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CONVECTION IN THE VENUS IONOSPHERE

by

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IN PARTIAL FULFILLMENT OF THE
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MASTER OF SCIENCE

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HOUSTON, TEXAS

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ABSTRACT

Convective studies involving ion flow in the Venus dayside ionosphere are used to understand the nature of the observed O$_2^+$ distribution. Flows are modeled (not calculated) from previous data and theory which are incorporated to determine the ion distributions for O$^+$, CO$_2^+$, and O$_2^+$. Current understanding of ion chemistry and related parameters are used in solving the continuity equation in two dimensions to provide ion profiles at different solar zenith angles. To explain the O$_2^+$ distribution, downward flow with speeds of approximately 500 m/s are required.
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1. INTRODUCTION

Since the Pioneer Venus (PV) mission encountered Venus in 1978, large amounts of atmospheric data have been collected. Ionospheric measurements (such as plasma densities and temperatures; neutral gas composition and temperature; and magnetic field structure) provide a comparison with theoretical models to supplement our understanding of ionospheric physics and chemistry. The subsequent models attempt to describe the ion composition and density as a function of altitude and solar zenith angle (SZA).

Currently, it appears that the Venus dayside ionosphere is not completely understood. Nagy et al. [1980], who use ionospheric measurements (like neutral gas composition and plasma temperatures), report a significant disagreement between their calculated values and observations. Specifically, their modeled values of the \( \text{O}_2^+ \) density in the altitude range 150-180 km do not fit values measured by the orbital ion mass spectrometer (OIMS) on the Pioneer Venus Orbiter (PVO) [Taylor 1979,1980]. For example, their theoretical values for the major ion densities (\( \text{CO}_2^+ \), \( \text{O}_2^+ \), and \( \text{O}^+ \)) at the subsolar point are shown to be different from the OIMS measured values (see Figure 1). In particular, the OIMS data demonstrates the existence of a concentration peak in \( \text{O}_2^+ \) around 175 km. The calculated densities of \( \text{O}^+ \) agree well with the OIMS measurements, but [\( \text{CO}_2^+ \)] and [\( \text{O}_2^+ \)] are not well modeled in several altitude ranges. Even though this is an early model with respect to the PV mission, more recent models like Shimazaki et al. [1984] do not satisfactorily fit these measurements either.

In view of this discrepancy between the measurements and previous
theoretical model calculations, it seems likely that a neglected physical process may be important in determining the dayside ion density distribution. In this thesis, plasma convection, a result of the solar wind interaction with Venus, is included to demonstrate its importance in determining ionospheric densities and to enhance understanding of the $\text{O}_2^+$ peak.

The first half of Chapter 2 describes the basic observations concerning the Venus dayside ionosphere. The second half of Chapter 2 reviews recent ionospheric calculations to identify what physical and chemical processes have been used to model the Venus ionosphere. Chapter 3 explains the model calculations and results, and Chapter 4 discusses these results. Chapter 5 presents the conclusions.
2. BACKGROUND

2.1 Observations of the dayside ionosphere

Prior to 1978, there was little empirical knowledge of the Venus ionosphere even though electron density measurements by radio occultation experiments were performed in two flyby missions: Mariner 5 in 1967 and Mariner 10 in 1973. Later, the Pioneer Venus (PV) program launched two spacecraft in 1978 to gather data concerning the Venus atmosphere [Colin, 1979, 1980]. In contrast to the two previous flybys, new scientific instruments used in the PV mission were designed to make in situ measurements of the ionosphere and thereby provide detailed information about ion composition and densities. Other ionospheric and atmospheric parameters were also measured: plasma temperatures; electron densities; neutral gas composition, densities, and temperatures; and magnetic field structure.

The Pioneer Venus mission consisted of the Pioneer Venus orbiter (PVO) and the Pioneer Venus multiprobe. The multiprobe was composed of a bus that transported a large probe and three small entry-probes designed to separate before entering the atmosphere. Since most of the in situ measurements of the ionosphere were gathered by the Pioneer Venus orbiter, it is necessary to discuss the nature of the PV orbit. With an orbital period of 24 hours, apoapsis occurred at 11 Venus radii and periapsis was maintained between 140-160 km for over 600 orbits. During these 600 Earth days, periapsis moved slowly in latitude from 17° N to 14° N, and the orbital plane swept out all local times at the rate of .1 hour per orbit. With respect to Venus, periapsis was approached from the northeast, with the orbit altitude varying from ~ 600 km at 45° N latitude to the
range 150-180 km at periapsis (~ 15° N latitude). By 15° S latitude, the spacecraft climbed back to ~ 600 km.

With the ion mass spectrometer (OIMS) aboard the PV orbiter, Taylor et al. [1979] made in situ measurements of the ion composition in the Venus ionosphere. A number of ions were identified in the upper ionosphere: O⁺ is the dominant species, and C⁺, N⁺, H⁺, and He⁺ are important secondary ions. O₂⁺ dominates the lower ionosphere, and the molecular ions (e.g. CO₂⁺, CO⁺, and NO⁺) contribute less 10% of the ionization near the electron density peak. Trace amounts of Fe⁺ and Mg⁺ were also detected. Above 200 km, day-to-day variability in the ion scale height was measured, which seems to indicate that solar wind interaction is important in determining the ion density distribution. Global ion distributions were sampled from different solar zenith angles at 200 km and approximately 8° N latitude. The measurements demonstrated a slow decrease in the major ion densities toward the terminator similar to the observed neutral density variation. H⁺, however, increases toward the terminator and forms a bulge on the dawn side. In Figure 1.1, vertical density profiles of the major dayside ions, O⁺, O₂⁺, and CO₂⁺, illustrate unusual features not predicted by previous ionospheric models. Namely, the O₂⁺ "bump", a smooth peak around 175 km with typical values of ~ 4 × 10⁵ cm⁻³, has not been explained by photochemical equilibrium calculations. Furthermore, the molecular ions, like O₂⁺ and CO₂⁺, are not well modeled above 200 km. Observations show that the distribution height of the molecular ion species increases with altitude; the ions appear to turn upward as they slowly decrease with altitude. In contrast, calculations like those of Nagy et al. [1980] indicate these ion species decrease rapidly with altitude.
Ionospheric electron and ion temperatures were made by the retarding potential analyzer (ORPA) [Knudsen et al., 1979] and the orbiter electron temperature probe (OETP) [Brace et al., 1979]. Knudsen et al. [1979] reported average dayside ion temperatures as high as 2000° K for heights greater than 300 km and lower than 1000° K for altitudes less than 200 km. Between 175 and 225 km, Miller et al. [1980] showed that the ion temperatures measured from the ORPA remained nearly constant and were greater than the neutral temperatures. From their model calculations of ion temperatures, they attempted to account for the ion temperature profile between 175 and 225 km as a result of local heat sources in addition to heating by thermal electrons. They concluded that Joule heating provides most of the heat, and that the temperature is not maintained by chemical energy sources. Contrary to this result, Cravens et al. [1980] found that heating due to chemical processes is sufficient to reproduce the observed temperatures for altitudes less than 225 km. They also argued that the temperature profile may be due to a combination of these processes.

