jor ions from the upper regions of the dayside ionosphere followed by downward diffusion, and (iii) direct impact ionization by precipitating electrons or protons or both. The first of these suggestions can now be eliminated as the source responsible for the main density peak observed near 140 km, since the major ions at this altitude and higher have now been identified as O_2^+ and O^+ (*7*). Brace *et al.* (*8*) indicate that the second mechanism is still a possibility, and we show here that the third mechanism is consistent with the radio occultation observations and presents a viable explanation.

Using a nightside neutral density model consistent with Pioneer Venus in situ measurements (*9*), we calculated electron density profiles resulting from the precipitation of 30-, 75-, and 300-eV monoenergetic electrons (Fig. 4). The particle fluxes used were adjusted for each energy to give a peak electron density of 1.5×10^4 cm^{-3}, in agreement with the typical measured value at $\chi = 140°$. It is clear that 300-eV electrons penetrate too deeply, producing a maximum at about 130 rather than 140 km. However, Fig. 4 indicates that fluxes of about 10^8 cm^{-2} sec^{-1} of electrons with energies less than about 100 eV are capable of producing electron density profiles that agree with the observations. (Electrons with a bimodal energy spectrum could be responsible for the appearance of double-peaked ionospheric profiles.)

The ultraviolet airglow experiment and the plasma analyzer on the Pioneer Venus orbiter are expected to provide information on the viability of this proposed impact ionization mechanism. A preliminary sampling of plasma analyzer data (*5*) indicated the presence of electrons with energies of 20 to 250 eV inside the ionosphere with a downward flux of about 5×10^7 cm^{-2} sec^{-1} at an energy of 30 eV. If higher-energy electrons precipitated into the atmosphere at a shallow angle, they would also be able to produce ionization at the required altitude. At present, both impact ionization by precipitating particles and transport and diffusion of major ions are possible sources of the observed nightside ionosphere and may be occurring simultaneously.

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Empirical Models of the Electron Temperature and Density in the Nightside Venus Ionosphere

Abstract. *Empirical models of the electron temperature and electron density of the late afternoon and nightside Venus ionosphere have been derived from Pioneer Venus measurements acquired between 10 December 1978 and 23 March 1979. The models describe the average ionosphere conditions near 18°N latitude between 150 and 700 kilometers altitude for solar zenith angles of 80° to 180°. The average index of solar flux was 200. A major feature of the density model is the factor of 10 decrease beyond 90° followed by a very gradual decrease between 120° and 180°. The density at 150° is about five times greater than observed by Venera 9 and 10 at solar minimum (solar flux ≈ 80), a difference that is probably related to the effects of increased solar activity on the processes that maintain the nightside ionosphere. The nightside electron density profile from the model (above 150 kilometers) can be reproduced theoretically either by transport of O^+ ions from the dayside or by precipitation of low-energy electrons. The ion transport process would require a horizontal flow velocity of about 300 meters per second, a value that is consistent with other Pioneer Venus observations. Although currently available energetic electron data do not yet permit the role of precipitation to be evaluated quantitatively, this process is clearly involved to some extent in the formation of the nightside ionosphere. Perhaps the most surprising feature of the temperature model is that the electron temperature remains high throughout the nightside ionosphere. These high nocturnal temperatures and the existence of a well-defined nightside ionopause suggest that energetic processes occur across the top of the entire nightside ionosphere, maintaining elevated temperatures. A heat flux of 2×10^{10} electron volts per square centimeter per second, introduced at the ionopause, is consistent with the average electron temperature profile on the nightside at a solar zenith angle of 140°.*

Initial Pioneer Venus measurements (*1*) resolved the ion composition and ion and electron thermal structure of the daytime ionosphere at solar zenith angles (SZA) of about 70°. Since the time of these earlier measurements, periapsis has nearly completed its first movement through the nightside ionosphere. Thus direct measurements are now available from 70° SZA in the afternoon sector through 180° and back to about 120° on the dawn side. Brace *et al.* (*2*) used Pioneer Venus data from this period to define the global configuration of the ionopause across the nightside. We have employed orbiter electron temperature probe (OETP) data from these same orbits and a few more recent ones to construct empirical models of the electron density (N_e) and temperature (T_e) within the nightside ionosphere itself. These models describe the average conditions found in the region between 150 and 700 km and near 18°N latitude in the interval between 10 December 1978 and 23 March 1979. Although our goal in constructing these models was to provide a reference against which the spatial and temporal variations of the ionosphere might be resolved and studied, in this report we explore the implications of the models themselves for the maintenance and heating of the nightside ionosphere as a whole.

