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Near-terminator Venus ionosphere: How Chapman-esque?

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[1] We have modeled the near-terminator ionosphere of Venus for solar zenith angles $\chi$ between 60 and 85° in 5° increments, and from 86 to 90° in 1° increments. The most important neutral densities of the background thermospheres have been adopted from the VTS3 model of Hedin et al. (1983), which is based on densities from the Pioneer Venus (PV) Orbiter Neutral Mass Spectrometer (e.g., Niemann et al., 1980) that are normalized to the PV Orbiter Atmospheric Drag data (e.g., Keating et al., 1980). We compare the ion density profiles to those of a Chapman layer and to those obtained from radio occultation data. We determine the best fit values of $n_{\text{max},0}$ and $k$ in the Chapman expression $n_{\text{max}, \chi} = n_{\text{max},0} \cos(\chi)^k$ for each solar zenith angle interval; using a linear least squares regression for $\log n_{\text{max}, \chi}$ as a function of $\log \cos(\chi)$ we also derive the best fit values for the group of ten models for solar zenith angles from 60 to 89°. For a theoretical Chapman layer with plane parallel geometry, $k = 0.5$, and $n_{\text{max},0}$ is the peak electron density at the subsolar point. In the near-terminator region, the production rates and densities must be computed using spherical geometry, and this alone will cause the derived value of $k$ to be reduced below the theoretical factor of 0.5. For the solar zenith angle models in the range 60–85°, we find that the magnitudes of the both the main ($F_1$) and lower ($E$) peaks decrease as the solar zenith angle increases in a somewhat Chapman-like manner, but the altitudes of the $F_1$ and $E$ peaks increase only slowly from 140 to 144 km and from 125 to 129.5 km, respectively. The nearly constant altitude of the $F_1$ peaks has been attributed to the collapse of the thermosphere as it merges into the nighttime cryosphere (Cravens et al., 1981). This behavior is quite different from that of Mars, where the electron density peak altitudes have been observed to rise monotonically as the solar zenith angle increases. The predicted behavior for the Venus ionosphere is in general agreement with radio occultation data, but some differences also are observed. We discuss the differences between the modeled and observed peak altitudes and we attribute the differences partly to deficiencies in the VTS3 models and partly to uncertainties in the electron temperatures. There also may be some errors introduced into the radio occultation profiles in the very near-terminator region due to deviations from spherical symmetry. In addition, differences exist between the measured and model peak magnitudes at solar zenith angles near 60° that we ascribe partly to the use of the S2K v2.22 solar flux model of Tobiska (2004), for which the EUV and soft X-ray photon fluxes are significantly smaller than those of the S2K v1.24 or the Hinteregger solar flux models.


1. Introduction

[2] The electron density profiles in the Venussian ionosphere have been measured by many spacecraft beginning with the profile returned from Mariner 5 [Kliore et al., 1967], and from several subsequent spacecraft (see, for example, the introduction in the paper by Kliore and Luhmann [1991]). The Mariner 5 egress profile, for which the solar zenith angle (SZA) was $\approx 33^\circ$, exhibited two peaks: an upper peak near 140 km, characterized by a density of $\approx 5.5 \times 10^5$ cm$^{-3}$, and a lower peak near 125 km, characterized by a density of $\approx 2 \times 10^7$ cm$^{-3}$. We will here refer to the upper peak as an $F_1$ peak, and to the lower peak as an $E$ peak. This convention is the same as that adopted by Bauer [1973] and by Banks and Kockarts [1973] for the terrestrial ionosphere. The sources of the $F_1$ peak are photoionization by EUV photons with wavelengths of $\approx 150–1000$ Å and the concomitant......
photoelectron impact ionization. The $E$ peak arises from the absorption of solar soft X-ray photons followed by ionization by the high energy photoelectrons and secondary electrons that are produced. In the terrestrial ionosphere, ionization of $O_2$ by solar Lyman $\beta$ at 1026 Å contributes to the $E$ peak, but this source is not important in the ionosphere of Venus, where $O_2$ is a minor constituent. For the lower peak, electron-impact ionization dominates, while for the upper peak, photoionization is more important [cf. Fox and Sung, 1997]. This behavior is also seen on Mars [e.g., Fox, 2004; Fox and Yeager, 2006].

[3] Measurements by instruments on the Pioneer Venus (PV) spacecraft, which orbited the planet from 1978 to 1992, have provided the most comprehensive description of the thermosphere/ionosphere to date. The PV Orbiter Neutral Mass Spectrometer (ONMS) provided data about the thermospheric neutral densities at high solar activity [e.g., Niemann et al., 1980]. These densities were normalized to the mass densities derived from the PV Orbiter Ion Drag (OID) measurements [e.g., Keating et al., 1980]; a global model of the thermospheric densities, the VTS3 model, was developed by Hedin et al. [1983] using this data. During the initial phase of the mission, which was at fairly high solar activity, the PV Orbiter Ion Mass Spectrometer (OIMS) provided information about the composition of the ionosphere [e.g., Taylor et al., 1980]. There are no in situ data on the dayside about either the ions or the neutrals at low solar activity from PV measurements. The PV Orbiter Radio Occultation (ORO) experiment, however, provided electron density profiles throughout the 14 years of the mission, which encompassed the whole range of solar activity [e.g., Kliore and Mullen, 1989; Kliore, 1992; Fox and Kliore, 1997].

[4] The Venus ion and electron density profiles have been modeled by many investigators over the last 28 years [e.g., Chen and Nagy, 1978; Nagy et al., 1980, 1983; Cravens et al., 1981; Fox and Dalgarno, 1981; Fox, 1982; Kim et al., 1989; Cravens, 1992; Shinagawa et al., 1991; Fox and Kliore, 1997]. Fox and Sung [2001] modeled solar activity variations of the Venus thermosphere/ionosphere for neutral density profiles based on the VTS3 model for equatorial latitudes, and a solar zenith angle of $\sim 60^\circ$. Although the early ORO data applied largely to higher latitudes, the VTS3 model is most accurate for near equatorial latitudes, where the bulk of the in situ data was taken.