Ion temperature variations in solar zenith angle (SZA) were shown to be very small on the dayside [Miller et al., 1980], while the nightside measurements exhibited large variations with SZA. The median ion temperature increased by a factor of 2 between 150° and midnight. Temperatures above 300 km were shown to be independent of solar zenith angle for angles less than 150°; while below 300 km, temperatures increased with SZA for angles greater than 60°.

Initial electron temperature measurements taken by the ORPA and the OETP showed typical dayside values that varied from less than 1000° K at 150 km to greater than 4000° K at 500 km. Theis et. al. [1980] used the OETP measurements to empirically model the electron density and temperature in the
Venus ionosphere. At low altitudes below 200 km, they showed that the vertical gradient in the dayside electron temperature was about 30° K/km, and the dayside temperature was nearly independent of solar zenith angle. Above 200 km, the dayside temperature increased with SZA, and the nighttime electron temperatures remained high suggesting a large nightside heat influx [Hoegy et al., 1980].

Also measured by the OETP, electron densities were empirically modeled by Theis et al. [1980] who showed there was little variation over the dayside from 0° to about 50° SZA for altitudes greater than 170 km. The density was shown to decrease rapidly between 60° and 120° SZA and then remain approximately constant to midnight defining a nightside ionosphere. It has been suggested that horizontal transport of O⁺ might maintain the nightside ionosphere [Taylor et al., 1979b; Brace et al., 1979b; Cravens et al., 1983]. In support of this, Knudsen et al. [1980] reported large O⁺ ion velocities measured by the ORPA near the terminator.

They showed that the flow was horizontal in the antisolar direction with typical magnitudes of 2-3 km/s; however, horizontal velocities as large as 8 km/s near the ionopause at the terminator were observed. In the subsolar region, the flow appeared to be directed downward, and both radial and horizontal velocity vectors were seen in regions between the subsolar point and the terminator [Knudsen et al., 1982].

The absolute densities and composition of the neutral gases in the Venus thermosphere were measured by two mass spectrometers: the orbiter neutral mass spectrometer (ONMS) on the Pioneer Venus Orbiter [Niemann et al., 1977],
and the bus neutral mass spectrometer (BNMS) aboard the multiprobe bus [von Zahn et al., 1977]. These instruments identified the absolute densities of CO₂, CO, O, N₂, N, and He. Niemann et al. [1980] empirically modeled results of the ONMS measurements to demonstrate the characteristic vertical profiles of the subsolar and antisolar conditions at equatorial latitudes. For dayside conditions, atomic oxygen was shown to dominate above 170 km while CO₂ dominated below. At 150 km, the densities of atomic oxygen and CO₂ are determined to be \( \sim 3 \times 10^9 \text{ cm}^{-3} \) and \( \sim 5 \times 10^9 \text{ cm}^{-3} \) respectively. Global density distributions sampled by the ONMS showed density variations with solar zenith angle symmetric about the subsolar point. Densities decreased very slowly away from the subsolar point and then dropped off rapidly by an order of magnitude near the terminator. Although hydrogen densities were not measured directly by Pioneer Venus mass spectrometers, Brinton et al. [1980] were able to derive atomic hydrogen altitude profiles from other measured ion and neutral species by assuming photochemical equilibrium at 285° K.

These ONMS measurements were investigated due to reported differences with other experiments [von Zahn et al., 1983]. Comparisons between the ONMS values, which were extrapolated to the bus entry latitude, and the BNMS results indicated that the ONMS results were too low [von Zahn et al., 1980]. The total mass densities derived by Keating et al. [1980] from the atmospheric drag experiments also indicated that the ONMS densities were about 60% low. Subsequent model calculations attempted to match observations with theory and provided more support that the ONMS measurements were in error. To model the altitude of the electron density peak, Cravens et al. [1981] found it necessary to multiply the ONMS density measurements by a factor of 1.5 to fit the
observed ionospheric peak altitude. Additionally, the Venus thermosphere model of Hedin et al. [1983] assumed that the ONMS densities were too low by a factor of 1.63. To date, the discrepancy has not been resolved.

The neutral kinetic temperature was also derived from the ONMS, BNMS, and atmospheric drag experiments. Each experiment measured the same temperature to within 10 degrees. The daytime temperature derived from the ONMS measurement is about 285° K, which was calculated from the height variations in atomic oxygen under the assumption that diffusive equilibrium controlled species distributions [Niemann et al., 1980]. The diurnal variation in the exospheric temperature was found by the ONMS (after many orbits) to be symmetric about the subsolar point. The temperature decreased slowly with SZA away from the subsolar point, and then decreased rapidly past the terminator by a factor of 2.

Complex magnetic field structures on the dayside were measured by the PV magnetometer (OMAG) and showed a well defined bow shock at approximately 1.3 Venus radii [Russell et al., 1979]. Initial observations of the ionosphere exhibited variations in magnetic field strengths at periapsis that ranged from 30 to 60 gammas and which were highly correlated with the solar wind dynamic pressure. Typically, the measured field values along the orbit behind the shock increased as the spacecraft approached the planet, reaching a peak value between 30 and 100 gammas. Then, the field strength decreased rapidly to a local minimum and later increased slowly near periapsis. However, deviating from these profiles were instances in which the field structure became irregular in the ionosphere and the field strength was largest at periapsis.
These irregular structures, known as flux ropes [Russell et al., 1979], were shown to consist of large, straight field lines in the center wrapped with helical field lines that diminished in strength with distance away from the center. The helical angle of the flux ropes also increased with distance from the center. Elphic and Russell [1983] studied the global characteristics of these structures and found that flux ropes occurred mainly at lower altitudes, around 160 to 200 km. The scale sizes were smallest at low altitudes and largest at high altitudes, having typical diameters of ~ 10 km at 160 km altitude and ~ 30 km above 300 km altitude. The scale sizes were larger near the terminator and smaller in regions near the subsolar point. The frequency of their occurrence was shown to reach maximum at high solar zenith angles and decreased with decreasing SZA. To account for the observations, theories of flux rope formation induced by the Kelvin-Helmholtz instability have been modeled by considering velocity shears in the ionosphere [Cloutier et al., 1981] and by the flow of post-shock solar wind tangential to the ionopause [Wolfe et al., 1980].
2.2 Previous models

Ionospheric modeling requires input parameters based on fundamental atmospheric and planetary characteristics, such as neutral gas composition, neutral densities and temperatures, plasma temperatures, and magnetic field structure. When these characteristics are not properly known (as in the case of Pre-Pioneer Venus models), an attempt to model ion density distributions has little chance of success. Thus, in comparison with PV measurements, the pre-PV exospheric temperature has usually been taken to be too large (~ 350° K - 650° K) -- with the exception of Dickinson and Ridley [1977] who predicted an exospheric temperature of approximately 300° K. The neutral density models have varied from predicting densities that are larger than ONMS measurements [e.g. Dickinson and Ridley, 1978] to values that are smaller [e.g. McElroy et al., 1971]. As the pre-PV ionospheric models employed different values for input parameters than those known from PV measurements, and consequently do not match observations very well, they will be for the most part disregarded in what follows.

