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MODEL CALCULATIONS OF THE DAYSIDE IONOSPHERE OF VENUS

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ABSTRACT

Model calculations of the dayside ionosphere of Venus are presented. The coupled continuity and momentum equations were solved for O_2^+, O^+, CO_2^+, C^+, N^+, He^+, and H^+ density distributions, which are compared with measurements from the Pioneer Venus ion mass spectrometer. The agreement between the model results and the measurements is good for some species, such as O^+, and rather poor for others, such as N^+, indicating that our understanding of the dayside ion composition of Venus is incomplete. The coupled heat conduction equations for ions and electrons were solved and the calculated temperatures compared with Pioneer Venus measurements. It is shown that fluctuations in the magnetic field have a significant effect on the energy balance of the ionosphere.

INTRODUCTION

Theoretical model calculations combined with our increasing data base both from the instruments aboard the Pioneer Venus Orbiter (PVO) and from the Venera 9 and 10 radio occultation experiments [1] are helping to elucidate the controlling chemical and physical processes in the Venus ionosphere. This paper presents some results of such theoretical calculations. A more complete description of these calculations can be found in papers by Nagy et al [2] and Cravens et al [3]. The coupled continuity and momentum equations for seven ionic species were solved numerically for dayside conditions using measured plasma temperatures. The coupled electron and ion heat conduction equations were solved numerically using measured values for ion densities. It was felt that a better understanding of basic ionospheric processes could be reached at this time by uncoupling the energy equations from the continuity and momentum equations.

Whenever possible, information from the Pioneer Venus mission was used in solving the equations. In particular, we used values of the total neutral gas density and of composition obtained by a number of different PV experiments [4,5,6]. We used measurements of the electron and ion temperatures by the Langmuir probe (OETP) [7] and the retarding potential analyzer (ORPA) [8] on the Orbiter. Ion composition measurements from the PV ion mass spectrometer [9] were used. We will discuss our models of the ion composition and of the energy balance separately in the next two sections.

ION COMPOSITION

The coupled continuity and momentum equations which were solved for O_2^+, O^+, CO_2^+, H^+, He^+, C^+, and N^+ are:

$$\frac{\partial n_i}{\partial t} + \frac{\partial F_{iz}}{\partial z} = P_i - L_i \tag{1}$$

$$F_{iz} = n_i v_z = -D_i n_i \left[\frac{1}{n_i}\frac{\partial n_i}{\partial z} + \frac{m_i g}{kT_i} + \frac{T_e/T_i}{n_e}\frac{\partial n_e}{\partial z} + \frac{1}{T_i}\frac{\partial}{\partial z}(T_e+T_i) + \frac{\alpha_i}{T_i}\frac{\partial T_i}{\partial z} \right] \tag{2}$$

where n_i is the number density of the i^{-th} ion, t is time, z is altitude, P_i and L_i the production and loss of the i^{-th} ion respectively, F_{iz} is the vertical diffusive flux of i, D_i is the diffusion coefficient for i, m_i is the mass of i, g is the gravitational acceleration, k is Boltzman's constant, T_i and T_e are the ion and electron temperatures respectively, n_e is the electron density, and α_i is the thermal diffusion coefficient for the i^{-th} ion. The production term includes photoionization, photoelectron ionization, and chemical production. In addition to solving equations (1) and (2) for seven ion species, we also obtained photochemical solutions for NO^+, CO^+, and N_2^+.

We used the ion chemistry scheme summarized in Figure 1 to determine the L_i terms and part of the P_i terms. Solutions of (1) and (2) for five of the more important ion species are shown in Figure 2 for a solar zenith angle of 60 degrees on the dusk side of the planet. Measurements from the PV ion mass spectrometer are also shown in Figure 2.

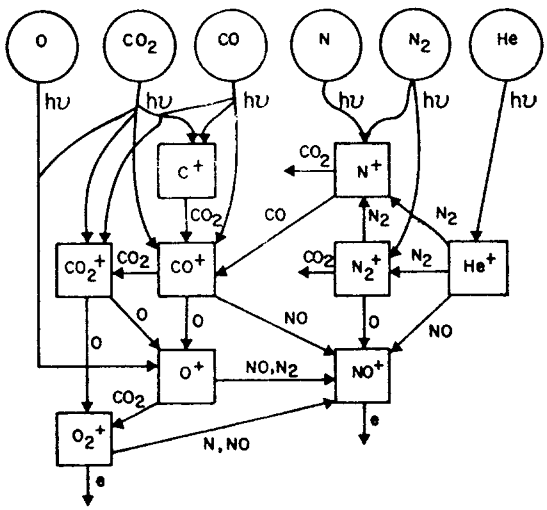

Fig. 1 Ion Chemistry Scheme

We will briefly discuss these results. CO_2 is the most abundant neutral species in the atmosphere of Venus but some atomic oxygen is present in the thermosphere and even becomes more abundant than CO_2 at altitudes greater than about 160 km. Even though CO_2 is the most abundant neutral species below 160 km, the peak electron density at 140 km is mostly composed of O_2^+ rather than CO_2^+ because atomic oxygen rapidly converts CO_2^+ to O_2^+ and O^+ to O_2^+ (refer to Figure 1). At higher altitudes where the chemical loss rates are small, O^+ becomes the major ion. At altitudes above the peak of the O^+ distribution near 200 km, diffusion rather than chemistry becomes the dominant process controlling the ion distributions. At altitudes greater than about 500 km, near the ionopause, processes associated with the solar wind-ionosphere interaction become important and our model calculations are not valid. It is evident from Figure 2 that C^+ and N^+ are also important ion species. Referring to Figure 1, both C^+ and N^+ are produced by dissociative ionization of CO_2 or N_2 and are primarily destroyed by reacting with CO_2. The agreement between the model and the measurements is reasonably good for O^+ and O_2^+, but the model does not do as well for N^+ and C^+. Uncertainties in the neutral densities and in the reaction rates for loss of N^+ and C^+ no doubt contribute to the poor agreement for these two ions.