[5] Several textbooks have described Chapman layer theory [Chapman, 1931a] specifically for ionospheres [e.g., Rishbeth and Garriott, 1969; Bauer, 1973; Banks and Kockarts, 1973; Schunk and Nagy, 2000], so our description here will be brief. A Chapman ion layer is one that is produced in an isothermal thermosphere that is characterized by a temperature $T_e$. The ions are produced by photoionization of a single molecular species, XY, by monochromatic radiation with a photon flux at the top of the atmosphere $F_\infty$ and a production rate $q_i(z)$, where $\chi$ is the solar zenith angle. The resulting molecular ion is destroyed locally by dissociative recombination: $XY^+ + e \rightarrow X + Y$, with a rate coefficient $\alpha_{dr}$. If $z = 0$ is defined as the altitude of maximum ionization for overhead sun, it can be shown that the maximum rate of ionization at the subsolar point ($\chi = 0$) is

$$q_{max,0} = \frac{F_\infty}{e} \frac{\sigma_i}{e^{\chi/T_e}},$$

where $H$ is the (constant) neutral pressure scale height, and $\sigma_e$ and $\sigma_i$ are the photoabsorption and photoionization cross sections, respectively [e.g., Bauer, 1973].

[6] In a Chapman layer photochemical equilibrium (PCE) prevails, so the production rate of the ions is equal to the loss rate due to dissociative recombination:

$$q_i(z) = \alpha_{dr} n_i(z) \sigma_i(z) = \alpha_{dr} [n_i(z)]^2,$$

where the ion density, $n_i(z)$, is equal to the electron density, $n_e(z)$. The ion or electron density in a Chapman layer for a solar zenith angle $\chi$ is given by

$$n_i(z) = \left[ \frac{q_i(z)}{\alpha_{dr}} \right]^{1/2} = \left[ \frac{q_{max,0}}{\alpha_{dr}} \right]^{1/2} \exp \left[ 1 - \frac{z}{2H} \right].$$

As equation (3) shows, the maximum ion density for overhead sun ($\chi = 0, z = 0$) is given by

$$n_{i, max,0} = \left[ \frac{q_{max,0}}{\alpha_{dr}} \right]^{1/2},$$

and is proportional to $(F_\infty)^{1/2}$. The maximum ion density for a solar zenith angle $\chi$ is

$$n_{i, max,\chi} = n_{i, max,0} (\cos \chi)^k$$

where $k$ is 0.5 for a Chapman layer.

[7] The actual ion density profiles are expected to differ from the ideal Chapman profiles for several reasons. The values of $T_e$ increase with altitude from the mesopause to the middle thermosphere, and reach constant values $T_e$ only near 200 km. The pressure scale height $H$ and the number density scale height $H_n$ are equal in a Chapman layer, but for a real atmosphere $H = kT/m_g$ should be replaced by $H_n$. The relationship between $H$ and $H_n$ (neglecting thermal diffusion) is

$$\frac{1}{H_n} = \frac{1}{H} + 1 \frac{dT_e}{T_e} dz,$$

where all of the quantities in equation (6) are altitude dependent.

[8] Electrons are produced by photoionization of a number of different species, which are characterized by different values of the cross sections, $\sigma_e$ and $\sigma_i$, over a range of photon wavelengths from Lyman alpha to the EUV to the soft and hard X-ray regions, all of which reach unit optical depth at different altitudes. The altitudes of optical depth unity for solar zenith angles of 60, 80, 85, 86, 87, 88, 89, and 90° over the wavelength range 0–2000 Å for our high solar activity models in the Venus thermosphere are shown
in Figure 1. In general, the altitudes of unit optical depth in the \(150–1000\ \text{Å}\) range show where the photoabsorption rates should peak. It is clear from this figure that the altitudes of unit optical depth in the models vary little from 60 to 80° SZA, but they rise at a significantly greater rate from 85 to 90° SZA.

Another difference between a real ionospheric layer and an ideal Chapman layer is that photoionization is supplemented by photoelectron-impact ionization. Because the more energetic photons penetrate to lower altitudes, the electron-impact ionization rates usually peak lower in the ionosphere than do those due to photoionization. In addition, in electron-impact ionization, the electrons are slowed down, but not extinguished, as are photons in photoionization.

The major ion produced near the ion peak in the Venusian ionosphere, \(\text{CO}_2^+\), is mostly transformed by reaction with \(\text{O}\) to produce \(\text{O}_2\) before it can recombine dissociatively. At very low and high altitudes, the major ion produced is \(\text{O}^+\), which, in the photochemical equilibrium region is also transformed to \(\text{O}_2\) by reaction with \(\text{CO}_2\). The rate coefficient for dissociative recombination is not a constant, but generally depends on the specific ion and on the value of \(T_e\). For \(\text{O}_2\), the major ion in the Venus ionosphere, our adopted values for \(\alpha_{dr}\) are \(1.95 \times 10^{-7}(300/T_e)^{0.56} \text{cm}^3\ \text{s}^{-1}\) for \(T_e < 1200\ \text{K}\), and \(7.4 \times 10^{-7}(1200/T_e)^{0.56}\) for \(T_e > 1200\ \text{K}\) [Alge et al., 1983; Mehr and Biondi, 1969]. Unlike a Chapman layer, the background atmosphere is not constant with solar zenith angle, and the variations in the VTS3 models are incorporated into our models. In addition, the assumption of PCE breaks down at altitudes above \(\sim 200\ \text{km}\). These differences will broaden the peak of the ion density profile, and shift the altitude of the maximum away from the maximum in the photoionization rate profile.

Finally, the version of Chapman layer theory described by the equations that we have presented applies only to plane parallel atmospheres. For grazing incidence, the sec \(\chi\) (or inverse cos \(\chi\)) is sometimes replaced with a Chapman Function \(Ch(x, \chi)\) [e.g., Chapman, 1931b] where \(x = R/H_n\), and \(R\) is the distance from the center of the planet. The Chapman function has been approximated by various combinations of analytical functions [e.g., Chapman, 1931b; Rishbeth and Garriott, 1969; Bauer, 1973]. Chapman functions are not often used in models because of the ease of computing the column densities for spherical geometry numerically, as described, for example, by Rees [1989].

Using the SC21REFW and F79050N solar flux models for low and high solar activity, respectively, from H. E. Hinteregger (private communication, 1979) [see also Hinteregger et al., 1981; Torr et al., 1979], Fox and Sung [2001] showed that the model peak electron densities for a solar zenith angle of 60° vary approximately as the square root of the solar flux, in good agreement with a theoretical Chapman layer, as expressed by equations (1) and (3), and with the radio occultation data. The solar activity variation of some of the minor ion peak densities were predicted to be approximately proportional to the solar EUV photon flux, but the variations of the peak densities of ions whose parent neutrals were photochemically produced were predicted to be amplified over that of the solar flux by factors of 5–18. Thus there is a large solar cycle variation in the composition of the ionosphere, with atomic ions becoming more prominent at high solar activity. Fox and Sung did not, however, address the solar zenith angle variation of the ionosphere. We here model the high solar activity Venus ionosphere for solar zenith angles in the range 60 to 85° in 5° increments, and in the range 86 to 90° in 1° increments. We compare the predicted ion density profiles to Chapman layers and to radio occultation data. Because we are modeling the near-terminator ionosphere, we compute the photoproduction rates numerically using spherical geometry. We find that, in fairly good agreement with PV ORO data, the relative magnitudes of the total ion density peaks are approximately Chapman-like, but the altitudes of the peaks remain near 140 km for the models from 60 to 80° SZA. For solar zenith angles from 85 to 90°, the peak rises from 144 to 149 km. We show also that at the peak of the 90° SZA production rate profile, the major ion produced is \(\text{O}^+\) rather than \(\text{CO}_2^+\). At the peak altitude of 149 km, however, PCE still prevails, and the \(\text{O}^+\) produced is transformed to \(\text{O}_2\) in the reaction with \(\text{CO}_2\).