Chen and Nagy (1978)

Even though it predates Pioneer Venus, the Chen and Nagy model is important to consider because it is not restricted to one dimension, unlike other early models, which considered vertical diffusion as the only transport process. Instead, it is a 2-dimensional calculation that also considers bulk horizontal ion flow. The model solves the coupled set of continuity, momentum, and energy equations to determine the plasma temperature and five ion densities: \( \text{CO}_2^+ \),
$O_2^+$, $O^+$, $He^+$, and $H^+$ In comparison with Pioneer Venus observations [Knudsen et al., 1979; Brace et al., 1979], the overall plasma temperatures determined in their model are too small by a factor of 3-4. The horizontal velocities, included in the continuity equation but neglected in the momentum equation, are taken from a thermospheric model by Dickinson and Ridley [1977]. This thermospheric model studied global neutral winds, temperature, and composition under the control of solar heating. With a calculated exospheric temperature of $\sim 300^\circ$ K, the winds were predicted to increase smoothly in the vertical direction, reaching maximum speeds of several hundreds of meters per second at the terminator. From this wind field model, Chen and Nagy assumed that the ion flow speed at each solar zenith angle remains constant with altitude above 180 km; however, the values at high altitudes are then too low in comparison with observations [Knudsen et al., 1980]. Photochemical equilibrium, the state of equilibrium between the rate of ion production and loss due to chemistry and photoionization, is taken to be dominant below 220 km. Depending on the ion species above 220 km, diffusive processes are assumed dominant, and the transition region between photochemical and diffusive equilibrium is located between 220-260 km. Also used in the model calculation, the neutral model is adapted from Dickinson and Ridley [1977]. Overall, the calculations of $[O^+]$ are an order of magnitude smaller than the PV results, while $[O_2^+]$ agrees fairly well with the observations at high altitudes but not lower.
Nagy et al. (1980)

The Nagy et al. model solves the coupled continuity and momentum equations to determine 7 ionic species: $\text{CO}_2^+$, $\text{O}_2^+$, $\text{O}^+$, $\text{C}^+$, $\text{N}^+$, $\text{He}^+$, and $\text{H}^+$. This model differs from the previous Chen and Nagy model in several ways. First, the energy equation is omitted from the simultaneous solution of the momentum and continuity equations. Instead, the measured values of the plasma temperature [Brace et al., 1979; Knudsen et al., 1979] are used to determine the ion densities, and the measured densities from the OIMS are used to solve the energy equation separately. In this way, the dynamics and chemistry are studied without the need to understand the energetics and vice versa. Second, the model is one-dimensional: it includes vertical diffusion and omits horizontal transport. The equations are solved to give vertical density profiles at various solar zenith angles that represent a 2-dimensional view of the dayside ionosphere. Third, the chemistry is more complex since there are 7 ionic species considered instead of 5. Fourth, the transition altitude between photochemical and diffusive equilibrium is lowered from 220 to 200 km.

In considering the production processes, photoelectron impact ionization is included. This contributes about 25-40% to the total production rate near the ionization peak around 140 km. Above the peak, it decreases to approximately 10% of the total production rate. In determining the production rate, Chen and Nagy used neutral density and composition based on a model that is reported to be within the limits of Pioneer Venus measurements.

The authors report a significant difference between their results and measured values of $[\text{O}_2^+]$ in the altitude range of 150-180 km. It is also seen
from Figure 1 that the measured and calculated values of $[\text{CO}_2^+]$ differ over a considerable altitude range, whereas there is good agreement over the entire region between the measured and calculated $\text{O}^+$ densities.

**Whitten et al. (1982)**

Whitten et al. do not attempt to model the dayside ionosphere; instead, they investigate the effect of horizontal plasma flow on ion density distributions near the terminator. Horizontal velocities are evaluated in an inconsistent manner since the continuity and momentum equations are not solved simultaneously. Some terms are simplified and neglected; specifically, only solar EUV-induced pressure gradients are considered, and the divergence of flux is zero in the continuity equation to simplify the problem (although realistically this is non-zero). Another problem is the that boundary condition for the velocity is chosen to be zero for a SZA of 57.5 which does not agree with observations given by Knudsen et al. [1980]. With these approximations, they show that horizontal ion flow is important in determining ion density distributions. Their model results for vertical density profiles of $\text{O}_2^+$ and $\text{O}^+$ show that horizontal flow can modify the dayside densities by as much as a factor of 5. These calculations do not necessarily provide a good comparison with the measured data; rather, they show that horizontal ion flux may be important in determining ion density distributions on the dayside and may provide for the maintenance of the nocturnal ionosphere.
Cravens et al. (1983)

This is similar to the Chen and Nagy model since both models consider horizontal ion flow; however, Cravens et al. use horizontal velocities that are empirical values based on measurements given by Knudsen et al. [1980,1982] which increase in SZA and altitude. In general, the horizontal speeds used by Chen and Nagy are too small compared to measurements since the observed velocities are on the order of 1 km/s at the terminator, and they use approximately 300 m/s. Like the Nagy et al. model, Cravens et al. consider a 2-dimensional model that solves the coupled continuity and momentum equations using empirical plasma temperatures rather than solving the energy equation as done by Chen and Nagy. The relevant dayside physical and chemical processes, except for the horizontal ion flow, are handled in essentially the same fashion as Nagy et al. [1980]. The neutral atmospheric densities used are similar to those derived from Hedin et al. [1983] which are about 60% greater than the values measured by the PVO neutral mass spectrometer [Niemann et al.,1980]. Although they do not include a complete description of the neutral model, they list dayside values of [CO₂] and [O] with an exospheric temperature of 292° K. With these assumptions, they calculate the ion densities for CO₂⁺, O₂⁺, O⁺, C⁺, He⁺, and either N⁺ or NO⁺ but not both. Unfortunately for our purpose, they concentrate their results on the nightside ionosphere and do not present dayside results. However, they do report good agreement between their results and those of Nagy et al. [1980] and conclude that one dimensional models are satisfactory descriptions of the dayside ionosphere.
Shimazaki et al. (1984)

Similar to the Nagy model, the Shimazaki model describes dayside ion density distributions without considering horizontal dynamics. They demonstrate the effects on ion densities by using different neutral density models. Neutral density profiles are calculated at different SZA where exospheric temperatures are assumed to vary from 225 - 300° K. These values are determined by PV measurements that show exospheric temperatures to be ~ 285° K at small SZA. In these neutral density calculations, they consider eddy and molecular diffusion that includes 21 neutral-particle reactions for an altitude range of 120-500 km.

