change production of energetic O_2^+ (*7*) is estimated to be less by an order of magnitude than that needed to raise the ion temperatures to the measured temperature. A small heat input to the ions of 1.7×10^{-4} erg cm^{-2} sec^{-1} uniformly distributed in altitude above 230 km was included to bring the model ion temperatures at high altitude into agreement with the measurements. Solar wind heating or Joule heating, or both, are possible sources for this heating. This latter ion heat input is approximately half of that which Cravens *et al.* had assumed would be present prior to the Pioneer Venus measurements (*8*).

We have assumed in the above computations of heat flux through the electron gas for both day and night that the magnetic field is sufficiently weak to be neglected or, equivalently, that the field is parallel to the heat flow. However, a magnetic field with a magnitude of 1 gamma and perpendicular to the direction of heat flow is expected to greatly reduce the heat conductivity. We have found it possible to match the observed dayside electron temperature profile reasonably well by reducing the heat conductivity by 20 percent and assuming no heat influx at the top boundary. With this modification, photoelectron heating of the electron gas was sufficient to heat the electrons to the observed temperature. Nevertheless, the electron gas heat conductivity within the ionosphere must be substantially greater than it is in the region of the ionopause boundary. The rapid decrease in T_e is going from the shocked solar wind into the ionosphere and the nearly constant temperature with altitude just inside the ionosphere imply an increase in the thermal conductivity within the ionosphere.

If the electron gas within the ionosphere has a conductivity that is close to its magnetic field-free value ($K_{ei} = 9 \times 10^{-7} T_e^{(5/2)}$ erg cm^{-1} sec^{-1} K^{-1}), it will conduct into the neutral atmosphere a substantial fraction of the solar wind energy expended in drag on the sunward ionopause hemisphere. The heat flux Q through the electron gas averaged over the day- and nightsides will be of the order of 0.05 erg cm^{-2} sec^{-1}. The energy expended in drag is equal to the product of the solar wind velocity v and the pressure $nm_pv^2 \cos^2$ SZA integrated over the sunward ionopause hemisphere, where n is the solar wind proton concentration and m_p is the proton mass. Thus, the upper bound for the fraction f of heat conducted into the atmosphere becomes

$$f = \frac{4\pi r^2 \cdot Q}{\pi r^2 \cdot 1/2 n m_p v^3} \simeq 0.1$$

where r is the radius of the ionopause. We have taken n to be 20 cm^{-3} and v to be 450 km sec^{-1}. This is a significant fraction of the expended energy and has significant implications for the theory of the solar wind–ionosphere interaction.

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Comparison of Calculated and Measured Ion Densities on the Dayside of Venus

Abstract. *Data from the Pioneer Venus ion mass spectrometers are compared with model calculations of the ion density distributions appropriate for daytime conditions. The model assumes diffusive equilibrium upper boundary conditions for the major ions (O_2^+, O^+, CO_2^+, He^+, and H^+); the agreement between the calculated and measured gross behavior of these ions is reasonably good except for H^+, which may be influenced strongly by convective transport processes. The distributions of five minor ions (C^+, N^+, NO^+, CO^+, and N_2^+) are also calculated for the chemically controlled region ($\lesssim$ 200 kilometers); the agreements are, in general, poor, an indication that our present understanding of the Venus minor ion chemistry is still incomplete.*

Data from the Pioneer Venus instrument complement (*1*) are providing the most comprehensive set of observations ever obtained of a planetary ionosphere-atmosphere system other than the terrestrial one. The purpose of this report is to present the results of model calculations of the ion density distribution of the dayside Venus ionosphere and to compare these with the observed

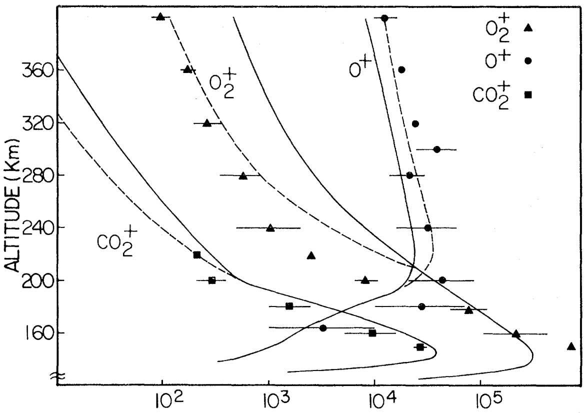

Fig. 1. Calculated ion density profiles for O^+, O_2^+, and CO_2^+. Data from OIMS and BIMS are also shown. The curves with dashed lines are for inhibited diffusion coefficients.

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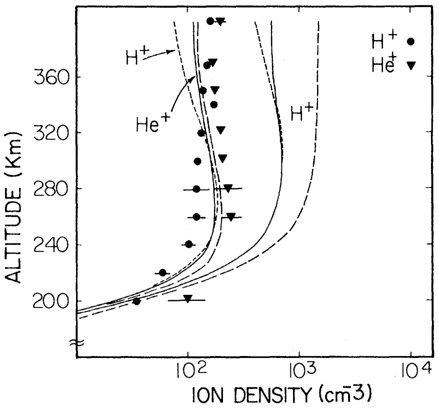

Fig. 2. Calculated ion density profiles for He^+ and H^+. Data from OIMS and BIMS are also shown. The curves with long dashes are for inhibited diffusion. The curves with short dashes are for an H^+ outflow of 500 m/sec at the upper boundary.

profiles in order to test and improve our understanding of some of the wide range of chemical and physical processes which control the ionosphere.