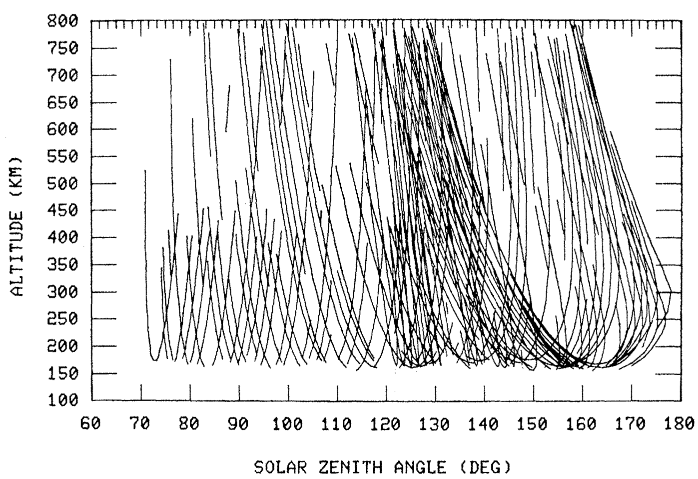
The operation of the OETP instrument was described elsewhere (*3*). Figure 1 shows the paths of the orbiter during the more than 120 periapsis passes employed in this study. Approximately 2700 values of T_e and N_e were measured along these orbits to define the models presented here. Although much higher spatial resolution is available from the onboard analysis provided by the OETP, we used only the results from the ground analysis of stored volt-ampere curves, as they provide sufficient resolution for our modeling purpose and have greater accuracy. We have not attempted to distinguish between measurements in the dusk-midnight and midnight-dawn sectors that cover the same solar zenith angles. We have combined inbound and outbound measurements at different average latitudes on either side of periapsis at 18°N. Thus the model represents average nightside variations in T_e and N_e as a function of SZA. For individual orbits, however, the ionosphere is often highly structured on both large and small scales (hundreds of meters to hundreds of kilometers), a fact that we ignore in the present model. For example, the measurements from orbit 98, shown in Fig. 2, are more or less typical of the nightside. In this orbit the ionosphere exhibited peaks and troughs in which N_e varied by more than an order of magnitude and T_e by a factor of 3 or 4 in a distance of a few hundred kilometers along the orbit. The nature of these features is the subject of current study and will not be discussed here.

Modeling was performed by using an expansion

$$\log_{10} y = \sum_{l=0}^{3} \sum_{n=-2}^{2} A_y(l, n) P_l(x) \left(\frac{h}{2000}\right)^n$$

where y refers to N_e or T_e, $P_l(x)$ are standard Legendre polynomials, x = cos SZA, and h is the height (kilometers). The measured values of N_e and T_e at each altitude and SZA were employed to determine the coefficients A_{N_e} and A_{T_e} by standard least-squares fitting procedures. The resulting coefficients are given in Table 1. To aid in visualizing the resulting models, Fig. 3, a and b, display log N_e and T_e in the form of contour plots, where successive ranges of values are plotted alternately as dark and light areas. Perhaps the most significant features of the N_e model are the dramatic decline in density at the terminator, SZA = 90°, followed by a very slow decline through midnight. A surprising aspect of the T_e model is the existence of relatively high temperatures and strong vertical gradients across the entire nightside.