Different combinations of [CO\textsubscript{2}] and [O] are assumed for modeling ion densities to determine which neutral model most successfully compares with observation. In determining the best model fit with the ORPA data, the values of [CO\textsubscript{2}] and [O] are 10\textsuperscript{12} and 5 × 10\textsuperscript{10} cm\textsuperscript{-3} respectively. At 150 km, the densities are both approximately 3 × 10\textsuperscript{9} cm\textsuperscript{-3}. An exospheric temperature of 250° K modeled at ~ 70° SZA is also included to determine neutral densities. Plasma temperatures are taken from ORPA measurements and assumed to equal neutral temperatures below 155 km.

Below 200 km, calculations show [O\textsubscript{2}\textsuperscript{+}] agrees well with ORPA measurements but is smaller than the corresponding OIMS values (by a factor of ~ 2). Also, [O\textsuperscript{+}] and [CO\textsubscript{2}\textsuperscript{+}] fit ORPA measurements within a factor of 2 but show less agreement with OIMS observations.

Above 200 km, [O\textsuperscript{+}] is slightly larger than ORPA values (a factor of 1.5) and the molecular ions are much less than observations (OIMS and ORPA). ORPA values are approximately 2 orders of magnitude larger than the modeled
molecular ions for altitudes greater than 250 km. Also, the general behavior of these ions does not model the OIMS and ORPA observations. Specifically, the gradient of these ions becomes less with increasing altitude and appear to turn up in ion profile graphs. In attempt to modify this behavior, they included vertical escape fluxes of O\(^+\) ions \((10^8 \text{ O}^+ \text{ ions cm}^{-3} \text{ s}^{-1})\). \([\text{O}^+]\] decreased to values very close to measurements; and though the behavior remained unchanged, \([\text{O}_2^+]\] increased by an order of magnitude while \([\text{CO}_2^+]\] increased only slightly.

**Solar Wind Interaction**

Models of the solar wind interaction with the atmosphere of Venus have been developed in a series of papers [Cloutier et al., 1969; Cloutier and Daniell, 1973; Cloutier et al., 1974; Cloutier, 1976; Daniell and Cloutier, 1977; Cloutier and Daniell, 1979; Cloutier et al., 1981]. From these models, it is shown that the Venus ionosphere acts as a hard obstacle to the solar wind and deflects most of the flowing plasma around the planet. Only a few percent of the solar wind flux is absorbed as a result of the formation for an upstream shock in response to mass loading of photoions to the flow. The interaction drives convection within the ionosphere from pressure gradients and electric fields induced by the flowing magnetized solar wind. Electric currents are produced by the induced electric field which flow within the ionosphere and connect across the ionopause surface to the post-shock solar wind where the total current is assumed to be a combination of ohmic and diamagnetic currents.

The current configuration and convection pattern are calculated by a variational technique that requires the joule heating to be a minimum over the
volume of the ionosphere. Electric fields are assumed to be related to the ionospheric currents by a form of Ohm's law where the conductivity is represented by a tensor. This assumes that variations in the plasma velocities are small (i.e. the convective derivative of the velocity set equal to zero), and the plasma is in hydrostatic equilibrium.

Since the conductivity tensor depends on ionospheric parameters, an iterative process is used to calculate the magnetic field, current density, electric field, electron density, and convection velocity. This is accomplished by choosing the initial conditions for the various parameters in the ionosphere to determine the conductivity, and then solving for the current density and the electric field everywhere. If the plasma temperatures and densities are known, the magnetic field is recalculated by using Ampere's law. The conductivity tensor is then recalculated with the new magnetic field and the process is repeated until a self-consistent solution is obtained where the solution from the variational principle is consistent with Ampere's law. However, if the plasma densities are not known, the convection velocity is determined by $E \times B$ drift, and the continuity equation is used to calculate the electron density in the same iterative process used for calculating the magnetic field. Further assumptions used in calculating the conductivity include the neutral composition and plasma temperatures in the ionosphere.

Results of these calculations show that currents are distributed throughout the ionosphere with a concentration at low altitudes where the conductivity is large. The vertical magnetic field profile is shown to be constant above 200 km and decreases rapidly near 150 km. Convection velocities within the ionosphere are shown to be mainly horizontal with a small radial velocity of $\sim 3$ m/s near the subsolar point, and the horizontal speeds vary from 0.1 to 100 km/s.
3. MODEL CALCULATION

We now consider the problem of calculating the ion density distribution in the dayside Venusian ionosphere. To help understand the physical processes in the ionosphere, the ion densities are modeled by assuming different 2-dimensional velocity fields that are similar to measurement (see Knudsen et al., 1982) and results of the solar wind interaction models [Cloutier et al., (1983)]. As discussed in the previous section, the solar wind interaction models calculate convective flows (due to $E \times B$ drifts) that are mainly horizontal in the dayside ionosphere with speeds that vary from ~3 to .1 km/s at 300 and 200 km, respectively, at 45° SZA (Figure 2). The model calculations are not self-consistent in the sense that the continuity, momentum, and energy equations are satisfied simultaneously; instead, the ion densities are calculated from the continuity equation:

$$\nabla \cdot (n_i \mathbf{V}) = P_i - L_i$$

(1)

The $n_i$ terms represent the number density of the $i^{th}$ ion species for $\text{He}^+$, $\text{H}^+$, $\text{N}_2^+$, $\text{N}^+$, $\text{CO}^+$, $\text{O}^+$, $\text{CO}_2^+$, and $\text{O}_2^+$; however, only three major ions ($\text{CO}^+$, $\text{CO}_2^+$, and $\text{O}_2^+$) are shown in the results. The production and loss rates are $P_i$ and $L_i$ respectively, which depend upon the ion and electron density. $\mathbf{V}$ is the velocity field which is assumed to model the flow.

3.1 Ionospheric parameters

The neutral density model used in the ion density calculations for determining processes such as photoionization and ion-neutral reactions is derived
from considering different experimental observations. A detailed discussion of these observations given by [Von Zahn et al., 1983] reports that the atmospheric drag experiments of Keating et al. [1980] are generally 60% larger than those of the orbital neutral mass spectrometer (ONMS). With respect to this, the model of Niemann et al. [1980] is adopted. The values of the subsolar point are multiplied by a factor of 1.6 and used for all solar zenith angles. Consequently, the neutral densities of CO, CO$_2$, O, N, N$_2$, and He are known. The other neutral densities included are H and NO; the H densities are adopted from a model by Krasnopol'sky and Parshev [1980], and NO was obtained from calculations of Rush and Cravens [1979].

