24. BASIC THEORY AND MODEL CALCULATIONS OF THE VENUS IONOSPHERE

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A review of the theoretical understanding of the chemical and physical processes controlling the behavior of the ionosphere of Venus is presented. The level of this understanding has advanced immeasurably during the last few years, both because of the considerable data base now available from the Venera and Pioneer Venus missions and because of the broadly based theoretical studies stimulated by these data. The basic theory currently used in the general studies of planetary ionospheres is reviewed, including a discussion of the equations which describe the controlling physical and chemical processes of the ionosphere. The present status of the various models of the ion composition, density, and thermal structure that have been developed to reproduce the basic observed ionospheric behavior is discussed. Comparisons of calculated and measured dayside ion composition and density values have shown an overall agreement, but have also indicated the need for more sophisticated models which, for example, would include metastable chemistry. At this time no truly comprehensive and successful model of the nightside ionosphere has been published; the present status of nightside models is reviewed and directions for further improvements indicated. Dayside energy balance calculations lead to electron and ion temperature values in reasonably close agreement with measured values; however the energetics of the night side is poorly understood.

The flyby of the Mariner 5 spacecraft of Venus in 1967 (Kliore et al. 1967) provided great impetus to quantitative calculations of the basic characteristics of the ionosphere of Venus. These basically photochemical models published shortly after the encounter (e.g. McElroy 1969) were relatively successful in reproducing the measured electron density profiles, assuming that the major ion is CO$_2^+$. The observed presence of a significant nighttime ionosphere on
Venus, where the night is very long (~ 58 Earth days) was difficult to explain; McElroy (1968), McElroy and Strobel (1969), and Banks and Axford (1970) suggested that horizontal transport of light ions may be responsible for the maintenance of the nighttime ionosphere. More comprehensive dayside models were presented by Whitten (1969,1970) and Herman et al. (1971) who still had CO₂⁻ as the major ion; but they also calculated the ion composition and structure of the upper ionosphere and found He⁺ to be the dominant ion above ~ 300 km. These authors solved the ion and electron energy equations using a variety of assumptions on the heat sources and boundary conditions, and predicted electron and ion temperatures significantly in excess of the assumed neutral gas temperature. The major advance in modeling the Venus ionosphere occurred in 1974, just before the Mariner 10 radio occultation data became available (Howard et al. 1974), with the publication of the work of Kumar and Hunten (1974). The two major changes in this model were the assumption of an exospheric temperature of only 350 K and an atomic oxygen mixing ratio of ~ 1% at the homopause. The ion chemistry in the presence of even such a small amount of oxygen leads to molecular oxygen as the major ion near the ionization peak. This Kumar and Hunten (1974) model agreed reasonably well with the Mariner 5 radio occultation data; a very similar model by Nagy et al. (1975) reproduced most of the observational features of both Mariners 5 and 10. In the time period between Mariner 10 and Pioneer Venus further daytime electron density profiles were obtained from Veneras 9 and 10 (Aleksandrov et al. 1976a); a number of more comprehensive and detailed ionospheric models were published (Butler 1975; Chen 1977; Chen and Nagy 1978). Bauer and Hartle (1974) attributed the apparent ionospheric ledges and topside scale heights observed by Mariner 10 to ionospheric compression by the solar wind. Cloutier and his coworkers at Rice University published a series of articles dealing with the general problem of solar wind interaction with a nonmagnetic planet in which they calculated the current, potential and flow velocity characteristics inside the ionosphere (e.g. Cloutier and Daniell 1973; Daniell and Cloutier 1977). The presence of a significant nighttime ionosphere was reconfirmed by the Mariner 10 (Howard et al. 1974) and Venera 9 and 10 radio occultation (Aleksandrov et al. 1976b) observations, which led to a number of additional suggestions for the necessary nighttime source of ionization. Butler and Chamberlain (1976) suggested that the nighttime ionosphere consists of metallic ions, which are either transported from the day side or produced locally by meteor induced ionization. Electron impact ionization was proposed as a potential nighttime source by two groups independently (Gringauz et al. 1977; Chen 1977; Chen and Nagy 1978; Gringauz et al. 1979).

The instrument complement aboard the Pioneer Venus (PV) orbiter began, on 4 December 1978, to carry out the most comprehensive investigation ever attempted of a planetary upper atmosphere-ionosphere system other than Earth's (Colin and Hunten 1977). Cravens et al. (1978) presented a summary
of the pre-Pioneer Venus understanding of the Venus ionosphere; the main purpose of this chapter is to summarize in some detail our present-day understanding of the physical and chemical processes controlling the Venus ionosphere. In Sec. I the basic theory underlying planetary ionospheres is discussed. The latest general models of the ion composition and density are discussed in Sec. II. Section III treats the energetics of the ionosphere, and in Sec. IV a brief outline of some of the special phenomena observed in the ionosphere is given. A critical review of the shortcomings of our present-day understanding, and suggestions for future work conclude this chapter.

I. BASIC THEORY

A. Controlling Equations

The Pioneer Venus ion mass spectrometer (H. Taylor et al. 1979c) detected the presence of over a dozen ion species in the dayside ionosphere of Venus. Therefore, a detailed ionospheric model should include all these species, requiring the solution of a large complex set of nonlinear partial differential equations and the consideration of over a hundred chemical reactions. The relevant conservation equations that need to be solved to describe the temporal and spatial variation of the concentration, drift velocity, and temperature of the different ionospheric species have been extensively discussed and reviewed (Schunk 1975, 1977; Schunk and Nagy 1980; Barakat and Schunk 1982). Only first-order transport processes have been included in past theoretical studies of the Venus ionosphere; processes such as supersonic plasma flows, diffusion thermal heat flow, and anomalous resistivity, which have been found to be important in the terrestrial ionosphere have not yet been considered quantitatively and self-consistently. In this chapter only the first-order processes and resulting equations will be reviewed but it should be remembered that some of the neglected effects may be important, e.g., supersonic flows and shocks in the nighttime ionosphere (Knudsen et al. 1980b), and diffusion thermal heat flow (Schunk and St-Maurice 1981). The continuity, momentum, and energy equations (cf. Schunk and Nagy 1980) for a given ionospheric species $s$ are

$$\partial n_s / \partial t + \nabla \cdot (n_s \mathbf{u}_s) = P_s^* - L_s n_s$$  

$$n_s m_s \frac{D \mathbf{u}_s}{Dt} + \nabla p_s + \nabla \cdot \tau_s - n_s m_s G - n_s e_s \left[ \mathbf{E} + \frac{1}{c} \mathbf{u}_s \times \mathbf{B} \right] = \frac{\delta M_s}{\delta t}$$  

$$\frac{D}{Dt} \left( \frac{3}{2} p_s \right) + 5/2 p_s (\nabla \cdot \mathbf{u}_s) + \nabla \cdot \mathbf{q}_s + \tau_s \cdot \nabla \mathbf{u}_s = \frac{\delta E_s}{\delta t} + Q_s - L_s$$