The existence of a substantial nightside ionosphere requires either transport of ionization from the dayside or local production by precipitation of electrons or ions. McElroy and Strobel (4) postulated transport of He ions to produce the nightside ionosphere before it was known that the dayside upper iono-



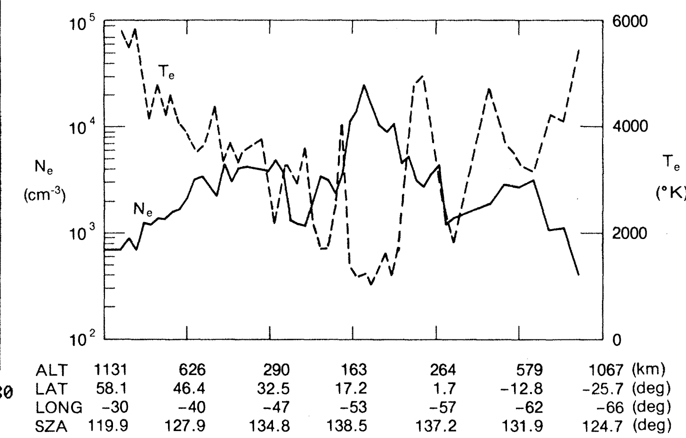


Fig. 1 (left). Portions of the orbits from which measurements were taken for use in the N_e and T_e models shown in Fig. 3. These data were recorded between 10 December 1978 and 20 March 1979 while the solar zenith angle at periapsis increased from 70° to 168° and then returned to 120°. Fig. 2 (right). Measurement of T_e and N_e from orbit 98, day 79071, illustrating a nightside passage through the Venus ionosphere. Although T_e generally decreases and N_e increases near periapsis, large-scale structure in both parameters are characteristic of the nightside ionosphere. The models represent only the average behavior with solar zenith angle.

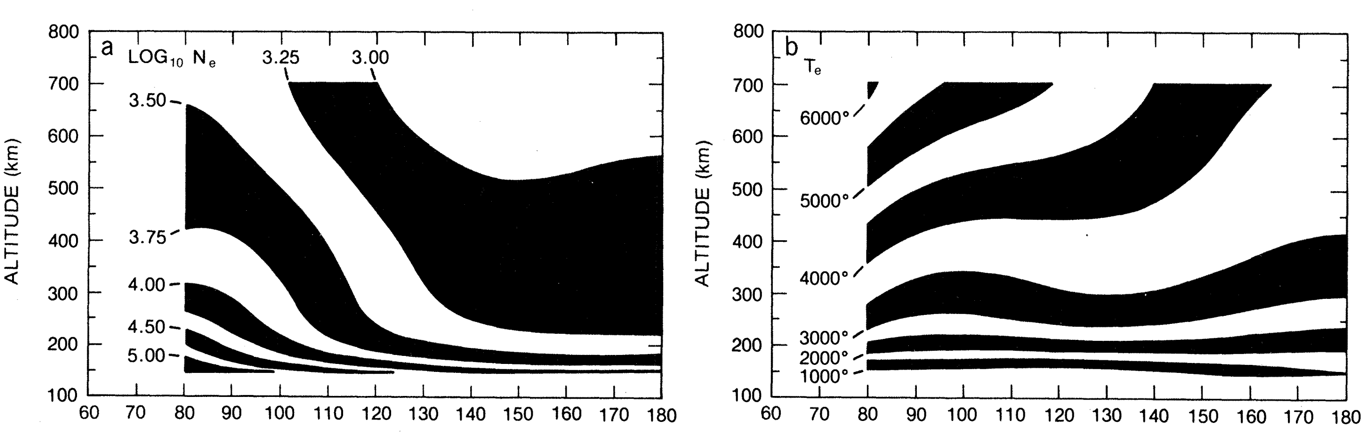


Fig. 3. (a) Model contour map of log N_e. The key feature discussed here is the maintenance of the nighttime ionosphere at densities of the order of 1×10^4 cm^{-3} at 150 km. (b) Model contour map of T_e. The surprising result is the maintenance of high temperatures through the entire nightside ionosphere.

sphere was composed primarily of oxygen ions (1). Gringauz *et al.* (5) and Cravens *et al.* (6) produced a nocturnal ionosphere by using energetic electron precipitation. However, in both cases the composition and density of the neutral atmosphere were obtained from models. In this report we employ simultaneous measurements of neutral gas concentration (7) to evaluate these possible sources of nightside ionization.