Since the loss of ions due to dissociative recombination depends on the electron temperature, a model of the electron temperature is derived from Theis et al. [1984]. The solar zenith angle variation of the electron temperature is not included because the temperature varies about 10% from subsolar to terminator.

In calculating the photoionization rates, the solar EUV flux values are obtained from Hinteregger [cf. Torr et al. 1979] for 1979 conditions. The photoionization and photoabsorbtion cross sections for CO, CO$_2$, O, He, and N$_2$ were taken from Torr et al. [1979], and the production rate for N was derived from Rush and Cravens. From this information, the production rate for each constituent, $P_j(z)$ at altitude $z$ is calculated by

$$P_j(z) = n_j(z) \sum_\lambda \sigma_{ij}(\lambda) F_\lambda(\lambda) \exp(-\sec\psi \cdot \sum_\lambda \sigma_{aj}(\lambda) H_j(z) n_j(z))$$  \hspace{1cm} (2)$$

In equation (2), $n_j(z)$ is the neutral constituent, $\sigma_{ij}(\lambda)$ and $\sigma_{aj}(\lambda)$ are the photoionization and photoabsorption cross sections for the $j^{th}$ constituent at
wavelength $\lambda$ respectively, $F_\infty(\lambda)$ is the solar flux upon the top of the atmosphere for the given wavelength, $H_j(z)$ is the scale height, and $\psi$ is the solar zenith angle. Nagy et al. [1980] have concluded that the contribution of photoelectron impact ionization to the total ion production rate above the ionization peak at $\sim 140$ km is about 10%; therefore it is not included as a source of production in these models.

Table 1 and Figure 3, respectively, summarize the chemical reactions and the overall chemistry scheme used in the model calculations. Particularly significant reactions include the production of $O_2^+$ from $CO_2^+$ with O and the reaction involving $O^+$ with $CO_2$, which have reaction rate coefficients given by R6 and R8 respectively. Losses of $O_2^+$ are due mainly to dissociative recombination with a reaction rate coefficient expressed by R28, and minor losses from ion-neutral reactions with N which has a rate coefficient given by R13. $O^+$ is produced mainly by photoionization and reaction R3 involving $CO_2^+$, while the losses are through reactions R8 and R11 that involve $CO_2$. The third major ion, $CO_2^+$, is produced by a combination of photoionization and reactions R1, R11, and R2. The charge exchange reaction of $O^+$ and $CO_2$ giving $CO_2^+$ is endothermic and assumed to occur for flow speeds greater than $\sim 1$ km/s which is an altitude dependent process. Losses involve dissociative recombination given by R29 and ion-neutral reactions R5 and R6 that involve O. C$^+$ has not been included in the model since its neutral composition is not known; however, this is not expected to alter the major ion composition since it contributes to the production of $CO^+$ at lower altitudes which would become a minor increase of $CO_2^+$ by reaction R1.
3.2 Results

The calculations are simplified by assuming that the subflow point and subsolar point are coincident even though this is not true in general. Hence, the ion densities are calculated in the plane defined by the Sun-Venus line with arbitrary angle of rotation about this axis. Since the average ionopause height at the subsolar point is ~ 300 km (Brace et al., 1980), the ionopause is considered to be spherical about the center of Venus with radius equal to 6350 km, which corresponds to an altitude of 300 km. Boundary conditions require values for the ion densities along the ionopause and are determined by using known densities at the subsolar point and Newtonian pressure balance

\[ P_1 = \rho_\infty V_\infty^2 \cos^2(\psi) \]

where \( \psi \) is the solar zenith angle, \( \rho_\infty \) and \( V_\infty \) are the upstream densities and velocities, and \( P_1 \) is the total ion pressure. The ion densities are then determined by integrating the continuity equation along each of the streamlines by calculating each ion density according to the chemistry scheme represented in Figure 3. Since dissociative recombination depends on the electron density, the calculation is iterated until the total ion density is equal to the electron density to insure electric neutrality.

The first set of figures (Figures 4 - 8) illustrate the situation where the flow is composed of radial and horizontal velocities, and the calculated density profiles are the best fit of these model calculations to the OIMS observations. Figure 4 shows the streamlines plotted as a function of altitude (or radial distance above the surface) and solar zenith angle. The streamlines are shown to be mainly radial near the subsolar point and below 200 km. To avoid problems involving
variations in some of the parameters with increasing solar zenith angle, the calculation is terminated at 40 degrees. The speed-altitude profile in Figure 5 plots the velocity components against altitude for various SZA. At 150 km, the speed is about 20 m/s and increases quickly to approximately 1 km/s at 200 km. The speed increases slowly from 200 km to 300 km where it becomes approximately 3 km/s. For SZA > 10°, the flow is mainly horizontal above 200 km with radial speeds < 100 m/s. Below 200 km, the flow is a combination of horizontal and radial velocities where the maximum radial speeds are ~ 500 m/s at 180 km.

The results of the calculations appear in Figures 6-8, which are density-altitude profiles for different solar zenith angles: 0°, 20°, and 40° respectively. The charge exchange reaction involving O⁺ and CO₂ to give CO₂⁺ is included for all heights in the calculations for comparison, but it is important to remember that the actual densities at lower altitudes for O⁺ and CO₂⁺ will be larger and smaller, respectively. This is demonstrated in these figures by including density calculations that exclude reaction R11 below 185 km where the speed is about 1 km/s. The CO₂⁺ values decrease by a factor of 5, and [O⁺] decreases slightly. It is also of interest to note that the O₂⁺ density is not affected when this charge exchange reaction (R11) is included. Figure 8 shows the model calculation at 40° compared to the measured values obtained from Taylor, which are averaged over 30° - 50°, and the error bars represent one standard deviation from the average. As in Figure 6, both types of ion distributions are included: with and without the charge exchange reaction giving CO₂⁺. Below 200 km, the agreement between measured and modeled densities appears to be good for O₂⁺ and O⁺. The CO₂⁺ measurement from Taylor shows the density to remain almost constant in
altitude below 175 km. This typically occurs at a concentration of $10^4$ cm$^{-3}$ where an instrument mode change occurs and the constant density may be an instrumental artifact (H. A. Taylor, private communication).