where $D_s / Dt = \partial / \partial t + u_s \cdot \nabla$ is the convective derivative of species $s$, $p_s = n_s k T_s$ is the partial pressure, $n_s$ is the number density, $m_s$ is the mass, $e_s$ is the
charge, \( T \), is the temperature, \( u \) is the drift velocity, \( q \) is the heat flow vector, \( \tau \) is the stress tensor, \( P' \) is the ionization production rate, \( L' \) is the ionization loss frequency, \( Q' \) is the heating rate, \( L_c \) is the cooling rate, \( G \) is the acceleration due to gravity, \( E \) is the electric field, \( B \) is the magnetic field, \( \partial / \partial t \) is the time derivative, \( \nabla \) is the coordinate-space gradient, \( c \) is the speed of light, and \( k \) is Boltzmann’s constant. The double-dot operator in Eq. (3) corresponds to the scalar product of the two tensors (cf. Chapman and Cowling 1970). The quantities \( \delta M_{ij} / \delta t \) and \( \delta E_{ij} / \delta t \) represent the rate of momentum and energy exchange, respectively, between species \( s \) and all other species in the plasma, due to elastic collisions.

These equations become a closed set only if appropriate expressions for the heat flow and stress tensor are used. A discussion and specific numerical values of the appropriate choice of these terms, along with those for the rate of momentum and energy exchange are given by Schunk and Nagy (1980) and will not be repeated here.

The most commonly used and greatly simplified one-dimensional form of Eqs. (1–3) are

\[
\frac{\partial n_s}{\partial t} + \frac{\partial F_{sz}}{\partial z} = P'_{sz} - L'_{sz}
\]

\[
F_{sz} = n_s u_e = -D_p n_s \left[ \frac{1}{T_i} \frac{\partial n_e}{\partial z} + m_e \frac{T_e}{T_i} \frac{\partial n_e}{\partial z} \right] + \frac{1}{T_i} \frac{\partial}{\partial z} (T_e + T_i) + \frac{a_e}{T_i} \frac{\partial T_i}{\partial z}
\]

\[
\frac{1}{2} n_m k \frac{\partial T_m}{\partial z} - \frac{\partial}{\partial z} (K_m \frac{\partial T_m}{\partial z}) = Q_m - L_m
\]

where \( F_{sz} \) is the vertical diffusive flux of \( s \)th ion, \( D_p \) is the diffusion coefficient of \( s \)th ion, \( g \) is the component of gravitational acceleration along \( z \), \( T_i \) is the ion temperature, \( T_e \) is the electron temperature, \( a_e \) is the thermal diffusion coefficient of \( s \)th ion, and \( m \) is the index indicating either electrons or ions. In Eq. (6) the subscripts \( m \) denote either ion or electron parameters depending on whether the ion or the electron energy equations are being considered; \( K_m \) is the thermal conductivity.

In the case of the terrestrial ionosphere, which has a strong intrinsic magnetic field, these one-dimensional equations are usually solved along a field line because of the preferred direction of the various transport processes parallel to magnetic field lines. Venus does not have such a strong and steady magnetic field (see Chapter 25); therefore these equations are solved normally as a function of altitude, using various simplifying assumptions concerning horizontal transport and transport coefficients. Multidimensional
models are generally necessary to calculate some of the ionospheric parameters in cases and regions where horizontal transport processes are important (e.g., terminator), but simpler approaches are also possible. A set of equations similar to Eqs. (4–6) but which include horizontal transport effects can be derived from Eqs. (1–3). The continuity equation which includes horizontal transport terms, and assumes the variables are a function only of altitude $z$ and solar zenith angle $\chi (=x/R)$, can be written as

$$\frac{\partial n_s}{\partial t} + u_x \frac{\partial n_s}{\partial x} + n_s \frac{\partial u_x}{\partial x} + \frac{n_s u_x}{R} \cot \left( \frac{x}{R} \right) \frac{\partial P_{\text{atm}}}{\partial z} = p_s^' - L_s^' \tag{7}$$

where $n_s(x,z)$ is the density of species $s$, $x$ is the horizontal arc length from the subsolar point, $R$ is the radial distance from the center of the planet and $u_x$ is the horizontal velocity, which is generally a function of $x$ and $z$. This equation can be solved rather easily for steady-state conditions if $u_x$ and $\partial u_x/\partial x$ are known. In principle Eq. (2) can be used to calculate $u_x$, but quantitative information on many of the driving mechanisms responsible for horizontal ion motion is not generally available. Whitten et al. (1982) have, however, used a simplified form of this equation to derive horizontal velocities on the night side in the vicinity of the terminator.

An energy equation, analogous to Eq. (6) but which also includes the effects of horizontal transport can be derived from Eq. (3). Such an equation for the temperature $T_m(x,z)$ can be written, using the assumptions employed in obtaining Eq. (7), as

$$\frac{3}{2} n_m k \frac{\partial T_m}{\partial t} + \frac{3}{2} n_m k \left( u_x \frac{\partial T_m}{\partial x} + u_z \frac{\partial T_m}{\partial z} \right) + n_m k T_m \left( \frac{\partial u_x}{\partial x} \right. \left. + \frac{u_x}{R} \cot \left( \frac{x}{R} \right) \frac{\partial u_z}{\partial z} \right) + \nabla \cdot \mathbf{q}_m = Q_m - L_m \tag{8}$$

where the heat flux, $\mathbf{q}_m$, is given by

$$\mathbf{q}_m = -K_m \nabla T_m \tag{9}$$

and $u_x$ is the vertical velocity. This equation can also be solved rather easily for steady-state conditions if the horizontal contribution to the divergence of the heat flux can be neglected.

The ambipolar diffusion coefficient usually selected for use with Eq. (5) is the one derived by Conrad and Schunk (1979) for a fully ionized plasma which is given by

$$D_x = \frac{kT_i}{m_i v_i} \left( \frac{1}{1 - \Theta_s} \right) \tag{10}$$
where \( v_{ij} \) is the momentum transfer collision frequency between ion species \( s \) and \( j \), and \( \Delta \delta \) is a corresponding diffusion correction factor. Expressions for the collision frequencies and correction factors may be found in Conrad and Schunk (1979). The thermal diffusion effect is highly simplified if it is expressed by the simple form given by the last term in Eq. (5). Bauer et al. (1979) presented values for the thermal diffusion coefficient \( \alpha \) based on earlier work of Schunk and Walker (1969), which gives a reasonable approximation for typical ionospheric conditions on Venus. Note that the sign of the numerical values given by Bauer et al. must be reversed to be consistent with Eq. (5).

As mentioned earlier, magnetic fields as well as collisional processes influence the motion of charged particles. Diffusive transport takes place preferentially along rather than perpendicular to strong magnetic fields. This means that in the terrestrial ionosphere, which is permeated with a strong and steady magnetic field, the transport equations are usually solved along magnetic field lines; however for Venus, which has a weak and fluctuating magnetic field the problem is much more complex.

