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The post-terminator ionosphere of Venus

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A B S T R A C T

We have modeled the near and post-terminator thermosphere/ionosphere of Venus with a view toward understanding the relative importance of EUV solar fluxes and downward fluxes of atomic ions transported from the dayside in producing the mean ionosphere. We have constructed one-dimensional thermosphere/ionosphere models for high solar activity for seven solar zenith angles (SZAs) in the dusk sector: 90°, 95°, 100°, 105°, 110°, 115° and 125°. For the first 4 SZAs, we determine the optical depths for solar fluxes from 3 Å to 1900 Å by integrating the neutral densities numerically along the slant path through the atmosphere. For SZAs of 90°, 95°, and 100°, we first model the ionospheres produced by absorption of the solar fluxes alone; for 95°, 100°, and 105° SZAs, we then model the ion density profiles that result from both the solar source and from imposing downward fluxes of atomic ions, including O^+, Ar^+, C^+, N^+, H^+, and He^+, at the top of the ionospheric model in the ratios determined for the upward fluxes in a previous study of the morphology of the dayside (60° SZA) Venus ionosphere. For SZAs of 110°, 115° and 125°, which are characterized by shadow heights above about 300 km, the models include only downward fluxes of ions. The magnitudes of the downward ion fluxes are constrained by the requirement that the model O^+ peak density be equal to the average O^+ peak density for each SZA bin as measured by the Pioneer Venus Orbiter Ion Mass Spectrometer. We find that the 90° and 95° SZA model ionospheres are robust for the solar source alone, but the O^+ peak density in the "solar-only" 95° SZA model is somewhat smaller than the average value indicated by the data. A small downward flux of ions is therefore required to reproduce the measured average peak density of O^+. We find that, on the nightside, the major ion density peaks do not occur at the altitudes of peak production, and diffusion plays a substantial role in determining the ion density profiles. The average downward atomic ion flux for the SZA range of 90–125° is determined to be about 1.2×10^8 cm^{-2} s^{-1}.

1. Introduction

The ionosphere of Venus was first detected in radio occultation electron density (n_e) profiles measured by the Mariner 5 flyby in 1967 (e.g., Mariner Stanford Group, 1967; Kliore et al., 1967). The egress portion of the flyby trajectory returned a dayside n_e profile at a solar zenith angle (SZA) of 40°. It was found to exhibit two peaks: an F_1 peak of $(5–6) \times 10^5$ cm^{-3} near 140 km, and an E peak or shoulder of slightly less than 2×10^4 cm^{-3} near 125 km. In the ingress portion of the trajectory, an n_e profile was detected on the nightside at an SZA of 140°. It showed a single peak near 150 km, with a density of about 1×10^4 cm^{-3}. Over the next 25 years, nightside n_e profiles were returned from many subsequent radio occultation measurements by Soviet and American spacecraft, including the Pioneer Venus (PV) orbiter radio occultation (ORO) experiment. (For a historical account, see, for example, the introduction to the paper by Kliore and Luhmann (1991).) The European Venus Express (VEX) spacecraft was placed into orbit in 2007, and the Radio Science Experiment (VeRa) has been returning electron density profiles up to the present (e.g., Häusler et al., 2006; Svedhem et al., 2009; Pätzold et al., 2009). Unfortunately, these radio occultation (RO) profiles are not yet available to study, and there are no companion in situ data about the underlying neutral atmosphere, or the individual ion densities.

The appearance of a substantial nightside ionosphere on Venus was puzzling in view of the 58 days of darkness that result from the slow retrograde rotation of the planet. There have been many suggestions for the sources of the nightside ionization. (See, for example, the introduction to the paper by Fox (1992).) It is now generally accepted that the nightside ionosphere is mostly maintained by transterminator fluxes of atomic ions, which originate on the dayside and flow nightward in response to the plasma pressure gradient force (e.g., Knudsen et al., 1981; Whitten et al., 1984; McCormick et al., 1987; Nagy et al., 1991; Brannon et al., 1993; Shinagawa, 1996). The nightside ionosphere has been found to be highly variable, especially in the regions near and above the peak (e.g., Taylor et al., 1980; Breus et al., 1985; Fox and Kliore, 1997). It has been suggested that this is due to variability in the supply of ions from the dayside, which are determined by the solar fluxes