2. Model

The background neural models for 60, 65, 70, 75, 80, 85, 86, 87, 88, 89, and 90° SZA consist of 12 species, including \(\text{CO}_2\), \(\text{Ar}\), \(\text{N}_2\), \(\text{O}\), \(\text{CO}\), \(\text{O}_2\), NO, N, C, He, H and H2. We have included photoionization, and electron impact ionization and excitation for each species, and photodissociation, photodissociative ionization, electron-impact dissociation, and electron-impact dissociative ionization for each molecule. For solar fluxes in the wavelength range from 18 to 2000 Å, we have adopted the Solar 2000 (S2K) 99178
v2.22 solar flux model of Tobiska [2004]. In this version of the model, the continuum fluxes are given at a 1 A resolution, and the strong solar lines are given as delta functions at the appropriate wavelengths. The 99178 model is characterized by an $F_{10.7}$ of $\sim 207$ and an 81-day average $F_{10.7}$ of 166, and is therefore appropriate to the first three seasons of the PVO spacecraft, which were at high solar activity, and for which the average values of $F_{10.7}$ were in the range 175–215.

The density profiles of CO$_2$, N$_2$, O, CO, N and He, and the neutral temperature profiles were taken directly from the VTS3 models of Hedin et al. [1983] for each SZA at equatorial latitudes. The eddy diffusion coefficient (in cm$^2$ s$^{-1}$) was assumed to be of the form $A/n^{0.5}$, where $n$ is the total neutral density (in cm$^{-3}$) and $A$ is a free parameter. The maximum eddy diffusion coefficient was assumed to be $4 \times 10^5$ cm$^2$ s$^{-1}$. For each model, the parameter $A$ was determined by equating the N$_2$ densities computed with eddy and molecular diffusion at 90 and 150 km to those generated by the VTS3 models. N$_2$ was chosen as a reference because its density profiles are not expected to be affected by photochemistry. The eddy diffusion parameters $A$ derived for each model are shown in Table 1, and are in the range $(7.5–9.3) \times 10^{12}$ cm$^2$ s$^{-1}$. These values are less than, but within a factor of 2 of the value $1.4 \times 10^{13}$ cm$^2$ s$^{-1}$ derived from the PV Bus Neutral Mass Spectrometer data by von Zahn et al. [1980].

The derived eddy diffusion coefficients were then used to construct the density profiles of O$_2$, Ar, NO, C, H and H$_2$. The density profiles of NO, N and C were computed self-consistently in the models, although for the photoabsorption calculations, we used the VTS3 model values for N. Fox and Sung [2001] showed that there is little difference between the computed N profiles at high altitudes for 60° and those specified in the 60° VTS3 models. The computed densities of N at high altitudes become increasingly smaller than those of the VTS3 models as the SZA increases. For the 90° SZA model the computed N density at 300 km is a factor of $\approx 7$ smaller than that of the VTS3 model. This discrepancy could be caused by a variety of factors, including the assumed eddy diffusion profile, and the chemistry of odd nitrogen near the peak.

Fortunately, the N density profiles are not expected to affect greatly the electron density peak.

Downward fluxes of NO and N are potential sources of odd nitrogen to the mesosphere, and the density profiles of NO were computed assuming downward fluxes at the lower boundary. No fine tuning was done, although the densities at the lower boundary were required to be positive. The downward fluxes of N that the model could accommodate were, however, found to be nearly zero. The downward fluxes of NO are shown in Table 1, and were in the range $(0.1–1.2) \times 10^4$ cm$^{-2}$ s$^{-1}$. The magnitude of the downward fluxes affects the density profiles only to within $\sim 2$ scale heights, about 7 km, above the lower boundary. Zero flux lower boundary conditions were adopted for C, and fixed densities for O$_2$, Ar, H and H$_2$. The O$_2$ mixing ratio of $3 \times 10^{-4}$ at the bottom of the model was adopted from the study of the C and C$^+$ densities in the Venus ionosphere of Fox and Paxton [2005]. At the bottom boundary, the 40Ar mixing ratio was taken to be 33 ppm [von Zahn et al., 1980; see also Fox and Sung, 2001]; the H$_2$ mixing ratio, $1 \times 10^{-7}$, was adopted from the model of Yung and DeMore [1982]. The densities of H at the bottom boundary were varied so that the densities near 165 km approximated those derived from the H$^+$ chemistry as a function of local time by Grebowsky et al. [1995]. Values near $1 \times 10^3$ cm$^{-3}$ were derived for solar zenith angles less than $\sim 88^\circ$. The H densities begin to increase sharply near and beyond the terminator. We imposed a value of $2 \times 10^3$ cm$^{-3}$ at 165 km for the 90° model. The nightside hydrogen bulge reaches values of $\sim 10^7$ to $10^8$ cm$^{-3}$ in the vicinity of 0400 local time.

Since we do not include full chemistry of H in our models, the densities of H at the bottom boundaries are rather ad hoc, and limited validity should be assigned to them. Altitude profiles of the resulting background neutral densities for the 60 and 90° SZA models are shown in Figure 2.

The lower boundaries for the computed ion densities and minor neutrals were located at 90 km for the 60–80° SZA models, at 95 km for the 85–88° models, and at 105 km for the 89 and 90° SZA models. The upper boundary was taken to be 400 km for the 60–80° SZA models, but was lowered to 380 km for the 85–88° SZA models, and to 360 km for the 89 and 90° SZA models. The variations of altitudes of the boundaries were necessary in order to overcome the effects of very small or zero computed ion production rates on the calculations of the density profiles in the models. In Table 1, we present the details of the various SZA models, including the exospheric temperatures (which are specified in the VTS3 models), the H densities at 165 km, the A values in the expression for the eddy diffusion coefficient derived as described above, and the assumed downward fluxes of NO and N at the lower boundary.

