A TIME-DEPENDENT THEORETICAL MODEL OF THE POLAR WIND: PRELIMINARY RESULTS

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Abstract. The coupled time dependent continuity, momentum and energy equations of a two ion (O⁺ and H⁺) quasineutral plasma were solved in order to extend our understanding of polar wind behavior. This numerical code allows studies of the time dependent behavior of polar wind-type flows into and out of the ionosphere. Initial studies indicate that the typical time constants for electron and ion temperature changes are of the order of minutes and tens of minutes, respectively. The response time of the minor high altitude ion O⁺ is less than an hour, whereas that of the major ion, H⁺, is many hours. The initial test runs also demonstrate the fact that temporary supersonic flows of both O⁺ and H⁺ are possible, especially in the presence of significant ion heating.

Introduction

The existence of high speed ionospheric plasma outflows along open magnetic field lines was originally suggested by Axford (1968) and Banks and Holzer (1968). The term "polar wind" was first coined by Axford (1968). A large number of papers dealing with various aspects of the polar wind have since been published (for the latest review see Raitt and Schunk (1983)). However, even though both the formulation of the governing equations and the methods of solution have been improved significantly since the initial work, effectively all polar wind studies to date have been based on steady-state calculations. Mitchell and Palmadesso (1983) and Khazanov et al. (1984) recently carried out time-dependent calculations of high speed plasma flows, which included both parallel and perpendicular temperatures. However, the auroral region calculations of Mitchell and Palmadesso (1983) assumed a lower boundary altitude of 800 km and assumed that the O⁺ density was fixed; and the Khazanov et al. (1984) study was only for the plasmasphere and employed large time steps (≥15 minutes). In this paper, we introduce a hydrodynamical model for O⁺, H⁺, and electron flows in the polar ionosphere with a time resolution of about 0.1 seconds and lower and upper boundaries at 200 km and 12,000 km, respectively. The first quantitative measurements of supersonic polar wind behavior were obtained recently by the retarding ion mass spectrometer (RIMS) carried onboard the Dynamics Explorer 1 (DE-1) satellite, which observed supersonic H⁺ (Nagai et al., 1984) and O⁺ ion flows (Waite et al., 1985). These observational results prompted us to develop a new hydrodynamical numerical code to study the time dependent behavior of ionospheric plasma flows along magnetic field lines. In section 2 we briefly outline the governing equations, the numerical method and the parameters selected for our calculations. Section 3 gives the results of a few representative sets of calculations. Finally the implications of these preliminary studies are considered in the discussion section.

Model

The numerical model simultaneously solves the time dependent hydrodynamic continuity, momentum and energy equations for O⁺ and H⁺ ions along vertical magnetic field lines. We everywhere assumed local charge neutrality and the absence of net field-aligned electric currents. The electron momentum equation was used to determine the field-aligned electric field. The time dependent electron energy equation was solved simultaneously with the six ion equations. In order to be able to compare our time dependent results with earlier steady-state calculations as a benchmark, we have adopted most of the assumptions and approximations of Raitt et al. (1975). Our ion equations are:

\[
\begin{align*}
\frac{3}{3t}(Au_i) + \frac{3}{3z}(Au_i) & = AS_i \\
\frac{3}{3t}(Au_i) + \frac{3}{3z}(Au_i) & = -\frac{3}{2} + \\
& + Ap_i(E - g) + \frac{5M_i}{8t} \\
\frac{3}{3t}(Au_i) + \frac{3}{3z}(Au_i) & = \frac{3}{2} + \\
& + \frac{5M_i}{8t} \\
\end{align*}
\]

where \(\rho_i\), \(u_i\), \(T_i\) and \(p_i\) are the mass density, velocity, temperature and pressure of the \(i\)-th ion species, respectively. \(\gamma\) is the specific heat ratio, \(A\) is the area function, \(\gamma/m_i\) is the charge to mass ratio, \(K_i\) is the heat conductivity, \(E_z\) is the field aligned electric field, and \(g\) is the local gravitational acceleration. \(S_i\), \(\delta M_i/\delta t\), and \(\delta E_z/\delta t\) are the total mass production, the momentum exchange and the energy exchange rates due to collisions, respectively. \(Q_i\) is the external ion heating rate. The collision terms are the same as those used by Raitt et al. (1975).
The electron energy equation is:

\[ \frac{2}{3c} (\Delta u_e) + \frac{2}{\sigma_2} (\Delta u_p_e) = (\gamma - 1) \Delta u_e \frac{\partial P_e}{\partial z} + \frac{\partial}{\partial z} (K_{\text{Te}}) + \frac{\partial}{\partial z} (K_{\text{T}}) + A_0 e \]

where \( P_e, u_e, T_e \) and \( P_e \) are the mass density, velocity, temperature and pressure, respectively, while \( Q_e \) is the external electron heating rate. The collision term \((K_{\text{Te}})/\partial z\) and the heat conductive term \((K_{\text{T}})/\partial z\) are considered as sources of the \( T_e \) and \( T \) equations. Zero ion velocities were set and zero charge-exchange with \( O_2 \). At the lower boundary (200 km), we assumed chemical equilibrium, zero velocity, and thermal equilibrium between neutrals and ions. The electron temperature at the lower boundary was set at 1000 K. At the top, the density was taken to be zero and the scale height (corresponding to the electron temperature variations) was imposed at each time step at the upper boundary.

The model of the neutral upper atmosphere includes \( N_2, O_2, O \) and \( H \) (Raitt et al., 1975). \( O^+ \) ions are produced by photoionization and \( H^+ \) ions are created by charge exchange. \( O^+ \) is chemically removed by reactions with \( N_2 \) and \( O_2 \), and \( H^+ \) by charge-exchange with \( O \).

The coupled time dependent partial differential equation system was solved with a combined Godunov scheme/Crank-Nicholson method. The original Godunov scheme (c.f., Holt, 1977) was modified to handle the heat conduction term. The model also includes \( 0_2, O \), and \( H \) (Raitt et al., 1975). The coupled time dependent partial differential equation system was solved with a combined Godunov scheme/Crank-Nicholson method. The original Godunov scheme (c.f., Holt, 1977) was modified to handle the heat conduction term.

Recovering ionosphere. We have carried out a number of calculations to help us elucidate the relevant time constants of ionospheric behavior at high latitudes as well as to get some initial insights into some of the possible controlling physical mechanisms. Many questions related to the recovery of the ionosphere-plasmasphere system after major plasma depletions have been raised during the last fifteen years (e.g. Park, 1970; Banks et al., 1971). To address these issues with our new model, we carried out a first order calculation in which we started with a very cold \((T_e = T_i = T_o)\), stationary, and highly depleted ionosphere. At \( t=0 \) we turned on the ionization source and a topside electron heat flux of \( 10^{-2} \text{ erg/cm}^2/\text{s} \). What follows is a strong ionosphere in the process of refilling. At the beginning of the calculation, the electron temperature increases very rapidly, reaching a new equilibrium in less than about 100s. The \( H^+ \) temperature responds with a typical time scale of about half an hour (the \( O^+ \) temperature behaves in a similar manner). A significant upward \( H^+ \) velocity develops in a few tens of seconds, while \( O^+ \) follows a little later. Both \( H^+ \) and \( O^+ \) become strongly supersonic above 1500 km by \( t=200 \text{ms} \). The \( O^+ \) density is slow to respond initially, but about 250s the density starts to increase due to the upward \( O^+ \) flux. The \( H^+ \) density responds much more slowly than the \( O^+ \) density. The characteristic time scale for \( H^+ \) replenishment is a few hours and is determined by its production rate at the lower altitude model. Topside \( O^+ \) densities are almost as large as \( H^+ \) densities by about \( 1000 \text{s} \), and the ion velocities start to decrease as the new equilibrium is gradually approached. A gradual evolution of the ionosphere begins for times greater than \( 200 \text{ms} \). Relatively low speed upward \( H^+ \) velocities persist and a gradual increase of \( H^+ \) densities continues to refill. In this phase, all other parameters remain almost unchanged as the upper ionosphere is gradually refilled with \( H^+ \).