To understand the 2-dimensional model calculations in the previous section, it is instructive to consider several examples of 1-dimensional models involving varying speed-altitude profiles at 0° solar zenith angle. The density-altitude profiles in Figures 9-13 are calculated using the chemistry and ionospheric parameters discussed earlier. The charge exchange reaction, R11, is included at all altitudes for comparison, and only the speed parameter is allowed to vary in the different models. Figure 9 is an example of downward convection with an exponential velocity profile that has an e-folding scale length of approximately 46 km, and the speed varies from 4 km/s at 300 km to 200 m/s at 150 km. Starting at the top and working downward, all ion densities increase in decreasing altitude with a scale length equal to the speed scale length since $\nabla \cdot (n \, \mathbf{V}) \sim 0$ in the region where production and loss processes are small compared to convective processes. The density of each ion continues to increase until chemical loss processes become important.

Examining each ion profile separately, CO$_2^+$ increases in decreasing altitude until losses from reactions involving O are comparable to convection at $\sim 230$ km. Below this, CO$_2^+$ decreases slightly in this region since $\mathbf{V} \cdot \nabla n \sim -L$, where L represents the chemical losses. Production dominates losses below 210 km and the density increases again until losses are comparable at $\sim 185$ km where a peak forms. In this case, production is due mainly from reactions involving O$^+$ with CO$_2$; otherwise, solar production would dominate and the peak would not be observed. At $\sim 170$ km, convection becomes small and
photochemical equilibrium is established.

Simpler in structure, O$^+$ is determined by downward convection to $\sim$ 190 km, where losses from reactions with CO$_2^+$ (R8 and R11) become important and produce a peak that is $\sim 10^5$ cm$^{-3}$. As with CO$_2^+$, convection remains important to 170 km and then chemistry dominates below.

O$_2^+$, the last ion to be considered, is dominated by convective processes to about 220 km where production from CO$_2^+$ and O$^+$ (R6 and R11) are important. The density continues to increase to about 175 km where a bump is formed as a result of convection and production. It is important to note that the production rates from O$^+$ (R8) and CO$_2^+$ (R6) are approximately equal in the altitude range of 150 - 200 km, and that a decrease in CO$_2^+$ will not significantly change the O$_2^+$ density profile. Overall, the density profiles are similar to the measurements with regard to the O$_2^+$ bump; however, the O$^+$ density values are larger than the data, and the O$_2^+$ peak density is smaller.

Figure 10 is an example of convection in which the speed profile is basically the same as that used in the 2-dimensional model calculations. In comparison with Figure 9, the speed profile is composed of two scale lengths. At high altitudes, the scale length is less than in the previous case and becomes larger at lower altitudes. The net effect is enhanced densities at lower altitudes, since convection is important in lower regions. Specifically, O$^+$ at higher altitudes does not have a peak density as large as seen in Figure 9, since the speed scale length is less; and below 190 km, the density is increased. Hence, with larger production rates due to an increase in the O$^+$ density and convective processes, the O$_2^+$ peak is larger and at lower altitudes than in the previous example.
In comparison with Figure 10, Figures 11-13 involve convection with the same basic speed-altitude profile, except that the velocity at 300 km decreases in the sequence of plots. Convection becomes less important in the sequence of model calculations as seen in these figures, which results in decreasing ion peak densities that occur at higher altitudes. The $O_2^+$ peak gradually disappears in the figure sequence and becomes smooth in Figure 13, which indicates that convective processes are less important for smaller speeds and photochemical equilibrium dominates at higher altitudes.

As another example, a 2-dimensional model is calculated for the streamline geometry shown in Figure 14. The flow is radial and downward for a large region near the subsolar point and becomes mainly horizontal for solar zenith angles greater than 30°. The speed-altitude profile is basically the same as that used in the previous 2-dimensional model calculation and the 1-dimensional model in Figure 10; consequently, the results near the subsolar point in Figure 16 are essentially the same as those in Figure 10 for the above reasons. For larger solar zenith angles, the flow is horizontal, and the speed profile does not change with increasing angle. The sequence of plots shows the density variation with solar zenith angle. The $O_2^+$ peak is seen only in regions where downward flow is sufficient; and for SZA $> 20^\circ$, the flow is mostly horizontal and the peak is not observed.
4. DISCUSSION

In the previous chapter, the 2-dimensional calculation that most successfully models the OIMS measurements is solved using a convection pattern that agrees in general with ORPA observations. The measured $O^+$ velocities [Knudsen et al., 1982] are mainly horizontal except near the subsolar point and low altitudes. Low altitude measurements show radial and horizontal velocity components that are approximately equal for SZA $< 50^\circ$. Also, measurements indicate that velocities are mainly radial at the subsolar point with speeds substantially smaller than in other regions. In comparison with these measurements, the model speeds in the subsolar region are $\sim 3$ times the values that the data suggests. Outside this region, the model and measured speeds are approximately equal. Excluding these large radial convection speeds (0.5 - 1.0 km/s) in the subsolar region as the data indicates, the model densities disagree with measurements in the altitude ranges of interest. For radial speeds less than .5 km/s, the $O_2^+$ peak density is not modeled in the low altitude range of 150 - 190 km, and the molecular ion behavior is not modeled above 200 km. At high altitudes, data and model densities differ by 2 orders of magnitude, and $[CO_2^+]$ is not modeled well except near 150 km.

Another problem associated with this model is the effect produced by flow lines diverging from the subflow point. For SZA $< 40^\circ$, the model shows that flow geometry does not significantly affect ion densities below 200 km, however; the distance between flow lines increases with SZA. As the flow lines diverge, densities are expected to decrease with increasing SZA which is contrary to observations. Also, since the flow originates in a small region about the subflow point, 3-dimensional effects are important in determining densities. This
enhances the flow line divergence and will further decrease ion densities.

Increasing the region where the downward flow originates at the ionopause (in the subsolar region) decreases these geometric effects, however; this region in the model is approximately the maximum area that is consistent with Faraday's law for steady state conditions. To estimate the size of this region, consider a contour along the ionopause that connects to the lower ionosphere near the terminator. The contour continues along the lower ionosphere boundary and forms a closed loop through the subflow line. Since the flow speed is approximately $E/B$ near the ionopause, $E = 10^{-4}$ V/m in the subflow region assuming $B = 100 \gamma$. Near the terminator, $E = 8 \times 10^{-5}$ V/m given $B = 20 \gamma$ and horizontal speeds of 4 km/s. Along the lower ionosphere boundary, $E = 10^{-6}$ V/m which contributes little to the line integral around the contour. For an ionosphere thickness of $10^3$ km near the terminator (and assuming a constant electric field along the contour), the maximum distance along the ionopause (where the radial speed $\approx$ 1 km/s) is $< 10^3$ km. This represents an upper limit to the horizontal distance of the downward flow region and constrains large radial velocities (along the ionopause) to SZA $< 10^\circ$ from the subflow point.