Collisions tend to decouple charged particles from magnetic field lines and facilitate transport perpendicular to the field. The coefficients for transport perpendicular to the field, for a uniform and steady magnetic field can be obtained by multiplying the standard noninhibited coefficients by the factor \( F \) (Hochstim and Massel 1969; Johnson 1978),

\[
F = \frac{\left( \frac{f^V}{\Omega} \right)^2}{\left( \frac{f^V}{\Omega} \right)^2 + 1}
\]  

(11)

where \( \Omega \) is the gyrofrequency and \( f \) is a correction factor of order unity. This factor \( F \), for the case of Venus where the magnetic field is weak and thus the gyrofrequency is small, is close to unity for ions. However, even for Venus, this factor is much less than unity for electrons and consequently electron transport on Venus is basically constrained along magnetic field lines.

The average magnetic field direction in the dayside ionosphere of Venus is horizontal (see Chapter 25). The presence of a strictly uniform and horizontal field means that, while vertical ion transport would not be seriously impeded, the vertical transport of electrons and electron heat would be severely restricted. However, the magnetic field in the dayside ionosphere is not at all uniform but highly structured; even though the average field tends to be horizontal, the field at any given time and location may be in any direction. A possible simplifying assumption, which was made by Cravens et al. (1980a), is to postulate a magnetic field which is completely random (or fluctuating) with a specified correlation length \( l \). If the mean free path of the charged
particle in this random field is \( \lambda \) then the thermal conductivity can be approximated by

\[
K_m = \frac{3}{4} A n_m \bar{v} \lambda
\]  

(12)

where \( n_m \) is the particle density, \( \bar{v} \) is the mean thermal velocity and \( A \) is a correction factor of order unity. For electrons the gyroradius (typically 0.2 km for thermal electrons) is smaller than the correlation length and consequently an electron will move along a field line. Since the field line performs a random walk with correlation length \( l \), the electron mean free path will be equal to \( l \). The ion gyroradius (typically 20 km for thermal ions) is usually larger than the correlation length (which is on the order of a few km) so the ion mean free path tends to be considerably larger than the correlation length and the ions do not really "feel" the magnetic field.

The actual magnetic field on the day side is really neither entirely uniform nor entirely random. Throughout most of the ionosphere are located complex magnetic structures called flux ropes (Russell and Elphic 1979) and between the flux ropes there exists a very weak and random background field. Perhaps a more accurate description of charged particle transport in such an ionosphere would involve diffusion or conduction towards a flux rope followed by rapid diffusion or conduction along the flux rope.

B. Ionization Processes and Photochemistry

Solar extreme ultraviolet (EUV) radiation is the main source of ionization in the dayside ionosphere. The calculation of the photoionization rate requires a knowledge of the number densities of the neutral constituents \( n_n \) as a function of altitude \( z \), the absorption \( \sigma^a_n(\lambda) \), and ionization \( \sigma^i_n(\lambda) \) cross sections of these constituents as a function of wavelength \( \lambda \), the branching ratios of the various excited ion states \( p_m(\lambda, E_i) \), and the spectrum of solar radiation incident upon the top of the atmosphere \( I_{00}(\lambda) \). In terms of these quantities, the primary photoelectron (ion) production rate \( P^i_e \) as a function of energy and altitude is given by

\[
P^i_e(E, z) = \sum_n n_n(z) \int_0^{\infty} \lambda J_{00}(\lambda) \sigma^a_n(\lambda) p_m(\lambda, E_i) \exp \left[ -\tau(\lambda, z) \right]
\]  

(13)

where the optical depth \( \tau \) is given by

\[
\tau(\lambda, z) = \sum_n \sigma^a_n(\lambda) n_n H_n \cosh(R_n \chi)
\]  

(14)
and where

\[ H_n = \frac{kT_n}{m_n g} \]

\[ R_n = \frac{(R + z)}{H_n}. \]

In Eqs. (13–16), \( E = E_\lambda - E_t \), \( E_\lambda \) is the energy corresponding to wavelength \( \lambda \), \( E_t \) is the ionization energy of a given excited ion state \( t \), \( R \) is the planetary radius, \( \chi \) is the solar zenith angle, and \( \chi(R_n, \chi) \) is the Chapman grazing incidence function (Chapman 1931). Approximate expressions for this Chapman function valid for both large and small solar zenith angles have been presented by F. L. Smith and C. Smith (1972); for \( \chi \leq 80^\circ \) the Chapman function can be replaced by \( \chi \). As mentioned earlier, a knowledge of the neutral densities, the absorption and ionization cross sections, and the incident solar flux is required. The neutral composition and its dependence on solar zenith angle is described in Chapter 13. The absorption and ionization cross sections for the neutral constituents of importance in the Venus upper atmosphere are given in Table I. The solar extreme ultraviolet radiation spectrum has been measured at Earth by spectrophotometers carried aboard the Atmosphere Explorer (AE) Satellites C, D, and E (Hinteregger et al. 1973, 1977). A reference spectrum, based on these measurements and appropriate for low solar cycle conditions, was compiled by Hinteregger for use by the AE investigator team. Some of the EUV spectra measured by Hinteregger during solar cycle maximum are available in the open literature (Torr et al. 1979; Hinteregger et al. 1982) and also daily values of 15 representative wavelength group covering the time period from mid-1977 to mid-1981 are available through the AE team. Of course, these solar flux values must undergo the appropriate \( r^{-2} \) scaling (≈1.93) to make them appropriate for Venus; also, if time-dependent comparisons are attempted, the relative location of Venus and Earth with respect to solar longitude must be considered.

On the night side of the ionosphere, electron, and maybe even ion, impact ionization is believed to play an important role. Calculations of the impact ionization rates are significantly more complex than those for the photoionization case because particle transport as well as elastic and inelastic collision processes must be taken into account. The most commonly used form of electron (or ion) transport calculations is based on the so-called multistream approach. As an illustration, a simplified form of this formulation for the case of monoenergetic electrons in a single constituent atmosphere is given below:

\[
\mu \frac{d\Phi(\mu, z)}{dz} = -n_a(z) \left[ \sigma_e + \sigma_a \right] \Phi(\mu, z) + \frac{1}{2} n_a(z) \sigma_e \nonumber
\]

\[
\left. \int_{-1}^{+1} \rho(\mu', \mu) \Phi(\mu', z) d\mu' + P'(\mu, z) - L'(\mu, z) \right) \]

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*Data are taken from M. R. Torr et al. (1979).

bPhotoabsorption is denoted by (abs), photoionization by (ion).
where $\Phi(\mu,z)$ is the electron flux with $\mu = \cos \alpha$, $\alpha$ is the angle of electron with respect to reference direction, $n_\sigma(z)$ is the number density of atmospheric species, $\sigma_e$ is the total elastic scattering cross section at energy $E$ and $\sigma_\alpha$ the total inelastic scattering cross section at energy $E$, $1/2\rho(\mu',\mu)$ is the probability that an elastic scattering of an electron at $\mu'$ will result in an electron at $\mu$, $P'(\mu,z)$ is the differential production rate of electrons in $\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$, and $L'(\mu,z)$ is the differential loss rate of electrons in $\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$. The first term on the right-hand side of Eq. (11) represents scattering out of $\mu$, while the second term corresponds to scattering from all other angles $\mu'$ into $\mu$. A large number of papers (e.g., Nisbet 1968; Nagy and Banks 1970; Stolarski 1972; Cicerone et al. 1973; Oran and Strickland 1978; Mantas and Hanson 1979) have dealt with such transport calculations of auroral electrons and ionospheric photoelectrons, and discussed the equivalence and/or relationship among the various techniques; a comprehensive review paper on this subject is in progress (Oran 1983).