The profile in Fig. 4 labeled O^+ flux invokes a downward ion and electron flux of 6×10^7 cm^{-2} sec^{-1}, which produces and maintains a nightside ionosphere through various chemical reactions with the neutrals according to the theory described by Mayr *et al.* (8). Such a downward ion flux could be caused by transport of dayside O^+ across the terminator with uniform subsidence across the entire nightside. If this ion flow were uninhibited by magnetic fields and no ionization was lost by outward flow, the required ion flow velocity at the terminator would be about 300 m/sec. The other two profiles in Fig. 4 show the ionization that would be produced locally by vertical precipitation of 30- and 500-eV electrons with fluxes of 4.4×10^8 and 1×10^8 cm^{-2} sec^{-1}, respectively. The points represent the model N_e at 140° SZA.

Considering the variability of the nightside electron density, such as that evident in Fig. 2, the three source functions provide equally acceptable agreement with the empirical model, which applies only above 150 km. However, the occultation measurements from Pioneer Venus (9) provide a more critical test of the nightside ionization source because they resolve the altitude of the peak electron density, which was found to be at 142 ± 4.1. As seen in Fig. 4, only electrons below about 30 eV could produce a peak that high in altitude, assuming that the electron flux was vertical.

Preliminary analysis of Pioneer Venus plasma analyzer data (10) indicates that electrons in the range 5 to 250 eV are indeed present in the nightside ionosphere, although information on their energy spectra, absolute fluxes, and occurrence frequencies is too preliminary to evaluate the role of precipitation in the formation of the nightside ionosphere. However, even without electron precipitation, transport of ions from the dayside would appear capable of producing an electron density peak at the desired altitude, and with the observed magnitude without exceeding the flow velocities typically observed by the Pioneer Venus ion mass spectrometer (11). It appears likely that both ion transport and electron precipitation will be found to play important roles in the formation of the nightside ionosphere.

The densities at the lowest altitude of the model (150 km) are about five times higher than were indicated at this altitude by Venera 9 and 10 occultation data (12). This suggests that the processes that maintain the nightside ionosphere strongly depend on solar activity, since the Venera observations were made in 1975, when the average solar flux index was 80, while the average index for February 1979 was about 200.

The fact that the nightside electron temperature is high and exhibits a steep positive gradient indicates that energy is being deposited high in the ionosphere across the entire nightside. This is also suggested by the existence of a well-defined ionopause across the nightside (2), a feature that marks the boundary where wave-particle interactions deposit energy in the dayside ionosphere (13). The source of this energy for the nightside is not known; however, we calculate that the T_e profile at 140° SZA could be maintained in the absence of a magnetic field by downward heat conduction with a flux of 2×10^{10} eV cm^{-2} sec^{-1}. If a horizontal magnetic field were present, vertical heat conduction would be inhibited, and the observed temperatures would imply lower heat fluxes than we have calculated.

As more extensive measurements are acquired, the empirical models presented here will be extended to describe the dayside ionosphere and to include dawn-dusk asymmetries and latitudinal differences to the extent permitted by the orbit.

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Table 1. Model coefficients.