The model used for the calculations presented here is a modified and updated version of the one described in (*2*). This model is based on the solutions of the coupled continuity, momentum, and energy equations for electrons and the ion species under consideration. For the present set of calculations the energy equations were not solved simultaneously; instead, the measured electron and ion temperatures (*3*) were adopted. A study of the energetics of the dayside ionosphere was published separately (*4*). The effects of thermal diffusion were included in the momentum equations, and, on the basis of earlier findings, the horizontal bulk transport effects, caused by neutral winds, were neglected (*2*). The chemistry scheme used for the major ion production and loss processes is the one outlined earlier (*5*). We calculated the photoionization rates using (i) the solar extreme ultraviolet (EUV) flux data of Hinteregger and his co-workers appropriate for 1978 solar conditions (*6*) and (ii) the various photoabsorption and photoionization cross sections referenced by Banks and Kockarts (*7*) and by Cravens and Green (*8*). The standard diffusion coefficients were calculated in the same manner as in earlier work (*2*), and the thermal diffusion coefficients were adopted from St. Maurice and Schunk (*9*).

The initial Pioneer Venus daytime measurements are for solar zenith angles greater than 60°; the model calculations presented here were carried out for conditions representative of about 70°, which was considered to be a reasonable compromise between data availability and the desire to avoid changing conditions near the terminator. The neutral atmospheric density values adopted for these calculations were tabulated in an earlier paper (*4*) and were based on data obtained by a variety of Pioneer Venus instruments (*1*).

The results of the model calculations (the model assumes diffusive equilibrium upper boundary conditions) are shown in Figs. 1 and 2. The solid lines show the calculated ion densities obtained with the standard diffusion coefficient. The early magnetometer results (*10*) have indicated that an average magnetic field of about 10 γ is present in the dayside ionosphere; although at this time there is no orientation information available, the field is likely to be nearly horizontal on the average, which means that there will be some inhibition of the diffusion rates. The dashed curves in Figs. 1 and 2 were calculated on the basis of a decreased diffusion coefficient, corresponding to a magnetic field strength of 10 γ with a dip angle of 20°. The horizontal bars indicate the range of representative ion densities obtained from the bus ion mass spectrometer (BIMS) and orbiter ion mass spectrometer (OIMS) (*11*), corresponding to a range in solar zenith angle between about 60° and 80°.

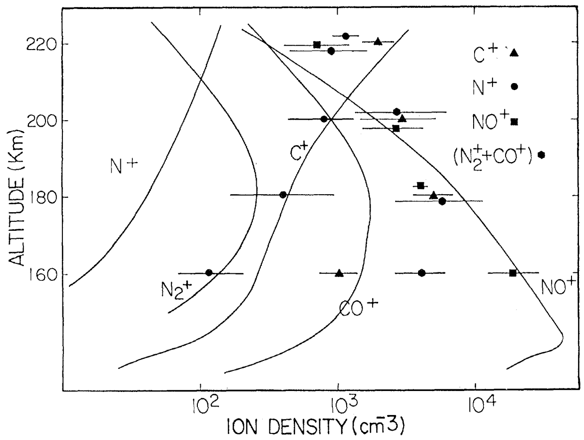

Fig. 3. Calculated ion density profiles for some minor ions. Photochemical equilibrium was assumed. Data from OIMS and BIMS are also shown.

The agreement between the calculated and observed O^+ and $CO_2{}^+$ densities (Fig. 1) is reasonably good; however, the situation with $O_2{}^+$ is not quite so satisfactory. The calculated density near the peak (~140 km) appears to be somewhat low, but no significant increases in the values are possible within the constraints set by the observed values of the solar EUV flux unless particle impact ionization also plays a role. The measured $O_2{}^+$ densities also fall off more rapidly than the calculated ones at altitudes above about 200 km. There are a number of possible reasons for this discrepancy. A somewhat smaller exospheric temperature than the one adopted (300 K) or a slightly greater O/CO_2 ratio, or both, would result in a decrease in the $O_2{}^+$ densities while keeping the O^+ and $CO_2{}^+$ densities still consistent with the observations.

The diffusive and chemical lifetimes become approximately equal near 200 km, and at higher altitudes the ion distributions are controlled by diffusive and bulk flow processes. There is no information available at this time on the magnitude and direction of the convective velocities in the upper ionosphere, and thus no attempt was made in these model calculations to include such bulk transport effects. The agreement between the observed and calculated He^+ densities (Fig. 2) is also reasonable, but there are large disagreements in the H^+ densities. It is quite feasible that the H^+ ions are influenced most by convective flows around the planet near the ionopause region (*12*); therefore, in Fig. 2 H^+ density profiles are also shown which were calculated based on an assumed upper boundary outward velocity of 500 m/sec for H^+, to indicate the effect that flows might have on the H^+ distribution.