We compute here density profiles for 14 ions, including CO$_2$, Ar$^+$, N$_2$, O$(^3S)$, O$(^3D)$, O$(^3P)$, CO$^+$, C$^+$, N$^+$, NO$^+$, O$^+$, He$^+$, H$^+$, and 9 neutral species, including NO, N$(^5S)$, N$(^5D)$, N$(^2P)$, C, H, H$_2$, O$(^3D)$, and O$(^1S)$. We include molecular and eddy diffusion for the neutrals and ambipolar diffusion for the ions, except for O$^+$, which was assumed to be in photochemical equilibrium. Although the upper altitudes of the models for the predicted ions and minor neutrals is 360–400 km, in order to compute the local photon fluxes, we have extended the neutral background model to 700 km.
The models include 220 chemical reactions, with rate coefficients taken from those given by Fox and Sung [2001], and updates as given by Fox [2003, 2004]. The photoabsorption and photoionization cross sections are largely unchanged from those of Fox and Sung [2001], as are the electron impact cross sections. 

Miller et al. [1980] presented median altitude profiles of $T_e$ for $30^\circ$ SZA ranges from 0 to 180$^\circ$, based on early measurements of the PV Retarding Potential Analyzer (RPA). The values of $T_e$ were shown to be nearly identical for the SZA range of 0 to 90$^\circ$, but for 30$^\circ$ increments from 90 to 180$^\circ$ they increased monotonically for altitudes greater than \(~160$ km. We have adopted the altitude profiles for $T_e$ from Miller et al. [1980] for the 60$^\circ$ SZA model. We have estimated the values of $T_e$ for the 65–90$^\circ$ models at each altitude by computing the difference between the VTS3 neutral temperatures for the 60$^\circ$ model and that for the SZA in question, and adding that difference to the values of $T_e$ for the 60$^\circ$ model. This somewhat arbitrary method has the advantage that the values of $T_e$ and $T_i$ in all the models are equal in the lower thermosphere, and the values of $T_e$ at higher altitudes are equal to or larger than those of $T_i$. Since the values of $T_e$ do not vary substantially from 60 to 90$^\circ$ in the VTS3 model, the ion temperature profiles are all similar to those for 60$^\circ$ SZA.

The $T_e$ profiles were constructed in the following way. The value of $T_e$ was first assumed to be equal to that $T_i$ below 140 km. Above 140 km, the electron temperature was computed using the formula

$$T_e(z) = 4500 + [T_i(140) − 4500] \exp[(140 − z)/76].$$  

In order to minimize the effects of slope discontinuities at 140 km the profiles were then smoothed by an exponential fit between 130 and 150 km. This resulted in electron temperatures above 145 km that were in fairly good agreement with those measured by the PV Langmuir probe, as presented by Theis et al. [1984]. We note here, however, that the values of $T_e$ in the Venus ionosphere have been found to be partly controlled by the interaction of the ionosphere with the solar wind [e.g., Brace et al., 1980], and with the presence or absence of an induced magnetospheric field [e.g., Dobe et al., 1993]. An inverse correlation between $n_e$ and $T_e$ in the Venus ionosphere has been found by Knudsen et al. [1979], Dobe et al. [1993] and Mahajan et al. [1994]. Thus the potential variability of the $T_e$ profiles is a significant source of uncertainty in the model. The $T_e$, $T_i$, and $T_o$ values adopted for the 60 and 90$^\circ$ SZA models are shown in Figure 3.

For the computed ion density profiles (other than O$^{++}$), we have adopted fixed densities at the lower boundaries of the model, and zero-flux conditions at the upper boundaries. In some 1-D models, upward fluxes of the order of $3 \times 10^5$ cm$^{-2}$ s$^{-1}$ have been imposed on the ions [cf. Fox, 1992]. As for Mars, it should be noted that these upward fluxes in a 1-D model probably actually represent the divergence of the horizontal fluxes of ions at high altitudes [e.g., Shinagawa and Crayens, 1989]. Trans-terminator ion fluxes of $\sim 2 \times 10^5$ cm$^{-2}$ s$^{-1}$ have been measured by the PV RPA [e.g., Miller and Knudsen, 1987], and similar downward fluxes of ions on the nightside are necessary to account for the nightside ionosphere [e.g., Brace et al., 1982; Fox, 1992; Brannon and Fox, 1994; Dobe et al., 1995; Fox and Kliore, 1997]. The nature of the top boundary conditions is not expected to affect the altitude or magnitude of the $F_1$ and $E$ peaks, since they appear in the region between 125 and 149 km. This subject will be investigated in a future publication (J. L. Fox, manuscript in preparation, 2007).

### 3. Results and Discussion

In Figure 4, we present the photoionization and electron impact ionization rate profiles for all the models. As is clear from the figures, there is little difference between
the shapes of the profiles for the various solar zenith angles from 60 to 90° SZA, but the production rates are smaller for larger solar zenith angles. The production rate profiles show upper peaks in the range 139–149 km for photoionization, and in the range 135–144 km for electron impact ionization. For both the photoionization and electron impact ionization profiles, lower peaks or shoulders are observed in the range 125–135 km. One notable difference between the profiles for the two production mechanisms is that, in the electron impact ionization rate profile, the magnitude of the lower peak is nearly equal to that of the upper peak, whereas only a lower shoulder is visible in the photoionization rate profiles. We note here that we have identified the altitude of a shoulder in an altitude profile as that for which the difference between the adjacent values is a minimum. Thus, since our altitude increment is 1 km, a shoulder may be located at the nearest half kilometer, but high accuracy is not assigned to this value.

The altitude profiles of the production rates for the 60 and 90° SZA models are shown in Figures 6 and 7, respectively. In the 60° SZA model, the major ion produced from photoionization near the upper peak at ~139 km is CO$_2^+$, but that at the lower peak near 126 km is O$^-$. There the major source of O$^+$ is dissociative ionization of CO$_2$. The major ion produced by electron impact ionization is CO$_2$ for both the upper and lower peaks. Both peaks appear in the PCE region, and the peak loss rates are near the altitudes of peak production. The altitudes above which total production of O$^-$ exceeds that of CO$_2$ ranges from 153 to 150 km for the 60–85° SZA models, and from 149 to 147 km for the 86–90° SZA models. For the 89 and 90° SZA models the major ion produced at the ion density peak is O$^+$. Since PCE prevails here, the O$^+$ produced is also transformed to O$_2$ in this region also. Thus the chemistry at the 89 and 90° SZA model $F_1$ peaks differs from that at the $F_1$ peaks in the smaller SZA models.

The predicted major ion density profiles for the 60° and 90° models are shown in Figure 8. For the 60° SZA model, O$_2^+$ is the major ion in the lower ionosphere, near 140 km, with O$^+$ becoming more important near 191 km. At 90° SZA, O$_2^+$ is also the major ion near the ion peak at 149 km, and the O$^+$ densities exceed those of O$_2^+$ above ~174 km.