$A(l, n)$	A_{T_e}	A_{N_e}
$A(0, 0)$ =	−2.6013	−24.9929
$A(1, 0)$ =	−9.4599	−74.9759
$A(2, 0)$ =	−7.1292	−61.5155
$A(3, 0)$ =	−5.0624	−22.4388
$A(0, 1)$ =	20.7333	98.8441
$A(1, 1)$ =	32.3639	259.8912
$A(2, 1)$ =	23.5901	212.9605
$A(3, 1)$ =	16.1021	78.5383
$A(0, 2)$ =	−23.5743	−121.6280
$A(1, 2)$ =	−38.8493	−312.3033
$A(2, 2)$ =	−28.6329	−256.6772
$A(3, 2)$ =	−18.4619	−96.5431
$A(0, -1)$ =	0.8247	3.2214
$A(1, -1)$ =	1.2537	8.6238
$A(2, -1)$ =	0.9943	6.9035
$A(3, -1)$ =	0.7060	2.4503
$A(0, -2)$ =	−0.0399	−0.1120
$A(1, -2)$ =	−0.0557	−0.3224
$A(2, -2)$ =	−0.0456	−0.2570
$A(3, -2)$ =	−0.0328	−0.0894

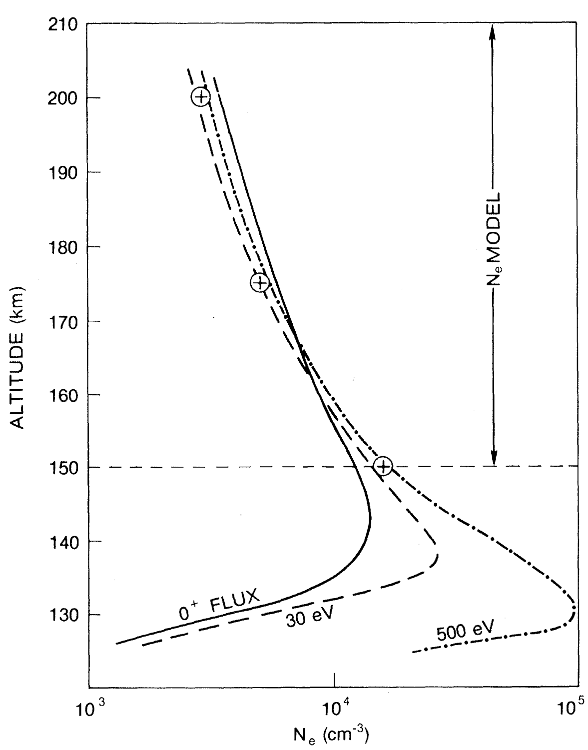

Fig. 4. Comparison of model N_e profile at 140° SZA (points) with theoretical N_e profiles calculated by assuming O^+ flow from the dayside to produce a downward O^+ flux of 6×10^7 cm^{-2} sec^{-1}, or electron precipitation at 30 and 500 eV with fluxes of 4.4×10^8 and 1×10^8 cm^{-2} sec^{-1}, respectively. Although all three sources can be made to fit the model adequately, electrons with energies greater than 30 eV tend to produce the N_e peak below the altitude of 142 km observed by occultation from Pioneer Venus (9). Currently available data on ion flow and electron precipitation do not yet permit the relative roles of these processes to be evaluated.

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Thermal Structure and Energy Influx to the Day- and Nightside Venus Ionosphere

Abstract. *Pioneer Venus in situ measurements made with the retarding potential analyzer reveal strong variations in the nightside ionospheric plasma density from location to location in some orbits and from orbit to orbit. The ionopause is evident at night as a relatively abrupt decrease in the thermal plasma concentration from a few hundred to ten or fewer ions per cubic centimeter. The nightside ion and electron temperatures above an altitude of 250 kilometers, within the ionosphere and away from the terminator, are comparable in magnitude and have a value at the ionopause of approximately 8000 K. The electron temperature increases from a few tens of thousands of degrees Kelvin just outside the ionopause to several hundreds of thousands of degrees Kelvin further into the shocked solar wind. The coldest ion temperatures measured at an altitude of about 145 kilometers are 140 to 150 K and are still evidently above the neutral temperature. Preliminary day- and nightside model ion and electron temperature height profiles are compared with measured profiles. To raise the model ion temperature to the measured ion temperature on both day- and nightsides, it was necessary to include an ion energy source of the order of* 4×10^{-3} *erg per square centimeter per second, presumably Joule heating. The heat flux through the electron gas from the solar wind into the neutral atmosphere averaged over day and night may be as large as 0.05 erg per square centimeter per second. Integrated over the planet surface, this heat flux represents one-tenth of the solar wind energy expended in drag on the sunward ionopause hemisphere.*