There are myriads of chemical reactions that are potentially important in the Venus ionosphere. A summary of the most important ion-neutral reaction and dissociative recombination rates is given in Tables II and III, respectively, along with the best available values of these reaction coefficients. Figure 1 is a schematic diagram, that attempts to illustrate the ion chemistry dominating the $\text{O}_2^+$, $\text{O}^+$, $\text{CO}_2^+$, $\text{CO}^+$, $\text{C}^+$, $\text{N}_2^+$, $\text{NO}^+$, $\text{N}^+$ and $\text{He}^+$ abundances in the chemically controlled region of the ionosphere. For example, one can see from this figure that the major primary ions, $\text{CO}_2^+$ and $\text{O}^+$, are very rapidly transformed to $\text{O}_2^+$ which is the dominant ion in this region, via reactions N2 and N23. Reactions involving metastable species are not listed in Tables II and III and have not yet been included in any published models; Fox (1982) has shown that certain metastable reactions play an important role in the chemistry of some of the observed species, and that their inclusion improves the agreement between the observed and calculated values. A more detailed discussion of the general ion chemistry is left for Sec. II.

**C. Heating and Cooling Processes**

The main source of energy for the mid- and low-latitude terrestrial ionosphere is the EUV radiation from the Sun; however, for Venus, processes associated with the solar wind interaction also appear to be important. The absorption of EUV radiation by the neutral atmosphere results in both photoionization and excitation of the neutral gases. The resulting excited atoms and molecules lose their energy in quenching collisions with electrons and other neutral particles and by radiation. Photoionization produces energetic photoelectrons since the energy carried by the ionizing photons exceeds, in general, the energy required for ionization. The initial photoelectron energy depends not only on the energy of the ionizing photon and the identity of the neutral species but also on the ionization state of the photoion. Typically,
<table>
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<td>$9.6 \times 10^{-11}$</td>
</tr>
<tr>
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<td>CO$_2^+$ + O $\rightarrow$ O$_2^+$ + CO</td>
<td>$1.64 \times 10^{-10}$</td>
</tr>
<tr>
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<td>CO$_2^+$ + NO $\rightarrow$ NO$^+$ + CO$_2$</td>
<td>$1.2 \times 10^{-10}$</td>
</tr>
<tr>
<td>N4</td>
<td>CO$_2^+$ + H$_2$ $\rightarrow$ CHO$_2$ + H</td>
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<td>CO$_2^+$ + H $\rightarrow$ CHO$^+$ + O</td>
<td>$5.0 \times 10^{-10}$</td>
</tr>
<tr>
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<td>CO$_2^+$ + H $\rightarrow$ H$^+$ + CO$_2$</td>
<td>$1.0 \times 10^{-10}$</td>
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<tr>
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<td>CO$_2^+$ + N $\rightarrow$ products</td>
<td>$\approx 1.0 \times 10^{-11}$</td>
</tr>
<tr>
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<td>CO$^+$ + O $\rightarrow$ O$^+$ + CO</td>
<td>$1.4 \times 10^{-10}$</td>
</tr>
<tr>
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<td>CO$^+$ + CO$_2$ $\rightarrow$ CO$_2^+$ + CO</td>
<td>$1.0 \times 10^{-9}$</td>
</tr>
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<td>$3.3 \times 10^{-10}$</td>
</tr>
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<td>$\approx 2.0 \times 10^{-11}$</td>
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<td>$7.4 \times 10^{-11}$</td>
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<tr>
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<tr>
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</tr>
<tr>
<td>N41</td>
<td>H$^+$ + NO $\rightarrow$ NO$^+$ + H</td>
<td>$1.9 \times 10^{-9}$</td>
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$^a$300/T$^{0.44}$ for $T \leq 1500$ K.

$^b$300/T$^{0.23}$ for $T \leq 1500$ K.
photoionization produces photoelectrons with initial energies of some tens of electron volts.

Only a relatively modest amount of the initial photoelectron energy is deposited directly in the ambient electron gas. Most of the excess kinetic energy is lost in both elastic and inelastic collisions with the neutral particles and in Coulomb collisions with the ambient electrons. If the photoelectrons lose their energy at an altitude near where they are produced, the heating is said to be \textit{local}, while if the photoelectrons lose their energy over a distance greater than a neutral scale height, the heating is termed \textit{nonlocal}. Nonlocal heating effects occur mainly at high altitudes, where ambient densities are low, and at high photoelectron energies.

The heat gained by the ambient electron gas from the photoelectrons and from superelastic collisions with the neutrals acts to raise the electron temperature above the ion and neutral temperatures. The hot ambient electrons then lose energy in Coulomb collisions with the ambient ions and in elastic and inelastic collisions with the neutral atmosphere. The energy gained by the ion gas is generally sufficient to raise the ion temperature above the neutral gas temperature when \( n_i \approx 10^{-3} n_n \). The extent to which the electron and ion temperatures are elevated depends on the relative importance of the various heating, cooling, and energy transport processes.
TABLE III
Dissociative Recombination Rates

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<td>R1</td>
<td>$\mathrm{O}_2^+ + e \rightarrow \mathrm{O} + \mathrm{O}$</td>
<td>$1.6 \times 10^{-7} (300T_e)^{0.55}$</td>
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<tr>
<td>R2</td>
<td>$\mathrm{CO}_2^+ + e \rightarrow \mathrm{CO} + \mathrm{O}$</td>
<td>$3.8 \times 10^{-7} (300T_e)$</td>
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<td>R3</td>
<td>$\mathrm{CO}^+ + e \rightarrow \mathrm{C} + \mathrm{O}$</td>
<td>$\sim 2.0 \times 10^{-7}$</td>
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<tr>
<td>R4</td>
<td>$\mathrm{NO}^+ + e \rightarrow \mathrm{N} + \mathrm{O}$</td>
<td>$4.2 \times 10^{-7} (300T_e)^{0.85}$</td>
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<tr>
<td>R5</td>
<td>$\mathrm{N}_2^+ + e \rightarrow \mathrm{N} + \mathrm{N}$</td>
<td>$1.8 \times 10^{-7} (300T_e)^{0.39}$</td>
</tr>
</tbody>
</table>

*Data are taken from D. G. Torr and M. R. Torr (1978), Weller and Biondi (1967), and M. A. Biondi (personal communication, 1979).*

Comparisons between observations and model calculations (e.g., Cravens et al. 1979, 1980a) have indicated that heating processes other than solar EUV play an important role in the energetics of the ion and electron gases for both the day and night ionospheres of Venus. The main proposed heating mechanisms for the ions are chemical heating and frictional (Joule) heating (Cravens et al. 1979; Knudsen et al. 1979b) and the transformation of kinetic energy into thermal energy (Knudsen et al. 1980b). Landau damping of low-frequency whistler mode waves in the ionopause region is a likely source of heat for the electrons in the dayside ionosphere (Scarf et al. 1979). The pertinent energy exchange rates among the electron, ion, and neutral species have been discussed in detail and tabulated in two reviews by Schunk and Nagy (1978, 1980) and will not be repeated here.