Even though the 2-dimensional model calculations agree well with OIMS measurements for SZA $< 40^\circ$, the model in 3-dimensions is expected to disagree with observations for SZA $> 40^\circ$ due to flow line divergence. Furthermore, no evidence exists either in theory or measurements that suggests radial speeds $\approx$ 1 km/s. Therefore, the model calculations presented as the best fit to observation are not regarded as a realistic approximation to the situation in the dayside ionosphere.
Other ionospheric convection studies show that low altitude densities of $O_2^+$ peak densities of $\sim 2 \times 10^5 \text{ cm}^{-3}$ are calculated for flow that originates at the ionopause and rapidly becomes horizontally directed near 180 km. Flow speeds are assumed to be small ($\sim 50 \text{ m/s}$) which are constant for all SZA and altitude ranges. In the low altitude region, the horizontal flow lines are concentrated in a narrow altitude range of $\sim 20 \text{ km}$. Although this type of model shows $O_2^+$ behavior similar to measurement, the model is not acceptable since there are no physical mechanisms to rapidly change the flow direction.

With respect to flow line geometry, previous ionospheric models consider the flow to be constrained to the horizontal direction, however; this is not necessarily true. Below $\sim 200 \text{ km}$, ion-neutral collision frequencies ($\nu_i$) and ion-cyclotron frequencies ($\omega_i$) are equal at an altitude that depends on the magnetic field strength. For $B = 100 \gamma$ and ionospheric parameters taken from Theis et al., (1984), this altitude is about 180 km. With the approximation that vertical current densities are small ($\sim 0$) and radial pressure gradients balance gravitational forces, electric field components are equal and opposite for $\nu_i = \omega_i$, where the tensor form of Ohms law is used (Krall and Trivelpiece, 1973). In this region, the field direction changes from near horizontal to vertical with decreasing altitude. For $\nu_i < \omega_i$ (near 200 km), the flow is directed downward in the direction defined by $\mathbf{E} \times \mathbf{B}$. At lower altitudes where $\nu_i > \omega_i$, the flow is directed with a component parallel to $\mathbf{E}$ due to collisions with neutrals. Even though this is a simplified argument, these conditions agree fairly well with observations between 180 - 200 km; therefore, the flow is expected to be deflected toward the planet at low altitudes.
Since the flow is expected to have a radial component for all SZA below 200 km, the $O_2^+$ behavior may be explained by accelerating flows at low altitudes. As discussed before, convection is dominant for large speeds that increase (or decrease) substantially in short distances at low altitudes. Models with accelerating flows in this region, show that $O_2^+$ is similar to observation in behavior; however, the peak density is $\sim 1/3$ as large as OIMS measurements. Recently, Cloutier (1986) verified this by solving the coupled MHD equations in the vertical direction and concludes that a shock forms in this region. At this time, this is the best physical explanation of the problem and will be investigated in further detail for 2-dimensions.

Finally, it is of interest to consider photochemical equilibrium models that match OIMS measurements of $[O_2^+]$. To reproduce $O_2^+$ measurements, $[CO_2] = [O] = 9 \times 10^9$ cm$^{-3}$, and photoproduction rates of $O^+$ are twice the calculated values obtained from using equation (2). Electron temperatures fit measurement within a factor of 2 and increase rapidly with altitude. Since the total neutral density is larger than measurements indicate, this model is not considered to be correct and implies $[O_2^+]$ is not a result of photochemical equilibrium.
5. CONCLUSIONS

To date, OIMS observations of \([\text{O}_2^+]\) in the dayside ionosphere of Venus are not modeled. The data illustrate peak densities of \(\text{O}_2^+ (\sim 4 \times 10^5 \text{ cm}^{-3})\) at \(\sim 175\) km for all SZA covered by PVO. Previous ionospheric models assume horizontal flow with vertical diffusion as mechanisms for plasma transport and model \([\text{O}_2^+]\) without exhibiting a peak above \(150\) km.

Instead of attempting to solve the coupled MHD equations, ion flow velocities are assumed and the continuity equation is solved in 2-dimensions. This provides a method to investigate the relation between ion densities and convection. From these studies, the ion flow is believed to be directed downward (not completely radial) for all SZA below 200 km. At low altitudes, \([\text{O}_2^+]\) is shown to be depleted (or enhanced) for large downward velocities (\(\sim 500\) m/s) that change rapidly within short distances (\(\sim 10\) km). For increasing velocities, \(\text{O}_2^+\) densities are reduced in this region which agrees in behavior (not density) with OIMS measurements.

Providing further support that downward flow exists at low altitudes, Cloutier (1986) recently solved the coupled MHD equations in the vertical direction using small downward velocities (\(\sim 50\) m/s) at the ionopause. At low altitudes, ion flow increases with decreasing altitude where it forms a shock, and therefore \(\text{O}_2^+\) densities decrease and form a peak above 150 km. Since there is better understanding of the physical processes involved in the dayside ionosphere, future work will be concentrated on self-consistent MHD solutions in 2-dimensions.
FIGURE CAPTIONS

1. Vertical density profiles of OIMS data and theoretical calculations for 0° SZA taken from Nagy et al., (1980). Solid lines represent model values and labeled points (O⁺, CO₂⁺, and O₂⁺) are the OIMS values averaged between 0 and 30° SZA.

1.1a Representation of the ionospheric streamlines calculated by Daniell and Cloutier (1977) which show the flow to be mainly horizontal.
1.1b Model calculations of plasma flow at 30° SZA. Horizontal velocity profile determined from electrodynamic model where the velocity increases exponentially from lower altitudes toward the ionopause.

2. OIMS values for O⁺, CO₂⁺, and O₂⁺. Values are averaged over 30 - 50° SZA.

3. Chemistry scheme used in model calculations. Broken line indicates the endothermic reaction, RN11, used in the model.

4. Streamline geometry used in model. Results using this geometry are given in Figures 6 - 8. Streamlines are plotted as altitude against solar zenith angle (SZA).

5. Velocity profiles for streamlines given in Figure 4. Horizontal and radial components are plotted separately for 0, 20, 30, and 40° SZA. Horizontal and radial components are represented by broken and solid lines respectively. The maximum speed is ~ 3 km/s at 300 km.
6. Vertical density profiles calculated at 0° SZA for flow described by Figures 4 and 5. The profiles labeled O\(^+\), CO\(_2\)\(^+\), and O\(_2\)\(^+\) are calculated with reaction RN11. Parenthesis indicate that RN11 is excluded below 200 km, e.g. (O\(^+\)) and (CO\(_2\)\(^+\)).

7. Vertical density profiles calculated at 20° as in Figure 6.

8. Vertical density profiles calculated at 40° SZA. Square, triangle, and oval symbols represent CO\(_2\)\(^+\), O\(_2\)\(^+\), and O\(^+\), respectively. Error bars represent 1 sigma deviation in measurements which are averaged over 30 - 50°

9. Density profiles calculated in 1-dimension at 0° SZA for downward (radial) velocity. Flow speed is labeled at top where the axis varies from .1 - 10 km/s, and the unmarked solid line represents the speed profile. At 300 km, the speed is ~ 4 km/s and decreases exponentially to ~ 200 m/s at 150 km.