Figure 3. Neutral, ion, and electron temperature profiles assumed in the 60 and 90° SZA models. The solid curves are for the 60° model, and the dashed curves are for the 90° model.

Figure 4. Altitude profiles of the ionization rates for all the models: (top) photoionization rate profiles and (bottom) electron impact ionization profiles. The curves are, in order of decreasing peak ionization rate and increasing peak altitude, those for 60, 65, 70, 75, 80, 85, 86, 87, 88, 89, and 90° SZA.
Figure 5. Altitude profiles of the total ion production rates and total densities of ions for all the models: (top) total production rates and (bottom) total ion or electron densities. The curves represent, in order of decreasing peak value and increasing peak altitude, those for 60, 65, 70, 75, 80, 85, 86, 87, 88, 89, and 90° SZA.

At altitudes above the O\(^+\) peaks, the O\(^+\) ions are lost by downward diffusion, rather than by chemical reactions. The altitudes of the peak densities of O\(^+\) range from 209 to 188 km for the 60–90° SZA models, with decreasing magnitudes of \((8.9–4.3) \times 10^4\) cm\(^{-3}\). The model electron density profiles from 60 to 80° SZA show a hint of an \(F_2\) peak near the O\(^+\) peak, but none is evident for larger solar zenith angles.

In Figure 9, we show the computed \(F_1\) and \(E\) peak densities as a function of \(\cos \chi\) for all the models. As expected, the predicted peak densities decrease with increasing SZA. In Figure 10, we present the altitudes of the \(F_1\) and \(E\) peaks as a function of SZA. The predicted altitudes of the \(F_1\) peak densities are fairly constant from 60 to 80°, but there is a sharp rise in the altitude of the peak for the 85–90° SZA models. Slightly different behavior is actually seen in the radio occultation data, as shown in Figure 11, which is taken from Cravens et al. [1981]. As the right side of the figure shows, the data from PV measurements exhibit slowly increasing main peak altitudes from \(\sim 25°\) to 70° SZA, which are, however, close to 140 km, as are our models for 60–70° SZA. A slight decrease to about 135 km in the altitude of the \(F_1\) peak electron density appears in the PV data (but not in the low solar activity the Venera data [e.g., Ivanov-Kholodny et al., 1979]) as the SZA increases from 70 to 85°, which our models do not reproduce. The simplest explanation of the discrepancies is that the actual neutral atmospheres in the 75–85° SZA range “collapse” more rapidly than do the VTS3 models. A calculation shows that the peak altitude for an 85° SZA model appears lower by \(\sim 4\) km if the VTS3 densities are reduced by a factor of 2. Another factor that could contribute to lowering the peak altitudes is that the actual values and gradients of \(T_e\) may be smaller than those that those we have assumed in our models.

Finally, a sharp increase in the \(F_1\) peak altitude is seen in the PV data for solar zenith angles greater than 85°: for solar zenith angles of 90–96°, the peak altitude appears in the range of \(\sim 147\) to 157 km, with error bars of 1–2 km [Cravens et al., 1981]. In our 90° SZA model, the peak is near 149 km, and thus is in acceptable agreement with the data.

In Figure 12, we show a plot of the log of the \(F_1\) and \(E\) peak densities as a function of log \(\cos \chi\) for the models from 60 to 89° SZA. We carried out linear least squares regressions to determine the slopes \(k\) and intercepts \(n_{max,0}\). For the \(F_1\) and \(E\) peaks, the best fit values of \(k\) are 0.39 and 0.35, respectively. As mentioned before, \(k = 0.5\) for the version of Chapman theory expressed by equations (3) and (5), which applies to plane parallel geometry. For solar zenith angles of 60° or more, it is necessary to use spherical geometry to determine the photoionization and photoabsorption rates. In the near terminator region, the value of \(k\) should be less than 0.5 due to the effect of spherical geometry alone. In fact, for a constant background atmosphere, the value of \(k\) should decrease as the solar zenith angle increases due to the increasing importance of spherical geometry as the terminator is approached. Table 3 shows, however, that the predicted values of \(k\) for both peaks remain fairly constant for the five SZA intervals between 60–65° and 80–85°, showing near Chapman behavior. For the SZA intervals from 85–86° to 88–89°, however, the predicted values of \(k\) in general decrease rapidly. For the latter SZA interval, the values of \(k\) are very small, \(\sim 0.22\) and \(\sim 0.166\), for the \(E\) and \(F_1\) peaks, respectively.

The best fit subsolar peak densities \(n_{max,0}\) from the linear regression for the models for the SZA intervals from 60–65° to 80–85° are \((5.5 \pm 0.2) \times 10^7\) cm\(^{-3}\) and \(2.8 \pm 0.1) \times 10^7\) cm\(^{-3}\) for the \(F_1\) and \(E\) peaks, respectively. Table 3 shows that the predicted values of \(n_{max,0}\) decrease substantially for the SZA intervals greater than 85–86°. Thus very near the terminator, the model values of \(k\) and \(n_{max,0}\) are not “Chapman-like”. The apparently anomalous values of \(k\) and \(n_{max,0}\) for the \(E\) peak in the range 85–86° are probably due to the departure of \(T_e\) from \(T_n\) at the peak altitude of 131 km of the 86° SZA model.

In Table 3, we present also the neutral and electron temperatures at the \(E\) and \(F_1\) peaks, along with the number density and pressure scale heights. As pointed out previ-
ously, in a Chapman layer, if the altitude dependence of the acceleration of gravity \( g \) is ignored, the pressure scale height, which is given by the expression \( H = k T m g \), where \( m \) is the mass of the single constituent, is a constant and is equal to the neutral number density scale height, \( H_n \). As equation (6) shows, however, \( H_n(z) \) depends not only on the neutral temperature, but on its altitude gradient, the acceleration of gravity, \( g(z) \), and the average mass \( m_n(z) \), none of which is constant over the ionospheric layer. For the model values shown Table 3, \( H_n \) is computed numerically and is based on the sum of the densities of all 12 species as a function of altitude, while \( H \) is computed as \( k T m g \), where \( m_n \) is the average mass of the neutral constituents.

34] The neutral temperatures at the \( E \) peaks in the models decrease monotonically as the SZAs increases from 60 to 90°, and the values of \( H_n \) decrease from 60 to 85° SZAs, but are fairly constant from 86 to 90°. This behavior reflects small compensating changes in atmospheric composition at the altitude of peak production, in which O and other light species become more important as the altitude increases. Because the temperature gradients are small near the lower peak, the values of \( H_n \) and are close to the values of \( H \) over the whole range.