II. ION DENSITY AND COMPOSITION MODELS

The first step in any calculation of ionospheric densities is the determination of the ion production and loss rates. Photoionization is the major source of ionization in the dayside ionosphere; representative values of calculated photoionization rates for a solar zenith angle (SZA) of $60^\circ$ are shown in Fig. 2. The primary ion production indicated in the figure refers to direct photoionization, while the secondary ion production denotes secondary and tertiary production rates due to photoelectrons. The photoelectron fluxes were calculated using the two-stream method (Nagy and Banks 1970). The ionization rates were calculated (Nagy et al. 1980; Cravens et al. 1980a) by using solar EUV intensities appropriate for 1979 conditions, neutral density values based on the Pioneer Venus Orbiter (PVO) neutral mass spectrometer results (Niemann et al. 1979b) and the cross-section values shown in Table I.

It has been established by a number of authors (e.g., Chen and Nagy 1978; Cravens et al. 1981a) that in the dayside ionosphere, photochemical equilibrium conditions hold in the altitude region below $\sim 170$ km. The most
Fig. 2. O$^+$ and CO$_2^+$ primary photolization and photoelectron impact ionization rates for SZA $\chi = 60^\circ$. Solid line indicates primary ion production, dashed line secondary ion production. (From Nagy et al. 1980.)

Recent and comprehensive calculations of the total electron and ion density values in this region are those of Cravens et al. (1981a). These authors were interested in a detailed comparison of the absolute value and SZA dependence of the measured and calculated electron densities at the dayside electron density peak region. Their model calculations, based on solutions of the appropriate photochemical equations, included all the reactions listed in Tables II and III, which involve O$_2^+$, O$^+$, CO$_2^+$, N$_2^+$, NO$^+$, or CO$^+$. However as mentioned earlier, in order to understand the electron density behavior in the vicinity of the ionospheric peak, only the major ion O$_2^+$ is important. CO$_2^+$ is the main ion produced near the peak (see Fig. 1), but reactions N2 and N1, N23 quickly convert it to O$_2^+$, which in turn almost always recombines dissociatively (RJ). A reasonably accurate expression for the electron density in terms of the total ionization rate $P_e^*$, and the dissociative recombination rate for O$_2^+$ (Cravens et al. 1981a) is

$$n_e = 520 \sqrt{P_e^* T_e^{0.375}}.$$  

(18)

Figure 3, reproduced from the work of Cravens et al. (1981a), shows the comparison between measured and calculated peak electron densities as a
function of zenith angle. Excellent agreement was found between the calculated and measured peak densities, as well as the altitude of the peak, if the neutral gas densities were increased by a factor of 1.5 from the model values, which were based on the PVO neutral mass spectrometer results (A. Hedin, personal communication). Since the publication of the work of Cravens et al. (1981a) these neutral model density values have been increased, for various reasons, by ~75% (Hedin et al. 1983); therefore, the behavior of the daytime electron and total ion densities in the chemically controlled region is well understood.

In order to model the structure and composition of the dayside ionosphere above ~170 km, where transport processes become important, the full set of continuity and momentum equations must be solved. The most recently published set of such model calculations are those of Nagy et al. (1979, 1980) who solved the coupled set of Eqs. (4) and (5) for O$_2^+$, O$^+$, CO$_2^+$, C$^+$, N$^+$, He$^+$, and H$^+$. In these equations the terms for all horizontal transport and vertical bulk flows are omitted. Therefore the results obtained by this model
are not applicable near the terminator or the ionopause where the neglected terms are expected to be important. Chemical equilibrium solutions, describing conditions below \sim 200 km were also obtained by Nagy et al. (1980) for \( N_2^+ \), NO\(^+\), and CO\(^+\). The results of these calculations for a zenith angle of 60° are shown in Figs. 4 and 5, along with ion densities measured by the PVO ion mass spectrometer for corresponding conditions. The source and loss processes controlling \( O_2^+ \) behavior have been discussed earlier and will not be repeated. The second major ion O\(^+\) is produced directly by photoionization, electron impact, or by the ion-atom interchange reaction \( N_1 \). Numerous processes, including N22, N23, and N25 destroy O\(^+\). C\(^+\) is produced by dissociative photoionization and reaction N35 and is lost via reaction N20. The amount of neutral atomic carbon in the upper atmosphere is unknown at present and so the relative importance of photoionization is uncertain. Doubly ionized atomic oxygen can create both C\(^+\) and N\(^+\), through reactions with CO\(_3\) and N\(_2\) respectively (Fox and Victor 1981); however this source appears to be significant only above \sim 250 km even if rate coefficients as large as \(10^{-9}\) cm\(^{-3}\) s\(^{-1}\) are assumed. N\(^+\) can be produced by dissociative photoionization and the He\(^+\) reactions N36 and N37; the contribution of direct photoionization to the N\(^+\) production rate is negligible below \sim 200 km but becomes significant at higher altitudes.
Fig. 5. Calculated ion density profiles of He$^+$ (▲), H$^+$ (△), N$_2^+$ (○), CO$^+$ (○), and NO$^+$ (●) for SZA $\chi = 60^\circ$. The N$_2^+$, CO$^+$, and NO$^+$ values were calculated assuming photochemical equilibrium and are shown with dashed lines above 200 km, where this assumption breaks down. The measured ion density values are also shown for comparison; the horizontal bars are an indication of the data spread between the two selected orbits. (From Nagy et al. 1980.)