10. Vertical density profiles are calculated for downward flow as in Figure 9. In comparison with Figure 9, flow speed varies more rapidly below ~ 200 km, and the O\(_2\)\(^+\) peak is larger and appears at a lower altitude.

11. Density profiles as in Figure 9. At 300 km, the speed is ~ 2 km/s. Speeds vary rapidly below 200 km and are ~ 500 m/s at 180 km.

12. Density profiles as in Figure 9. Speeds are smaller than shown in previous figures. At 180 km, the speed is approximately 400 m/s and the O\(_2\)\(^+\) peak is smaller than in the previous figure.

13. Vertical density profiles calculated as in Figure 9. Below 200 km, speeds are < 400 m/s and approach ~ 700 m/s at 300 km, and O\(_2\)\(^+\) peak is not shown
as in previous figures.

14. Streamline geometry used in model calculation. Flow is mainly downward for angles $< 20^\circ$, and is mainly horizontal for SZA $> 30^\circ$. Results from using this streamline geometry are shown in Figures 16 - 18.

15. Velocity components corresponding to the streamline geometry shown in Figure 14. Broken and solid lines are horizontal and vertical velocity components respectively. Components are labeled according to SZA (3, 20, 40, 60$^\circ$).

16. Vertical density profiles calculated at 3$^\circ$ using flows described by Figures 14 and 15.

17. Vertical density profiles calculated at 20$^\circ$ SZA for flow defined by Figure 14 and 15.

18. Vertical density profile calculated at 40$^\circ$ SZA as in Figures 16 and 17 where the peak density of O$_2^+$ is not seen.
<table>
<thead>
<tr>
<th>REACTION NUMBER</th>
<th>REACTION</th>
<th>RATE CONSTANT (cm(^{-3}) s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>CO(^+) + CO(_2) → CO(_2)^+ + CO</td>
<td>1.0 × 10^{-9}</td>
</tr>
<tr>
<td>R2</td>
<td>CO(^+) + NO → NO(^+) + CO</td>
<td>3.3 × 10^{-10}</td>
</tr>
<tr>
<td>R3</td>
<td>CO(^+) + O → CO(_2)^+ + CO</td>
<td>1.4 × 10^{-10}</td>
</tr>
<tr>
<td>R4</td>
<td>CO(^+) + N → NO(^+) + C</td>
<td>2.0 × 10^{-11}</td>
</tr>
<tr>
<td>R5</td>
<td>CO(_2)^+ + O → O(^+) + CO(_2)</td>
<td>9.6 × 10^{-11}</td>
</tr>
<tr>
<td>R6</td>
<td>CO(_2)^+ + O → O(_2)^+ + CO</td>
<td>1.6 × 10^{-10}</td>
</tr>
<tr>
<td>R7</td>
<td>CO(_2)^+ + NO → NO(^+) + CO(_2)</td>
<td>1.2 × 10^{-10}</td>
</tr>
<tr>
<td>R8</td>
<td>O(^+) + CO(_2) → O(_2)^+ + CO</td>
<td>9.4 × 10^{-10}</td>
</tr>
<tr>
<td>R9</td>
<td>O(^+) + N(_2) → NO(^+) + O</td>
<td>1.2 × 10^{-12}</td>
</tr>
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<td>R10</td>
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<tr>
<td>R11</td>
<td>O(^+) + CO(_2) → CO(_2)^+ + O</td>
<td>1.0 × 10^{-9}</td>
</tr>
<tr>
<td>R12</td>
<td>O(_2)^+ + NO → NO(^+) + O(_2)</td>
<td>4.5 × 10^{-10}</td>
</tr>
<tr>
<td>R13</td>
<td>O(_2)^+ + N → NO(^+) + O</td>
<td>1.2 × 10^{-10}</td>
</tr>
<tr>
<td>R14</td>
<td>N(_2)^+ + CO → CO(^+) + N(_2)</td>
<td>7.4 × 10^{-11}</td>
</tr>
<tr>
<td>R15</td>
<td>N(_2)^+ + CO(_2) → CO(_2)^+ + N(_2)</td>
<td>7.7 × 10^{-10}</td>
</tr>
<tr>
<td>R16</td>
<td>N(_2)^+ + O → NO(^+) + N</td>
<td>1.4 × 10^{-10}</td>
</tr>
<tr>
<td>R17</td>
<td>N(_2)^+ + O → O(^+) + N(_2)</td>
<td>1.0 × 10^{-11}</td>
</tr>
<tr>
<td>R18</td>
<td>N(^+) + CO → CO(^+) + N</td>
<td>4.0 × 10^{-10}</td>
</tr>
<tr>
<td>R19</td>
<td>N(^+) + CO(_2) → CO(^+) + NO</td>
<td>2.5 × 10^{-10}</td>
</tr>
<tr>
<td>R20</td>
<td>N(^+) + CO(_2) → CO(_2)^+ + N</td>
<td>7.5 × 10^{-10}</td>
</tr>
</tbody>
</table>

**TABLE 1**
R21  $N^+ + NO \rightarrow NO^+ + N$  $9.0 \times 10^{-10}$
R22  $He^+ + CO_2 \rightarrow CO^+ + O + He$  $8.7 \times 10^{-10}$
R23  $He^+ + CO_2 \rightarrow CO_2^+ + He$  $1.2 \times 10^{-10}$
R24  $He^+ + CO_2 \rightarrow O^+ + CO + He$  $1.0 \times 10^{-10}$
R25  $H^+ + CO_2 \rightarrow CHO^+ + O$  $3.0 \times 10^{-9}$
R26  $H^+ + NO \rightarrow NO^+ + H$  $2.0 \times 10^{-9}$
R27  $H^+ + O \rightarrow O^+ + H$  $2.2 \times 10^{-11} \sqrt{T_I}$

R28  $O_2^+ + e^- \rightarrow O + O$  $1.6 \times 10^{-7} \times (300/Te)^{55}$
R29  $CO_2^+ + e^- \rightarrow CO + O$  $3.8 \times 10^{-7} \times (300/Te)$
R30  $CO^+ + e^- \rightarrow C + O$  $2.0 \times 10^{-7}$
R31  $NO^+ + e^- \rightarrow N + O$  $4.2 \times 10^{-7} \times (300/Te)^{85}$
R32  $N_2^+ + e^- \rightarrow N + N$  $1.8 \times 10^{-7} \times (300/Te)^{39}$

**TABLE 1**
FIGURE 1
FIGURE 1.1
FIGURE 2
FIGURE 5
FIGURE 7
FIGURE 14
FIGURE 15
FIGURE 17
FIGURE 18
References


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