35] At the model \( F_1 \) peak, the neutral temperatures at the peaks decrease from 60 to 80° SZAs, and the values of the scale heights tend to follow the \( T_n \) variations in this SZA range. At larger solar zenith angles, however, the average mass at the \( F_1 \) peak decreases by a larger amount than for the lower \( E \) peak. For solar zenith angles of 85 to 90°, the temperature at the peaks increases and the average mass decreases, causing both the number density and the pressure scale height to increase. O becomes more important than CO\(_2\) at altitudes that range from 149 km at 60° SZA to 145 km at 90° SZA. The density of O exceeds that of CO\(_2\) below the \( F_1 \) peak for solar zenith angles greater than 88°. The \( T_n \) gradients are larger at the \( F_1 \) peaks than at the \( E \) peaks, and therefore the differences between the values of \( H \) and \( H_n \) are significant. Table 3 shows that \( H \) exceeds \( H_n \) by factors that range from \( \sim 10 \) to \( \sim 20 \% \) at the \( F_1 \) peaks, and by factors of only about 2.5% at the \( E \) peaks.

36] The electron temperatures at both the \( E \) and the \( F_1 \) peaks remain fairly constant from 60 to 80° SZAs. For solar zenith angles greater than 85°, the values of \( T_e \) increase monotonically for both peaks. As explained previously, the rate coefficients for dissociative recombination of molecular ions decrease with increasing \( T_e \). Thus larger values of \( T_e \) will lead to larger peak densities. This will tend to weaken the dependence of the peak density on SZA, and lead to smaller values of \( k \) than that of a Chapman layer.

37] Cravens et al. [1981] fitted the main peak densities from the radio occultation data to Chapman layers, and predicted subsolar electron densities of \( 5 \times 10^5 \) and \( 7.3 \times 10^5 \text{ cm}^{-3} \), for low and high solar activity models. Our maximum predicted subsolar main peak density for our high solar activity model, \( 5.7 \times 10^5 \text{ cm}^{-3} \), is, however, significantly smaller than that determined by Cravens et al. [1981]. In addition, they showed measured peak electron densities at 60° SZA of about \( 4.7 \times 10^5 \text{ cm}^{-3} \) at 140–141 km. Our 60° model value exhibits a slightly smaller peak electron density of \( 4.2 \times 10^5 \text{ cm}^{-3} \) at an altitude of 140 km. We attribute these discrepancies between the peak values at least partially to the use of the S2K v2.22 models, for which the EUV and soft X-ray fluxes are smaller than those of the S2K v1.24 models, and than those of the Hinteregger models that we have used in the past. For example, Fox and Sung [2001] predicted a high solar

### Table 2. Predicted Peak Altitudes for the Photoionization, Electron Impact Ionization, and Total Ionization Rates, the Total Ion Density Peak Altitudes, and Magnitudes for the \( E \) and \( F_1 \) Regions as a Function of Solar Zenith Angle \( \chi \)

<table>
<thead>
<tr>
<th>SZA ( \chi )</th>
<th>Photo Production, km</th>
<th>Electron Impact Production, km</th>
<th>Total Production, km</th>
<th>Density Peak Altitudes, km</th>
<th>Peak Densities, cm(^{-3} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>60°</td>
<td>125.5</td>
<td>125</td>
<td>125</td>
<td>125</td>
<td>2.0(5)</td>
</tr>
<tr>
<td>65°</td>
<td>125.5</td>
<td>126</td>
<td>126</td>
<td>126</td>
<td>1.85(5)</td>
</tr>
<tr>
<td>70°</td>
<td>126.5</td>
<td>127</td>
<td>127</td>
<td>127</td>
<td>1.66(5)</td>
</tr>
<tr>
<td>75°</td>
<td>127.5</td>
<td>128</td>
<td>128</td>
<td>128</td>
<td>1.45(5)</td>
</tr>
<tr>
<td>80°</td>
<td>128.5</td>
<td>128</td>
<td>128</td>
<td>128</td>
<td>1.2(5)</td>
</tr>
<tr>
<td>85°</td>
<td>130.5</td>
<td>130</td>
<td>130</td>
<td>129.5</td>
<td>8.6(4)</td>
</tr>
<tr>
<td>90°</td>
<td>135.5</td>
<td>135</td>
<td>135</td>
<td>135</td>
<td>4.6(4)</td>
</tr>
<tr>
<td>95°</td>
<td>141.5</td>
<td>141</td>
<td>141</td>
<td>141</td>
<td>2.7(5)</td>
</tr>
<tr>
<td>100°</td>
<td>147.5</td>
<td>147</td>
<td>147</td>
<td>147</td>
<td>1.4(5)</td>
</tr>
<tr>
<td>105°</td>
<td>153.5</td>
<td>153</td>
<td>153</td>
<td>153</td>
<td>1.2(5)</td>
</tr>
</tbody>
</table>

*Read as \( 2.0 \times 10^5 \).*
activity 60° SZA peak electron density of $4.7 \times 10^5 \text{cm}^{-3}$ for a slightly different model based on the Hinteregger 79050N fluxes; the predicted peak electron density for the same neutral model and the analogous S2K v1.24 79050 fluxes was $5.6 \times 10^5 \text{cm}^{-3}$, and that for the S2K v2.22 79050 fluxes was $4.3 \times 10^5 \text{cm}^{-3}$. Similar discrepancies have been found for Mars [cf. Fox, 2004; Fox and Yeager, 2006].

[38] Our 90° SZA model is, however, characterized by an $F_1$ peak density of $1.21 \times 10^5 \text{cm}^{-3}$, which is larger than the average peak density of $0.9 \times 10^5 \text{cm}^{-3}$ of the six PV ORO profiles presented by Kliore et al. [1979] and Cravens et al. [1981], that were characterized by solar zenith angles between 89 and 91°. A reduction in the value of $T_e$ from 647 K to 300 K at the $F_1$ peak of the 90° SZA model would cause an increase in the dissociative recombination coefficient by a factor of $1.7$. This would lead to a reduction in the predicted electron density peak by a factor of about $0.76$ to values near $0.92 \times 10^5 \text{cm}^{-3}$, in substantial agreement with the data. Such small values of $T_e$ are difficult to reconcile, however, with the nearly SZA invariant median values of $T_e$ measured by the PV Langmuir probe near 147.5 km of $\sim940 \text{ K}$ presented by Theis et al. [1984; see also Theis et al., 1980], or that from the PV RPA data, [Miller et al., 1980], which showed a sharp increase in the altitude profile of the median values of $T_e$ near periapsis that was largely SZA invariant. The average electron temperatures at 150 km in the 80–90 and 90–100° SZA ranges are 800 and 1000 K, respectively, according the Venus International Reference Ionosphere [Bauer et al., 1985].

