of the ionosphere and