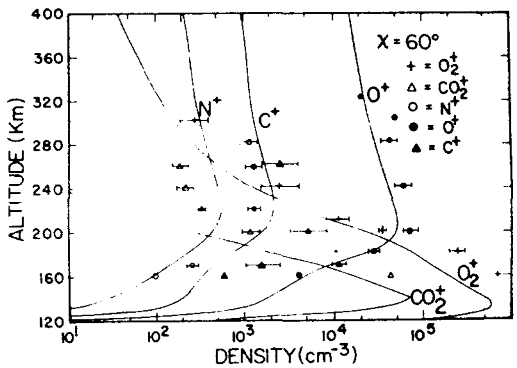

Fig.2 Calculated ion density profiles on the dayside of Venus. PV ion mass spectrometer data points are shown with typical orbit to orbit variability indicated.

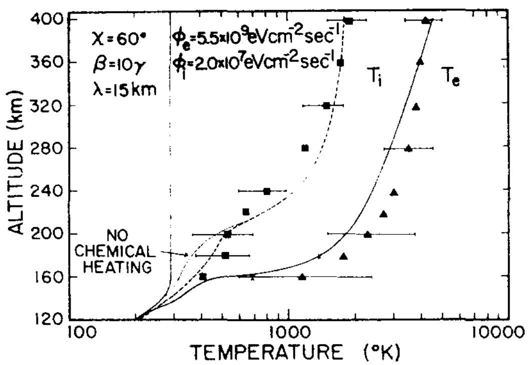

Fig.3 Calculated electron and ion temperature profiles for 60° solar zenith angle. OETP measurements are shown as triangles and ORPA measurements are shown as squares and crosses. Heat inputs are indicated.

ENERGY BALANCE

The coupled electron and ion energy equations are:

$$\frac{3}{2} n_m k \frac{\partial T_m}{\partial t} - \frac{\partial}{\partial z}\left(K_m \frac{\partial T_m}{\partial z}\right) = Q_m - S_m \qquad (3)$$

where m is an index for electrons or ions, T_m is the electron or ion temperature, n_m is the electron density, K_m is the thermal conductivity for m, Q_m is the heating rate for m, and S_m is the cooling rate for m. Q_m is obtained by solving the two stream transport equations [10] for photoelectrons on Venus. Among the cooling processes included in S_m for electrons are CO_2 and CO vibrational and rotational cooling and $O(^3P)$ and $O(^1D)$ cooling. Electron-ion Coulomb collisions are also taken into account. When equation (3) is solved using the standard Spitzer expression for K_m and assuming zero heat flow at the upper boundary, then electron and ion temperatures are obtained which are about a factor of two smaller than the measured temperatures. Two possible explanations for this are that:
(i) Fluctuations in the magnetic field inhibit the vertical conduction of heat.
(ii) There are heat inputs at the ionopause due to the solar wind interaction.

The magnetic field measured by PV in the dayside ionosphere of Venus is usually rather small and is highly irregular, with many small scale fluctuations [11]. These fluctuations can impede the transport of charged particles in the ionosphere, in effect reducing their effective mean free path. The thermal conductivity is proportional to the mean free path, λ, of the thermal electrons or ions;

consequently in the presence of a fluctuating magnetic field the thermal conductivity will be smaller and the vertical flow of heat inhibited. If the magnetic field is highly fluctuating and the gyroradius of the particles is less than the correlation length of the fluctuating magnetic field, then the effective mean free path of the particles is equal to this correlation length. Values of the mean free path of about 1 km to 20 km appear reasonable at this time. We use a value of 15 km.

The other possibility is the existence of heat inputs into the ionosphere at the ionopause due to the solar wind. In particular, it has been suggested that the whistler mode waves observed in the ionosheath by PV are Landau damped at the ionopause and dump heat into the ionospheric electrons [12]. We postulate heat inputs for both electrons and ions at the upper boundary of our model. Solar wind ion heating is also possible [13]. In addition, ion-neutral chemical reactions are an important source of heat for the ions below 200 km. Solutions of equation (3) are shown in Figure 3, and including heat inputs at the upper boundary as well as a thermal conductivity appropriate for a fluctuating magnetic field. The calculated electron and ion temperatures shown in Figure 3 agree rather well with values measured by PV. It should be noted, though, that the choices of heat flux values and mean free path used to obtain this agreement are not unique.

CONCLUSION

Our model calculations of ion composition and plasma temperatures indicate that a basic understanding of the chemical and physical processes controlling the dayside ionosphere of Venus has been partially achieved. But there are many important details requiring further investigation.

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