[39] We can also compare our model results for both peaks to the PV ORO profiles from 14 of the first 26 PV orbits, as reported by Kliore et al. [1979]. These orbits were among those listed by Cravens et al. [1981], although in their investigation they did not identify or model the
89–90° SZA models are larger, in the range \((4.6–5.7) \times 10^5 \text{cm}^{-3}\), and higher, at altitudes of 134.5 to 135.5 km.

It is possible that the discrepancies arise because the PV ORO data presented by Kliore et al. [1979], and the very large SZA ORO data presented by Cravens et al. [1981] were at high latitudes, and the VTS3 models that we have used pertain to equatorial latitudes. To test this hypothesis, we have constructed a 90° SZA polar model based on the VTS3 model. The exospheric temperature for this model, 250 K, is significantly lower than that for the equatorial 90° SZA model, which is 291 K. The derived \(A\) factor for the eddy diffusion coefficient of \(9.5 \times 10^{12}\) and the downward flux of NO at 105 km of \(1 \times 10^7 \text{cm}^{-2} \text{s}^{-1}\) are, however, similar to those of the equatorial terminator model. The upper peaks in the production rate profiles of ions and in the ion density profiles are both near 149 km, and the peak ion density is \(1.22 \times 10^5 \text{cm}^{-3}\), which are nearly identical to our 90° SZA equatorial model values.

The electron density peak in the \(E\) region of the polar model is located at \(\sim 136.5\) km, and is characterized by a density of \(4.8 \times 10^4 \text{cm}^{-3}\). These values are also close to those of the 90° SZA equatorial model profiles, in which the electron density peaks near 135.5 km, with a magnitude of \(4.6 \times 10^4 \text{cm}^{-3}\). It is probable that the VTS3 model is, however, less accurate at high latitudes than at low.

Since the neutral density profiles in the Venus atmosphere are changing rapidly near the terminator, lack of spherical symmetry may also play a role in the discrepancies between the 90° SZA model and the RO data. The RO profiles average the electron densities over a distance of approximately \(L = (2\pi RH_\text{n})^{1/2}\). For 150 km, \(R = 6200\) km, \(H_\text{n} = \sim 7\) km, we find that \(L = 522\) km, and the RO densities represent an average over an angular range of \(\sim 5^\circ\). At 200 km, \(R = 6250\), \(H_\text{n} = \sim 17\) km, \(L = 817\) km and therefore the RO densities average over an angular range of about \(7.5^\circ\). Although these angular ranges might be insignificant for smaller solar zenith angles, where the ionosphere changes slowly as the SZA changes, the large change in

**Figure 8.** Density profiles for various ions for the 60° and 90° SZA models: (top) 60° SZA and (bottom) 90° SZA. Note that the density profiles for \(N^+\) and \(C^+\) are nearly coincident. The \(N^+\) densities are everywhere slightly larger than those of \(C^+\).
the thermosphere/ionosphere close to the terminator may result in a significant error in the electron densities derived from the ORO data.

[43] The near-terminator model variation of $n_{\text{max}}$ with solar activity is slightly different from that derived from the peak electron densities at Venus as a function of $F_{10.7}$ by Kliore and Mullen [1989]. Kliore and Mullen analyzed 115 radio occultation profiles from the PV ORO. They derived an equation that represents a best fit to the $F_{1}$ peak electron densities as a function of solar activity and $c$:

$$n_{\text{max}} = \left( 5.92 \pm 0.03 \right) \times 10^{5} \left( F_{\text{euv}} / 150 \right)^{0.376 \pm 0.011} \cdot \left( \cos c \right)^{0.511 \pm 0.012} ,$$

where $F_{\text{euv}}$ is an estimated value of $F_{10.7}$ corrected to the position of Venus. Note that the exponent of $\cos c$, $(0.511 \pm 0.012)$, is apparently “Chapman-like”. This value is significantly larger than the exponent that we derived, using a linear least square regression fit for all the models, of 0.39, in part because the range of solar zenith angles included by Kliore and Mullen [1989] was larger than that in our study, and the plane parallel approximation is fairly accurate for solar zenith angles less than 60°. The $F_1$ peak density for an $F_{10.7}$ value of 200 and an SZA of 60° computed from equation (8) is $\sim 4.6 \times 10^{5}$cm$^{-3}$, which is slightly larger than our model value of $4.2 \times 10^{5}$cm$^{-3}$. Once again, we may attribute this small discrepancy partly to the use of S2K v2.22 solar fluxes, rather than to the v1.24 solar fluxes [Tobiska, 2004] or the Hinteregger et al. [1981] fluxes that we have used previously, and partly to deviations of the electron temperatures from those in our model.

4. Summary and Conclusions

[44] We have constructed 11 moderately high solar activity models of the Venus ionosphere in the near equatorial region for the solar zenith angle range 60–85° in 5° increments, and for the solar zenith angle range of 86–90° in 1° increments. The background atmosphere consists of 12 species and is based on the VTS3 models of Hedin et al. [1983], for the appropriate latitude, local time, SZA and an $F_{10.7}$ of 200. Using the 99178 S2K v2.22 solar fluxes from Tobiska [2004], we compute the ion production rates and total ion (or electron) densities for each model. We compare the predicted total ion density profiles with theoretical Chapman profiles and with radio occultation data. We show that the magnitude of the $F_1$ peak density in our models decreases from $4.2 \times 10^{5}$ to $1.21 \times 10^{5}$cm$^{-3}$ as the solar zenith angle increases from 60 to 90°. The corresponding $E$ peak densities decrease from $\sim 2.0 \times 10^{5}$ to $\sim 4.6 \times 10^{4}$cm$^{-3}$.

Figure 10. Altitudes of the $F_1$ and $E$ peaks as a function of SZA for all the models. The filled circles are the $F_1$ peaks, and the open circles are the $E$ peaks.

Figure 11. Peak electron densities and altitudes for the $F_1$ peaks as a function of solar zenith angle from radio occultation data. (left) Peak densities as a function of SZA. The curves through the data are the best fits to Chapman equations for low and high solar activities. (right) Peak altitudes as a function of SZA for radio occultation data. Figure taken from Cravens et al. [1981].
Figure 12. Plot of model log peak densities as a function of $\log \cos \chi$. The circles represent the values in order of decreasing peak densities for the 60, 65, 70, 75, 80, 85, 86, 87, 88, and 89° models. The filled circles are for the $F_1$ peak, and the open circles are from the $E$ peak. The best fit values from a linear least squares regression for $k$ and $n_{\text{max},0}^e$ from equation (5) are also shown for both peaks.