The major N$^+$ loss processes are reactions N29 and N30. NO$^+$ is produced by a variety of reactions but the most important source is the reaction of O$_2^+$ with atomic nitrogen (N14). The major source of He$^+$ is direct photoionization, while H$^+$, similar to the terrestrial case, comes from charge exchange with O$^+$. The calculations of Nagy et al. (1980), presented in Figs. 4 and 5, were carried out with an early version of the PVO neutral density model, based on the mass spectrometer measurements (A. Hedin, personal communication); as mentioned earlier, the most recent version of that model has density values greater by 75%. These uncertainties associated with the model neutral atmosphere and reaction rates used in the calculations, and the uncertainties attached to the measured ion densities, mean that only disagreements by factors significantly greater than 2 between the calculated and measured ion densities cannot be ignored at this time. Among the major ions the best agreement by far is for O$^+$. The worst agreement is for the measured mass 28, which is the sum of both N$_2^+$ and CO$^+$. Since the calculated CO$^+$ densities are considerably larger than the N$_2^+$ ones, only CO$^+$ can be meaningfully compared with the measurements. The calculated C$^+$ densities are on the low side and, if they were higher, the CO$^+$ agreement would improve because CO$^+$ is pro-
duced from C+ via reaction N20. The agreements for O\(_2^+\), CO\(_2^+\), NO\(^+\), He\(^+\), H\(^+\), C\(^+\), and N\(^+\) are reasonable considering the many uncertainties. The discrepancies and the factors that need to be considered for a better agreement are discussed in more detail by Nagy et al. (1980) and will not be repeated here; however, it is appropriate to repeat some of their general observations. During the last few years it has been established that excited neutral and ion species play an important role in the chemistry of the terrestrial ionosphere (cf. D. G. Torr and M. R. Torr 1982); it is possible that many of the present difficulties in modeling the Venus ionosphere arise because only cursory consideration has been given to the excited state chemistry. The neglect of many of the potentially important transport processes (e.g. Schunk and St. Maurice 1977) may also contribute to difficulties in a quantitative treatment of the topside ionosphere. As summarized by Nagy et al. (1980) "model calculations indicate that while a basic understanding of the chemical and physical processes controlling the composition and vertical distribution of the dayside Venus ionosphere, well below the ionopause, has been achieved, there are many important details requiring further investigations."

The mechanisms responsible for the maintenance of the nighttime ionosphere have been, as mentioned earlier, the subject of much debate ever since the first Mariner 5 measurements. The two favored source mechanisms, electron impact ionization and horizontal transport, were first evaluated quantitatively using new PVO results by Brace et al. (1979c) and Kliore et al. (1979b). These authors showed that either a precipitating low-energy (~30 eV) electron flux of ~2–4 \times 10^8 \text{ cm}^{-2}\text{s}^{-1} or a downward thermal O\(^+\) flux of ~6 \times 10^7 \text{ cm}^{-2}\text{s}^{-1} can account for the measured peak electron densities (~1.6 \times 10^6 \text{cm}^{-3}) at the observed altitudes (~142 km). Initial results from the PVO plasma analyzer (OPA) (Intriligator et al. 1979) and the retarding potential analyzer (RPA) (Knudsen et al. 1980b) indicated the presence of nighttime precipitating electron fluxes and thermal ion fluxes across the terminator of about the required order of magnitude, thus providing support for both of the candidate maintenance processes. Spener et al. (1981) have carried out detailed model calculations of the nightside ionosphere using precipitating electron fluxes and downward O\(^+\) fluxes consistent with values measured by the PVO retarding potential analyzer. These calculations show again that a downward flux of O\(^+\) ions of between 1 and 2 \times 10^8 \text{cm}^{-2}\text{s}^{-1} results in O\(^+\) and O\(_2^+\) ion density profiles comparable to the measured median values (see Fig. 6); furthermore, the PVO retarding potential analyzer results also show that the divergence of the horizontal O\(^+\) fluxes on the nightside is consistent with the required value (W. C. Knudsen personal communication). Spener et al. (1981) have also calculated the ionosphere resulting from typical precipitating suprathermal electron fluxes, measured by the RPA, and find that the calculated O\(_2^+\) density profile has a peak density of about one half of that typically observed and that the calculated O\(^+\) densities are about an order of magnitude too small. They conclude that the "transport
of $O^+$ ions from the dayside ionosphere is responsible for most of the ionization required to maintain the nightside ionosphere."

Implicit in models seeking to explain the maintenance of the nightside ionosphere by a downward flux of $O^+$ is the assumption that there is a high-altitude horizontal flow of $O^+$ across the terminator sufficient to generate the desired downward diffusion from high to low altitudes deep in the night side. A more self-consistent approach is to solve the two-dimensional Eq. (7), together with Eq. (5), for both the downward flux and the density rather than just assume a downward flux. Cravens et al. (1981b) followed this approach, assuming horizontal flow velocities on the order of 0 to 9 km s$^{-1}$, consistent with the measurements of Knudsen et al. (1980b) and H. Taylor et al. (1980).
The results confirm that horizontal transport can, for the most part, maintain the observed nightside ionosphere (see Fig. 7), at least out to a zenith angle of \( \sim 140^\circ \). The calculations shown in Fig. 7 were for an ionopause height of 1870 km. Horizontal transport can maintain an ionosphere quite deep on the night side if reasonable horizontal velocities and ionopause heights are used. Below 200 km, electron precipitation will certainly play a role, as discussed above. Whitten et al. (1982) have also shown that horizontal transport is a viable source for the nightside ionosphere, in the vicinity of the terminator.

### III. THE ENERGETICS OF THE IONOSPHERE

A comparison between model calculations and direct measurements of the daytime ion temperatures in the ionosphere on Mars indicated that solar EUV radiation is not the only major ionospheric heat source (Chen et al. 1978). This led Cravens et al. (1978) to postulate that in the Venus ionosphere, similar to Mars, heating mechanisms other than those due to solar EUV radiation must be considered in any study of the ionospheric energy balance. The choice of appropriate transport coefficients is also more complex than for the terrestrial ionosphere because of the very weak and variable magnetic field (see Sec. II). Temperatures presently recorded by the PVO instrument complement (see Chapter 23) confirm these prior suggestions concerning the presence of nonsolar EUV energy sources, and the need to consider some mechanisms capable of modifying classic transport processes.