In our earlier report we presented ion and electron temperatures and major ion composition data for six of the first ten orbits selected as representative of the dayside Venus ionosphere at a solar zenith angle (SZA) of about 70° (*1*). The ionosphere below the ionopause at that location appeared to be relatively constant in total ion concentration, ion and electron temperature, and ion composition. Strong changes did occur when the solar wind depressed the ionopause height to 300 km on orbit 9, but nonetheless a fairly consistent picture of the ionosphere appeared to have been achieved.

In contrast, the ionosphere on the nightside shows strong variations from location to location within some single orbits and from one orbit to the next (Fig. 1). The in situ measurements made by the Pioneer Venus retarding potential analyzer (RPA) experiment and companion experiments (*2*) are substantiating the existence of strong nightside ionospheric variability initially inferred from earlier radio occultation experiments (*3*) and are revealing its nature in more detail. Orbit 51 is representative of those orbits for which the nightside ion concentration is at its maximum value. Orbit 92 is representative of a minimum nightside ionosphere. Orbit 65 is intermediate. The ionopause is usually evident as a rather abrupt decrease in concentration from a few hundred to ten or fewer ions per cubic centimeter. Frequently, the ion concentration increases to a few hundred per cubic centimeter for a period of time before the final decrease in concentration. This behavior suggests an irregular ionopause surface or patches of detached ionospheric plasma. The concentrations in Fig. 1 are plotted as a function of altitude but are not "vertical" profiles inasmuch as the spacecraft is also moving horizontally. The total concentrations are derived from the ion saturation currents and are not corrected for ion drift velocity.

Strong variations in plasma concentration within a single orbit are illustrated in the lower half of Fig. 2. The wavelike variations are most pronounced at low altitude and decrease with altitude. The spacecraft travels approximately 1500 km horizontally between the major peaks in plasma density. At the higher altitudes, the plasma diffusion coefficient becomes large and diffusion is evidently able to smooth out the strong variations observed at low altitude. The relative plasma density is measured from the saturation current of the electron mode and is not as precise a measurement of the plasma density as that obtained in the ion mode (*1*).

The strong variation in the nightside ion concentration with time and location requires a strong variation in the ionization source mechanism, loss mechanism, or plasma transport mechanism. A determination of which of these mechanisms

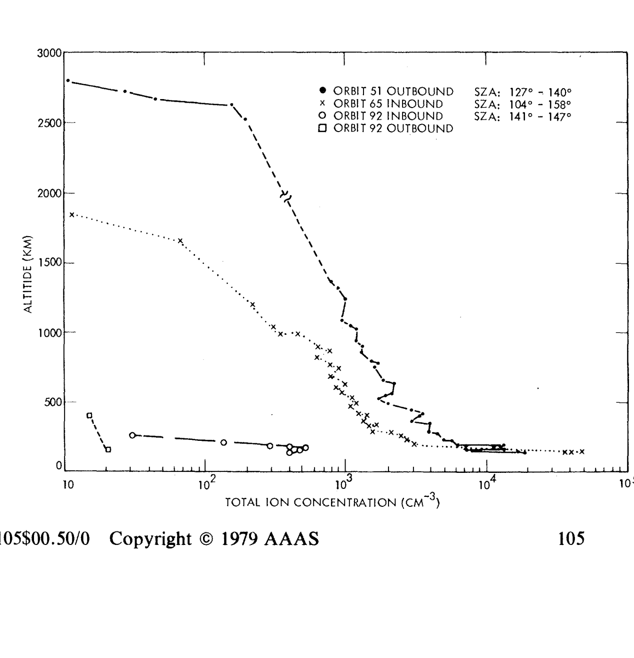

Fig. 1. Total ion concentrations for three representative nightside orbits, illustrating large orbit-to-orbit variation.

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