[45] We also fit each SZA interval, except that for 89–90°, to the Chapman expression for the variation in peak density with solar zenith angle $\chi$, $n_{\text{max},x}^e = n_{\text{max},0}^e \cos(\chi)^k$. The model values of $k$ generally decrease with increasing SZA, as we expect for a spherical atmosphere. For the 65–70° to 88–89° SZA intervals, the derived values of $k$ are in the range $0.43$ to $0.166$ for the $F_1$ peak, and in the range $0.51$ to $0.22$ for the $E$ peak. There is probably more uncertainty in the model values of the $E$ peak, due to the difficulty of identifying the $E$ peak when it appears as a shoulder in our model, and to the larger uncertainties in the soft X-ray fluxes, which are responsible for production of the lower peak. The values of the predicted subsolar peak densities for the $F_1$ peak are nearly constant at $5.7 \times 10^5$ for solar zenith angles of 60 to 80°, but then decrease to $2.7 \times 10^5$ cm$^{-3}$ for the 88–89° SZA range. For the $E$ peak the predicted subsolar peak densities were also nearly constant at $(2.7-2.9) \times 10^5$ cm$^{-3}$ for solar zenith angles of 60 to 80°, but then decreased to $1.4 \times 10^5$ cm$^{-3}$ for the 88–89° interval. As would be expected, the model atmospheres for solar zenith angles less than 80° show more “Chapman-like” behavior.

[46] We also carried out a linear least squares regression for the 10 models from 60 to 89° SZA, to determine the best fit values of $k$ and $n_{\text{max},0}^e$ in equation (5). For the $F_1$ and $E$ peaks, the best fit values for $k$ were $0.39$ and $0.35$, respectively; the best fit values of the subsolar peak densities were $5.1 \times 10^5$ and $2.5 \times 10^5$ cm$^{-3}$, respectively. The value for the subsolar $F_1$ peak density is smaller than that derived by Cravens et al. [1981] of about $7.3 \times 10^5$ for high solar activity. This difference may be due in part to the use of smaller solar zenith angles in the fit, and in part to the use of the S2K v2.2 solar flux models, which exhibit significantly smaller fluxes in both the EUV and soft X-ray regions than the S2K v1.24 solar fluxes or those from Hinteregger et al. [1981] (also private communication, 1980), which we have used previously [cf. Fox and Yeager, 2006]. The S2K v2.2x flux models are normalized to measurements of the Thermosphere Ionosphere Mesosphere Energetics and Dynamics mission Solar EUV Experiment [e.g., Woods et al., 2000, 2005], and thus appear to be better for modeling the terrestrial ionosphere. It appears that the EUV fluxes are slightly too small, however, for models of the ionospheres of Venus and Mars.

[47] The value of $k$ for an ideal Chapman layer for a plane parallel atmosphere is 0.5. In the near-terminator region, the plane parallel approximation breaks down and the values for $k$ should be smaller than 0.5 and decrease monotonically as the terminator is approached, as the effect of spherical geometry becomes more important. Our values of $k$ are indeed mostly smaller than 0.5, and decrease as the SZA approaches 90°. In addition to the use of spherical geometry, variations of and uncertainties in the $T_e$ profiles may also play a role. Larger values of $T_e$ and larger $T_n$ gradients produce electron densities that are larger than those of a Chapman layer, and smaller decreases in peak densities as the SZA increases. In the models, the altitudes of the $F_1$ peaks increase only slightly from 140 to 141 km, and those of the lower $E$ peaks increase also from 125 to 128 km, as the SZA increases from 60 to 80°. As the SZA increases further from 85 to 90°, the altitude of the $F_1$ peak increases from 144 to 149 km, and the $E$ peak rises from 131 to 135.5 km. In the data presented by Cravens et al. [1981], however, the altitudes of the upper peak remain essentially constant at 140 km in the solar zenith angle range from 25 to 70° SZA, and then decrease slightly to about 135 km from 70 to 85° SZA. This non-Chapman behavior has been ascribed to the variations of the near-terminator thermosphere, in which the values of $H_n$ and $T_n$, and thus the neutral densities, decrease with increasing SZA. The daytime thermosphere essentially collapses as it merges into the nighttime cryosphere. In the PV data, the peak rises sharply to altitudes of about 147–150 km, with error bars of 1–2 km from 90 to 95° SZA. Apparently, the effects of grazing incidence become more important than the collapse of the thermosphere near and beyond the terminator.

[48] The VTS3 model apparently reproduces the expected behavior of the $F_1$ ionospheric peak altitude for solar zenith angles in the 60–70° range, and for solar zenith angles near 90°. For solar zenith angles of ~70–88°, the decrease in the altitude of the $F_1$ peak shows that the neutral densities apparently decrease more rapidly than the VTS3 model densities do. For example, for the 85° SZA model, if we decrease the neutral background densities by about a factor of 2, the computed peak altitudes are roughly in agreement with the data. There also may be some effect due to uncertainties in the values of $T_e$ and its gradients. The effect of increasing $T_e$ is to increase the model density and raise the peak $O_2$ density to slightly higher altitudes than those of peak production in the PCE region. There are only a few studies of $T_e$ as a function of SZA. In fact it appears that the median altitude profiles of $T_e$ are nearly SZA invariant [Miller et al., 1980; Theis et al., 1980, 1984; Bauer et al., 1985].

[49] At 89 and 90° SZA the $F_1$ peak production rate is still within the PCE region, but the major ion produced is an atomic ion, $O^+$, rather than a molecular ion. The $O^+$
produced is transformed to O$_3$ by reaction with CO$_2$. Thus the chemistry at the $F_1$ peaks for these two models are different from that of the other, smaller SZA models. The early electron density profiles near 90° SZA measured by the PV ORO as reported by Kliore et al. [1979] and by Cravens et al. [1981], exhibit peak densities that are slightly smaller than our model values. If we used different solar flux models than the S2K v2.22 model that we used, as the data for smaller solar zenith angles indicates, this discrepancy would be exacerbated. The differences are probably due to deficiencies in the near terminator VTS3 models, and in the electron temperature profiles that we have adopted. We are currently carrying out a comparison of the VTS3 models to the in situ ONMS data in the near terminator region (J. L. Fox, submitted manuscript, 2007).

[50] There also may be some error incurred in the analysis of the RO electron density profiles near the terminator because of the assumption of spherical symmetry. We show that, near the electron density peak, the RO measurements average over a $\sim$5° range of electron densities. Although this range may be insignificant at smaller solar zenith angles, the ionospheric electron densities may change so rapidly in the near-terminator region that the assumption of spherical symmetry becomes less valid.

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References