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and the altitude of the terminator ionopause, which is anticorrelated with the solar wind dynamic pressure, P_{sw} (e.g., Cravens et al., 1981). Evidence has been adduced, however, that for small values of P_{sw}, the nightward flow saturates, and further decreases in P_{sw} (or increases in the altitude of the terminator ionopause) do not lead to increases in the transterminator fluxes or in the nightside peak densities (e.g., McCormick et al., 1987; Kliore and Luhmann, 1991; Brace et al., 1995). Sometimes the ionosphere is observed to be reduced to small patches of detached plasma (Cravens et al., 1982). Brannon and Fox (1994) excluded these "disappearing" ionospheres from their analysis, and we do here also. Although some of the transterminator fluxes of ions escape (see the discussion in Fox (2008)), most have been believed to converge and flow downward on the nightside, where they react with ambient species to produce molecular ions; the terminal molecular ions are ultimately destroyed by dissociative recombination.

In addition, there is believed to be a smaller source of ions that is due to the precipitation of relatively soft suprathermal electrons of uncertain origin into the nightside thermosphere. Such electrons have been detected at high altitudes in the wake of the planet by the plasma analyzers on the Venera 9 and 10 spacecraft (e.g., Gringauz et al., 1977, 1979; Breus et al., 1985) and by the PV Orbiter Retarding Potential Analyzer (ORPA) (e.g., Knudsen et al., 1980a; Spenner et al., 1981, 1996; Knudsen and Miller, 1985). Spenner et al. (1981) reported that the integral suprathermal electron fluxes between 5 and 45 eV, as measured by the PV ORPA in the Venus umbra, were found to be fairly constant with SZA, time and altitude. They also noted that the nightside ion density variations measured by the ORPA were not correlated with those of the suprathermal electron fluxes.

Other evidence for electron precipitation, however, was the appearance of continuous "auroral" emissions of O at 1304 Å and 1356 Å, which were measured by the PV Orbiter Ultraviolet Spectrometer (OUVS) (e.g., Stewart et al., 1980). These emissions, unlike the measured suprathermal electron fluxes alluded to above, were observed to be highly variable. Fox and Stewart (1991) used a simplified electron transport model to estimate the fraction of the electron spectrum presented by Knudsen and Miller (1985) that was required to reproduce the average intensity of 4 R for the O 1356 Å doublet, as measured by the OUVS. The proposed fraction of 0.28 was later refined to 0.23 in a model that included a multistream electron transport code (Fox et al., 1992). Fox and Taylor (1990) proposed that large mass-28 ion densities on the nightside, of the order of 10^3 cm^{-3}, were evidence for precipitating electrons.

Only the Pioneer Venus Orbiter (PVO) provided in situ data relating to the lower ionosphere/thermosphere; these data were obtained from day 339 of 1978 to day 209 of 1980, a period of high solar activity, and near peak ionospheric measurements were confined to a narrow latitudinal band around 16°N. Periapsis of the PVO was maintained below 200 km for the first 600 orbits of the mission, after which it was allowed to evolve to higher altitudes. The minimum altitude of periapsis was, however, below 150 km for only 12% of the orbits, about half of which were on the nightside. The PV Orbiter Ion Mass Spectrometer (OIMS) measured the densities of 12 ions: H^+, D^+, He^+, O^{++}, C^+, N^+, O^+, $^{18}O^+$, mass-28 ions (N_2^+ and CO^+), NO^+, O_2^+, and CO_2^+ (e.g., Taylor et al., 1980). Electron densities and temperatures were measured by the Orbiter Electron Temperature Probe (OETP) (e.g., Brace et al., 1980). The ORPA measured the densities of the major ions, including O^+, CO_2^+, and H^+, and those of a group of molecular ions called "mass-29" ions, which comprises the sum of the ions with masses between 28 and 32 amu: O_2^+, NO^+, N_2^+ and CO^+. The ORPA also measured the total ion densities, ion temperatures, ion bulk velocities, and electron temperatures (e.g., Knudsen et al., 1979, Knudsen et al., 1980b, Miller et al., 1980). The PV Orbiter Neutral Mass Spectrometer (ONMS) measured number densities of CO_2, O, CO, N_2, N and He in thermal mode, and fluxes of suprathermal ions in energetic ion mode (e.g., Niemann et al., 1980; Kasprzak et al., 1991). The total mass densities were measured by the Orbiter Atmospheric Drag (OAD) experiment (e.g., Keating et al., 1980, 1985). The PV Bus Neutral Mass Spectrometer (BNMS) measured the number densities of CO_2, N_2, O, CO, N, and He, and the total mass densities from 130 to 650 km as it entered the atmosphere during morning conditions (e.g., von Zahn et al., 1979, 1980).