The altitude distributions of five minor ions (C^+, N^+, NO^+, CO^+, and $N_2{}^+$) were calculated in the chemically controlled region, below about 220 km. In these chemical calculations 30 source and loss processes, involving the ten ion and nine neutral gas species, were used. Because of the lack of space, we cannot describe here the necessary details of the adopted chemistry scheme, rate coefficients, and references (*13*); however, an attempt will be made to indicate the major source and loss mechanisms for the various species. The results of these calculations are shown in Fig. 3 and are in general smaller than the observed values.

The two major source processes considered for C^+ were dissociative photoionization of CO_2 and charge exchange with He^+. The photoionization process was found to be more important by about a factor of 5 at lower altitudes (~180 km), but charge exchange becomes dominant above about 210 km. The calculated C^+ values (Fig. 3) are significantly lower than the measured ones. The major loss process is $C^+ + CO_2 \rightarrow CO^+ + CO$ at the altitudes under consideration; therefore, the calculated C^+ densities depend on the assumed CO_2 values. The uncertainties in these CO_2 densities are, however, small compared to the discrepancy in C^+. These calculations appear to indicate that an important source mechanism has been ignored; one such possibility is charge exchange with neutral carbon.

The calculated N^+ densities are also too small; in calculating these densities the main source mechanism was dissociative photoionization of N_2 with the He^+ charge exchange also making some contributions. The major loss processes were charge exchange with CO_2 and CO. Atomic nitrogen is probably also present in the upper atmosphere of Venus (*14*), so that direct photoionization will have to be considered when some quantitative information on the abundance of N becomes available.

We assumed an NO density of 3×10^6 cm^{-3} at 150 km in order to get general agreement between the calculated and measured NO^+ densities in the region under consideration. The resulting major source and loss mechanisms are charge exchange of NO with O_2^+ and dissociative recombination, respectively. There is only indirect information available (*14*) on the neutral NO and N densities to provide some limits on these assumptions, and atomic nitrogen could have also been used to arrive at the measured NO^+ densities.

Both ion mass spectrometers (*11*) observed significant signals at mass 28, which is probably the result of the presence of both N_2^+ and CO^+ ions; CO^+ and N_2^+ are created mainly by dissociative and direct photoionization, respectively; charge exchange processes also make some contributions. The calculated CO^+ densities are larger by nearly an order of magnitude than the N_2^+ values. The sum of these CO^+ and N_2^+ densities (Fig. 3) does fall short of the measured values. However, if the measured C^+ densities are used in the calculations, a good agreement is obtained because of the rapid reaction $C^+ + CO_2 \rightarrow CO^+ + CO$. This indicates that the difficulty in the model traces back to problems in accounting for the C^+ values.

The calculations presented here are just the beginning of the analysis and interpretation of this great wealth of Pioneer Venus data. The comparisons of the measured and calculated ion density profiles have led to the following conclusions. (i) There is a reasonably good agreement between the calculated and measured gross behavior of the major ions except H^+, which may be influenced significantly by convective transport processes even during quiet conditions. (ii) Our present understanding of minor ion chemistry is incomplete at this time. (iii) The O/CO_2 ratio and the abundances of the minor neutral constituents (for example, N, NO, and C) play a very important role in determining the ion chemistry. (iv) The inhibition of diffusion by quasi-horizontal magnetic fields may be important. (v) Contributions to the daytime ion production rates by particle impact may also have to be considered if the peak density measured by the bus needs to be explained. Finally, we would emphasize that the data used in this report were restricted to relatively quiet conditions; composition and structure change significantly during disturbed conditions when convective flows and other solar wind-ionosphere interaction processes take over from the diffusive one at higher altitudes.

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Venus Ionosphere: Photochemical and Thermal Diffusion Control of Ion Composition

Abstract. *The major photochemical sources and sinks for ten of the ions measured by the ion mass spectrometer on the Pioneer Venus bus and orbiter spacecraft that are consistent with the neutral gas composition measured on the same spacecraft have been identified. The neutral gas temperature* (T_n) *as a function of solar zenith angle* (χ) *derived from measured ion distributions in photochemical equilibrium is given by* $T_n (K) = 323 \cos^{1/5}\chi$. *Above 200 kilometers, the altitude behavior of ions is generally controlled by plasma diffusion, with important modifications for minor ions due to thermal diffusion resulting from the observed gradients of plasma temperatures. The dayside equilibrium distributions of ions are sometimes perturbed by plasma convection, while lateral transport of ions from the dayside seems to be a major source of the nightside ionosphere.*

The first in situ ion composition measurements by the Bennett radio-frequency (RF) ion mass spectrometers on the Pioneer Venus bus and orbiter spacecraft revealed a complex ionosphere not fully anticipated by earlier theoretical models (*1*). The observed ion composition, however, is consistent with the neutral gas composition of the upper atmosphere measured by several Pioneer Venus instruments (*2*). In addition, direct measurements of the plasma temperatures (*3*) have important implications for the distribution of ions at altitudes where plasma diffusion becomes effective.

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