To calculate the amount of energy received by the thermal electron gas from solar EUV radiation via the photoelectrons, it is necessary to calculate the equilibrium photoelectron flux. Butler and Stolarski (1978) established that even very small quasi-horizontal magnetic fields will inhibit the vertical transport of photoelectrons and force them to deposit their energy locally to fairly high altitudes. Cravens et al. (1980) also considered the effect of fluctuating magnetic fields on photoelectron transport. Photoelectrons will scatter and at least partially decouple from the magnetic field lines if the amplitude of the fluctuations is large enough. If the gyroradius of a typical photoelectron (\( \sim 3 \) km for a 10 \( \gamma \) field and 15 km for a 2 \( \gamma \) field) is equal to or smaller than the correlation length of the magnetic fluctuations (\( \sim 10 \) km), then photoelectrons will travel along magnetic field lines and, because we are assuming that the field lines are randomly oriented, the electrons traveling along them will perform a random walk. Typical characteristic distances for photoelectron transport in the ionosphere are on the order of a few hundred km (approximately the vertical extent of the ionosphere) while the mean free path due to the fluctuating magnetic field is on the order of the correlation length (\( \sim 10 \) km). This results in a sufficiently large number of scattering events to make this approach justifiable. To simulate crudely the effects of the increased total
Fig. 7. $O_2$ density profiles are shown for a number of solar zenith angles. The horizontal velocity used increased linearly from 0.05 km s$^{-1}$ at 120 km to 9 km s$^{-1}$ at the assumed ionopause height of 870 km.
photoelectron path length due to such scattering events, the two-stream transport method with a dip angle of 2° was employed. The photoelectron flux calculated for this inhibited vertical transport case is shown in Fig. 8. If the magnitude of magnetic fluctuations is quite large and if the photoelectron gyroradius is considerably larger than the correlation length of the fluctuations (or if the field is very weak), the photoelectrons will not "feel" the magnetic field and their vertical transport will not be inhibited. In this case the two-stream method with a dip angle of 90° can be used; the results of such calculations are also shown in Fig. 8. The limited published data on photoelectron fluxes supports the case of "uninhibited" transport (Knudsen et al. 1980a). The calculated heating rate of thermal electrons due to photoelectrons is shown in Fig. 9 for 4 zenith angles and for no inhibition of vertical transport. The heating rate for the subsolar inhibited case is also shown for comparison. The major difference between the heating rates calculated using the different assumptions on photoelectron transport is at high altitudes; while the differences in the heating rates can be as large as an order of magnitude above
Fig. 9. The electron heating rate due to photoelectrons is shown for four values of the SZA for the case of uninhibited transport. The heating rate appropriate to inhibited transport is only shown from the subsolar point, labeled by the letter (i). (From Cravens et al. 1980.a.)

300 km, the calculated temperatures are not, in general, significantly affected because energy transport processes rather than local energy deposition dominate the heat balance at these altitudes.

The major sources of heating for the ion gas are believed to be (1) energy transfer from the electron gas via Coulomb collisions, (2) exothermic ion-neutral chemical reactions, and (3) frictional (Joule) heating. The energy transfer rates via Coulomb collisions are well known but large uncertainties are associated with those due to chemical reactions and frictional heating. In the case of the chemical reactions, the difficulties are mainly due to the uncertainty of the fraction of the exothermic energy going into kinetic energy (Rohrbaugh et al. 1979; Cravens et al. 1979). Calculations of the frictional heating rates are uncertain due to our lack of knowledge of the neutral wind velocities and the limited data base on the ion velocities.

The various uncertainties associated with the heating rates, and in the proper choice of transport coefficients and topside heat input due to solar-wind interaction processes, leave a modeler with a practically unlimited choice of free parameters. The available data base on the electron and ion temperatures provides some constraints, but still does not lead to a unique answer.
A number of papers dealing with dayside ionospheric energy balance (Cravens et al. 1979; Knudsen et al. 1979a) were published shortly after experimental data on the electron and ion temperatures became available from the RPA (Knudsen et al. 1979b) and Langmuir probe (Brace et al. 1979c) carried by PVO. These model calculations, which were based on the solution of Eq. (6) for the electron and ion gases, obtained a reasonable fit to the observed daytime temperatures by (1) assuming a topside and/or distributed heat input not associated with solar EUV (Knudsen et al. 1979a), (2) modified transport coefficients (Cravens et al. 1979), and (3) both of the above (Cravens et al. 1979, 1980); an example of such a comparison from Knudsen et al. (1979a) is shown in Fig. 10. The most recently published comprehensive model calculations of the ionospheric energetics is that of Cravens et al. (1980), which is reviewed in some detail below.

The calculations of Cravens et al. (1979) demonstrated the fact that the presence of a weak, steady, and near-horizontal magnetic field reduces the necessary heat inputs; their work indicated that in order to match the measured temperatures using a reasonable magnetic field, topside heat inputs into the electron and ion gas on the order of a few times $10^9$ and $10^7$ eV cm$^{-2}$s$^{-1}$ respectively, are needed. The electric field experiment aboard PVO (Scar et al. 1979) has detected whistler wave signals in the dayside magnetosheath region which are strongly damped at the ionopause. The fraction of the wave energy that is reflected is not known; therefore only an upper limit on the energy deposited into the electron gas, via Landau damping, is available. The value of this upper limit is $3 \times 10^{10}$ eV cm$^{-2}$s$^{-1}$, well above the energy necessary to explain the dayside electron temperature observations. The required topside energy input for the ion gas is 2 orders of magnitude less, and it is reasonable to expect such energy to be available through some process associated with solar wind-ionosphere interactions. However, no suggestions have been made for a specific mechanism. The measured daytime ion temperature profile shows a clear bump in the altitude region between ~160 and 200 km, which implies the presence of some specific heat source(s). Cravens et al. (1979) found that exothermic chemical reactions can account for most of the required heat, while Miller et al. (1980) favor frictional heating as the dominant source. Schunk and St. Maurice (1981) have predicted that an ion temperature anisotropy will be present in this altitude region caused by large ion flow velocities. Their calculations have also indicated that diffusion-thermal heat flow is more important than ordinary ion thermal conduction in this lower ionospheric region.

The effect of magnetic field fluctuations on thermal conductivity, as discussed in Sec. 1, was included in some of the model calculations of Cravens et al. (1980); results of one set of such calculations are shown in Fig. 11. For the case shown, a magnetic field strength of 10 $\gamma$ and no inhibition on photoelectron transport was assumed; various values of effective mean free path $\lambda$ were used to approximate a potentially wide range of magnetic fluctua-
Fig. 10. Dayside ion (●) and electron (■) temperature profiles. A column heat input of $3 \times 10^{-3}$ erg cm$^{-2}$s$^{-1}$ uniformly distributed between altitudes of 150 and 250 km and presumably representing Joule heating was required to raise the model ion temperature to the measured temperature in this altitude interval. The model represented in the figure by a solid line included in electron heat input at the top of $3 \times 10^{-2}$ erg cm$^{-2}$ s$^{-1}$. The SZA was 72° ± 11°. (From Keaden et al. 1979c.)

The calculated ion temperatures are almost independent of the value of $\lambda$ chosen, because in a 10 $\gamma$ field the ion collision frequencies are of the same order as or larger than the ion gyrofrequency for all altitudes less than a few hundred km. As indicated in Cravens et al. (1979), only when the magnetic field strength is considerably larger than 10 $\gamma$ is the ion thermal conductivity significantly affected. Figure 11 also shows that reasonable electron temperatures result with an assumed $\lambda$ of $\sim 3$ km. As mentioned earlier, a large number of free parameters are present and no unique choices can be
made in fitting the observed data. As a final example of such temperature calculations, which fit the data well, Fig. 12 shows the results obtained by Cravens et al. (1980a) assuming a 10° field, a mean free path of 10 km due to fluctuations, and topside heat inflows into both the electron and ion gas.