Using one-dimensional models, the structure of the dayside ionosphere of Venus has been predicted with considerable success by many investigators over the past three decades (e.g., Chen and Nagy, 1978; Rusch and Cravens, 1979; Nagy et al., 1980, 1983; Fox and Victor, 1981; Cravens et al., 1981; Fox, 1982a,b, 2007; Kim et al., 1989; Fox and Sung, 2001; see also the reviews by Cravens, 1992, and by Fox and Kliore, 1997). Of these models, only Chen and Nagy (1978), Nagy et al. (1980), Cravens et al. (1981), and Fox (2007) constructed models at 90° SZA.

The nomenclature of the electron density peaks and regions that we use here for the sunlit ionospheres is based on the sources of ionization, and is the same as that generally used for the terrestrial ionosphere (e.g., Bauer, 1973; Bauer and Lammer, 2004). The F_1 peak, which is the main peak on the Venus dayside, is formed from local ionization by absorption of solar photons in the main part of the extreme ultraviolet (EUV), and by electron-impact ionization by the concomitant photoelectrons produced. The major ions in this region are molecular ions, which are either produced directly, or are formed by transformations via ion–molecule reactions. The "terminal ions" are those that are ultimately destroyed by dissociative recombination. The F_2-region is found higher in the dayside ionosphere than the F_1 region, and it consists mainly of atomic ions. These ions are destroyed below their peaks by ion–molecule reactions, and above the peak by downward transport. At the F_2 peak, the time constant for loss by chemical reactions is equal to the time constant for loss by diffusion. Thus in the F_2 region, both chemistry and transport are important. Some authors have used the term "F_2-like" for molecular ion density profiles on the Venus nightside, since their densities are determined by both chemistry and diffusion. The *E* region on the dayside is below the F_1 region; its formation mechanisms are photoionization by soft X-rays, and by the energetic photoelectrons and secondary electrons that are produced. In the dayside F_1 and *E* regions, the ions are in photochemical equilibrium (PCE). Ions in the *D* region are produced by absorption of very hard X-ray photons, usually those with wavelengths less than 10 Å, but mostly by ionization by the very energetic photoelectrons, Auger electrons, secondary electrons, and further ionizing electrons that are produced by ionization by hard X-rays. In the *E* and *D* regions electron-impact ionization is more important than photoionization.

We have recently investigated the near terminator ionosphere of Venus on the dayside for SZAs between 60° and 85° in 5° increments and from 86° to 90° in 1° increments (Fox, 2007). In this model, the altitude of the F_1 peak remained near 140 km from 60° to 75° SZA; the *E*-region peak or shoulder remained near 125 km over this SZA range. From 80° to 90° SZA the F_1 peak was predicted to rise from 141 to 149 km and the *E*-region peak or shoulder was predicted to rise from 128 to 135 km. The dayside model F_1 peak altitudes generally agreed with the data, except very near the terminator. The measured n_e peaks on the deep nightside appeared at 142 ± 4.1 km (Cravens et al., 1981; Kliore et al., 1979a).

The nearly constant altitude of the n_e peak on the dayside as a function of SZA shows that the neutral densities in this region decrease enough to offset the larger slant path through the atmosphere, as suggested by Cravens et al. (1981). The data show that between solar zenith angles of 70° and 85°, the peaks of the electron density profiles measured by the PV ORO decrease in altitude to about 135 km, but then rise sharply to altitudes of 147–159 km