We also carried out calculations in which we modeled a "collapsing ionosphere". The resulting time scales of the density, velocity and temperature variations were not significantly different from the just described "refilling" case, therefore, we will not describe them here. Instead of \( H^+ \) as a result of ion heating, large \( O^+ \) outflow \((>10^{10} \text{ cm}^2/\text{s})\) of low energy \((<1 \text{ eV})\) \( O^+ \) ions have been observed by particle detectors onboard the DE-1 satellite over the northern polar cap (Shelley et al., 1982; Waite et al., 1985). The electron heating calculations by Waite et al. (1985) suggested an origin of these ionospheric \( O^+ \) outflows near the dayside polar cap boundary. The region source appears to produce large, time-dependent outflows of not only \( O^+ \) ions, but also \( H^+, He^+, N^+, O^+ \) and molecular ions as well. Earlier theoretical calculations (Barakat and Schunk, 1983) have indicated that high electron temperatures can produce \( O^+ \) outflows as a result of increases in the ambipolar electric fields. In general, the observed \( O^+ \) outflows, which have been termed "upwelling ion events" by Lockwood et al. (1985), show signatures of strong ion heating, which probably takes place in the polar cusp.
In order to assess the role of high ion temperatures on plasma outflows from the ionosphere, we carried out a representative set of first order calculations using our new model. The initial values for the model were the diffusive equilibrium conditions mentioned earlier in this section. The distributed ion heating rate was increased up to 0.025 ergs/cm²/s over a time period of 150s, to stimulate the observed ion heating. The Gaussian shaped heating profile peaked at 2000 km with a half width of 250 km. The absorbed heat was divided between H⁺ and O⁺ according to their mass densities. The topside pressure (at an altitude of 12,000 km) was kept at a very low value for all times to simulate open field lines. Two and a half minutes after ion heating was initiated O⁺ temperatures already exceeded 20,000° between 2000 and 5000 km (Figure 1) causing significant (but still subsonic) upward flows in this region. The topside H⁺ pressure drop forces large H⁺ outflows (after 10 minutes we obtained 5x10⁶ cm⁻² s⁻¹ H⁺ flux at 10,000 km). The high altitude H⁺ velocities become supersonic for a time around t=30 minutes. After an hour (Figure 2) the H⁺ shows a highly depleted density profile because most of the H⁺ ions have already left the topside ionosphere. The H⁺ column production rate limits the outflow flux at this time to a 3x10⁶ cm⁻² s⁻¹ value (see Figure 4). On the other hand, the O⁺ temperature became highly elevated in the upper ionosphere causing a large density increase and a supersonic 5x10⁶ cm⁻² s⁻¹ outflow flux (Figure 3).

We carried out the ion heating calculations with the upper boundaries set at both 3000 and 12,000 km and found that the main features were the same in both cases: high H⁺ outflow in the first half an hour followed by large supersonic O⁺ outflows at later times. At later times the H⁺ flux became much smaller than the O⁺ flux. Our calculated flux values are quite consistent with those measured by DE/RIMS instrument in the welling ion outflow region near the cusp (Lockwood et al., 1985). In addition, the time-dependent response of the H⁺ outflow, followed by O⁺ outflow, is consistent with the "geomagnetic mass spectrometer" separation of outflowing ions observed by DE/RIMS (Lockwood et al., 1985; Moore et al., 1985). These results suggest that ion heating may be the dominant process for creating low energy ion outflow in the region of the polar cleft. More detailed comparison of observations and modeling for ion outflow events using a combined Dynamics Explorer 1 and 2 data set is needed to study in detail this important source of low energy ions for the magnetosphere.

Discussion

The first results of a time dependent model of the polar ionosphere were presented in this
paper. The time response of various ionospheric quantities to sudden changes in conditions was explored. The electron temperature responds extremely rapidly with a time constant of about a couple of minutes. The minor ion at the higher altitudes (O⁺) responds in about 20-30 minutes, and the major ion (H⁺) takes several hours to change significantly. These time dependent calculations also demonstrated that highly supersonic O⁺ and H⁺ outflows can develop temporally as transients, whereas only H⁺ was supersonic in the classical steady-state polar wind models. We also established that ion temperatures elevated to values consistent with observations lead to large, long lasting (i.e. 3 hours) and dominant O⁺ outflow.

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References


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