The energetics of the nightside ionosphere are even less well understood than those for the day side. Examples of the added difficulties for the nightside energy balance are (1) the role of precipitating particles, (2) the energetics associated with supersonic flows, and (3) the absence of a topside electron heat source due to whistlers. Only a few groups have so far attempted to carry out quantitative calculations of the nightside energetics. Hoegy et al. (1980) solved the two-dimensional electron energy equation between 80° and 170° SZA, using the observed mean temperature values as constraints. The free parameters in their calculations were the magnetic field direction and the topside heat inflow. They find that a good agreement between the calculated and measured values of \( T_e \) can be achieved if the magnetic field and corresponding heat flow directions are assumed as shown in Fig. 13. The assumed field configuration is not inconsistent with the observed mean values and implies that the lower nightside ionosphere is heated by conduction of heat from the
day side, while the upper ionosphere receives the necessary heat from the ionosheath. Cravens et al. (1981b) solved Eq. (8) for electron and ion temperatures, though they ignored the horizontal heat conduction terms (but included the other horizontal terms), thus restricting the validity of their calculations mainly to the ions. They found that adiabatic compression on the night side helps somewhat to maintain the nightside ion temperature but not nearly enough to explain the very high temperatures measured by the Pioneer Venus RPA (Miller et al. 1980). Knudsen et al. (1980b) suggested that the heat necessary to maintain the high nightside ion temperatures is derived from the kinetic energy of the plasma flowing rapidly past the terminator. Merritt and Thompson (1980) pointed out that there is an upper limit to the rate at which heat can be transported by thermal conduction in a plasma, and that this limit is probably reached for electrons on the night side of Venus.

IV. MISCELLANEOUS IONOSPHERIC PHENOMENA

The discussion in this chapter has been restricted, so far, to the general or average behavior of the ionosphere; however the observations, discussed in Chapter 23, indicate the presence of many unique and interesting spatial and/or time varying phenomena such as detached plasmas, ionospheric holes,
and disappearing ionospheres, to name only a few. No quantitative theoretical or model descriptions have been published of any of these features. As an example of our present understanding of these ionospheric phenomena, the mechanisms that may be responsible for the formation of ionospheric holes are reviewed briefly below.

The electron densities measured by the electron temperature probe carried by PVO through one of its periapsis passes, during which typical ionospheric holes were observed, are shown in Fig. 14. The observed general characteristics of these holes can be summarized as follows:

1. The densities in the holes are \( \sim \) 2 orders of magnitude lower than in adjacent regions;
2. The holes are typically found at altitudes above 200 km and in two broad zones. These zones extend from about midnight to 3 AM local time and are \( \sim \) 20° in latitude extent, centered at 30°N and 12°S;
3. The latitude extent of individual holes is on the order of 1000 km;
4. The magnetic field in the holes is approximately vertical and is enhanced compared to adjacent regions;
5. The electron temperature in the holes (\( \sim \) 2000 K) is substantially lower than in the surrounding ionosphere, except in the lowest density regions where highly elevated temperatures (\( \sim \) 20,000 K) are observed.

One of the first questions to be examined was whether there is a static pressure balance across the hole boundaries. Brace et al. (1982b) have shown that such a pressure balance does exist and thus the holes can be quasi-static.
features. Two potentially likely mechanisms responsible for hole formation, using terrestrial analogies, can easily be dismissed. The near vertical magnetic field lines in the holes leading back in the tail suggest that polar wind types of outflow may be present; however, the relative enhancement of H\textsuperscript{+} over O\textsuperscript{+} inside the hole region (H. A. Taylor, personal communication) is contrary to the general predicted behavior of the polar wind. Horizontal neutral wind velocities of 200 to 400 m s\textsuperscript{-1} are believed to be present in the thermosphere of Venus, and such velocities in conjunction with appropriately tilted near-vertical field lines could drive ionization downward to regions of rapid recombination and result in significantly decreased densities (R. W. Schenk, personal communication). However, an examination of the magnetic field data has indicated no meaningful correlation between the field tilt and the presence of holes (J. G. Luhmann, personal communication), thus removing this mechanism from among the viable ones.

Grebowsky and Curtis (1981) propose that the observed plasma depletions in the holes are caused by electric fields parallel to the observed near-radial magnetic fields. They do not present a specific and/or quantitative mechanism for the formation of this electric field but suggest, using terrestrial analogy,
that neutral sheet acceleration processes will result in an upward directed $E_t$ distribution with a potential drop on the order of kilovolts. Given such a field, electrons from the tail region will accelerate down into the ionosphere becoming a source of nighttime ionization and a heat source for the ionospheric thermal electron gas. This electric field would also accelerate thermal ions out of the ionosphere into the tail region. Using rough estimates of densities and field strength, Grebowsky and Curtis (1981) indicate that their proposed mechanism is not inconsistent with the data base presently available. Hartle (1981) has examined the abundance and altitude behavior of the various minor and major ions inside the holes and has concluded that the observed "height" profiles (there is always some ambiguity between horizontal and vertical variations) are consistent with the presence of $E_t$ and upward flowing ions.

This brief summary of our present understanding of the nightside ionospheric holes clearly indicates, as mentioned earlier, the lack of any quantitative theories of this well-documented ionospheric feature. There are intensive efforts under way to develop a detailed explanation for the various observed special ionospheric phenomena. Significant progress is expected as the available data base increases.

V. CONCLUSION

Our general understanding of the chemical and physical processes controlling the behavior of Venus's upper atmosphere and ionosphere has advanced greatly due to the significant observational data base now available together with broadly based theoretical studies. This chapter has reviewed briefly the controlling ionospheric chemical and transport processes and outlined the present status of the various general models of the ion composition, density and thermal structure developed to reproduce the basic observed behavior of the ionosphere. Comparisons of calculated and measured dayside ion composition and density values have indicated a basic and general agreement but they have also shown the need for (1) laboratory measurements of some of the rate coefficients, (2) inclusion of metastable chemistry (Fox 1982) and possibly certain nonconventional transport effects into the models, and (3) measurements of the ionospheric metastable populations. No truly comprehensive models of the nightside ion composition and density have yet been published and compared with data. Further advances in this area must wait for (1) the development of multidimensional models that include both the horizontal ion transport terms and particle precipitation effects, and (2) more data on ion (and maybe neutral gas) velocities as well as on precipitating particle fluxes.

It has been possible to reproduce, using model calculations, measured dayside ion and electron temperatures; however the controlling heating and
transport mechanisms cannot be established uniquely, because of too many free parameters. In the future, more sophisticated models of charged particle transport in realistic ionospheric magnetic fields will be required. Our understanding of the nightside energetics is very limited; we know the amount of heat required to explain the observations but we are not yet able to establish the mechanisms responsible for the heating and/or for transporting that heat. As mentioned in Sec. IV, the bulk of this chapter has only dealt with the general, gross, behavior of the ionosphere, and not with any of the detailed time and/or spatially varying phenomena, which the observations are now beginning to reveal. Attempts to understand the processes responsible for these phenomena have just begun and it will be sometime before any definitive models become available. The recent intensive exploration of the aeronomy of Venus has greatly expanded our knowledge, but at the same time exposed new areas of ignorance. As the Pioneer Venus data base grows and more sophisticated models evolve, we expect further and significant advances in our understanding of the ionosphere of Venus.

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