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

T. I. Gombosi[1], T. E. Cravens, and A. F. Nagy

Space Physics Research Laboratory, The University of Michigan
Ann Arbor, MI 48109

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:

$$\frac{\partial}{\partial t}(A\rho_i) + \frac{\partial}{\partial z}(Au_i\rho_i) = AS_i$$

$$\frac{\partial}{\partial t}(Au_i\rho_i) + \frac{\partial}{\partial z}(Au_i^2\rho_i) = -\frac{\partial p_i}{\partial z} + A\rho_i\left(\frac{e}{m_i}E_z - g\right) + A\frac{\delta M_i}{\delta t} \tag{1}$$

$$\frac{\partial}{\partial t}\left(\frac{A}{2}u_i^2\rho_i + \frac{1}{\gamma-1}Ap_i\right) + \frac{\partial}{\partial z}\left(\frac{A}{2}u_i^3\rho_i + \frac{\gamma}{\gamma-1}Au_ip_i\right) = \frac{A}{2}u_i^2S_i + A\rho_iu_i\left(\frac{e}{m}E_z - g\right) + Au_i\frac{\delta M_i}{\delta t} + A\frac{\delta E_i}{\delta t} + A\frac{\partial}{\partial z}\left(K_i\frac{\partial T_i}{\partial z}\right) + AQ_i$$

where ρ_i, u_i, T_i and p_i are the mass density, velocity, temperature and pressure of the i-th ion species, respectively. γ is the specific heat ratio, A is the area function, e/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 $\delta E_i/\delta t$ 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 collison terms are the same as those used by Raitt et al. (1975).

[1]Permanent address: Central Research Institute for Physics, Budapest, Hungary

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The electron energy equation is:

$$\frac{\partial}{\partial t}(A\rho_e) + \gamma\frac{\partial}{\partial z}(Au_e p_e) = (\gamma_{-1})Au_e\frac{\partial p_e}{\partial z} + (\gamma_{-1})A\frac{\delta E_e}{\delta t} + A\frac{\partial}{\partial z}\left(K_e\frac{\partial T_e}{\partial z}\right) + AQ_e \qquad (2)$$

where ρ_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 ($\delta E_e/\delta t$) and the heat conductivity (K_e) were taken from Raitt et al. (1975).

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.

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 held at 1000 K. At the top, ion velocities were taken to be zero and ion scale heights (corresponding to various external conditions) were imposed at each time step at the upper boundary. The numerical code also allowed for time-dependent, distributed ion and electron heat sources, which was an input parameter for the calculations. The effects of the location of the altiude of the upper boundary were investigated by making identical runs with 2000km, 3000km and 12,000km boundary values. The main features of the solutions turned out to be insensitive to the specific choice of the top altitude. Obviously, some details did change, especially near the upper boundary (for instance delay times, etc.).

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 heat conduction terms (an internal report describing this modification is available upon request).

Results of Calculations

Diffusive equilibrium and low velocity benchmark calculations. In order to test our new model we carried out several sets of calculations which can be compared with those of earlier models. Due to the steady-state or low speed nature of earlier high latitude calculations our benchmark runs were started with a near-diffusive equilibrium initial condition and were run until steady-state was reached. In all cases the topside electron heat flow was set at 9.0×10^{-3} erg/cm^2/s and the distributed heat input was zero for both ions and electrons. Zero ion velocities were enforced at the upper boundary for the first set, and zero O^+ and 1km/s outward H^+ velocities for the second set of calculations. The ion and electron density distributions obtained in these calculations are very close to the earlier results of Raitt et al. (1975). Our near steady-state results also compared very well with the density, velocity and temperature values obtained from the low velocity numerical code, described by Young et al. (1980). These satisfactory comparisons between our code and earlier and well established numerical codes provids confidence in the validity of our new model.

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 some of these issues with our new model, we carried out a first order calculation in which we started with a very cold ($T_e = T_i = T_n$), stationary, and highly depleted ionosphere. At t=0 we turned on the ionization source and a topside electron heat flux of 10^{-2} erg/cm^2/s. What follows is an upper ionosphere in the process of refilling. At the beginning of the calculation the electron temperatures increase 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=200s. The O^+ density is slow to respond initially, but by about 250s the density is starting 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 altitudes. Topside O^+ densities are almost as large as H^+ densities by about 1000s, 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 2000s. Relatively low speed upward H^+ velocities persist and a gradual increase of H^+ density is seen as the flux tube 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.

Ion outflow as a result of ion heating. Large outflows (>10^8 /cm^2/s) of low energy (<10 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). Convection mapping calculations by Waite et al. (1985) suggested an origin of these ionospheric outflows near the dayside polar cap boundary.The source region 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. However, the observed ion 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.

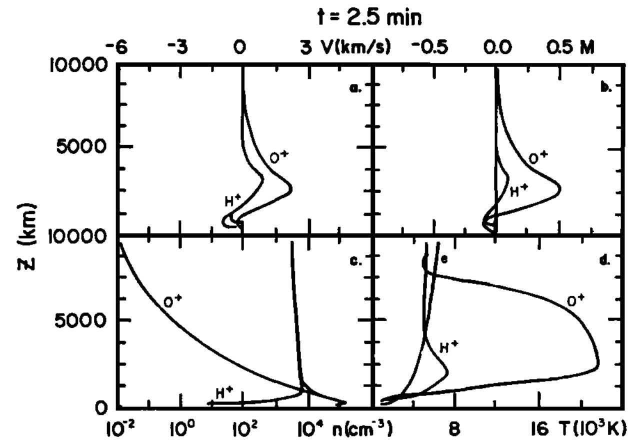

Fig. 1. Flow velocities, Mach numbers, number densities and temperature distributions in an ion heated ionosphere 2.5 minutes after ion heating was initiated.

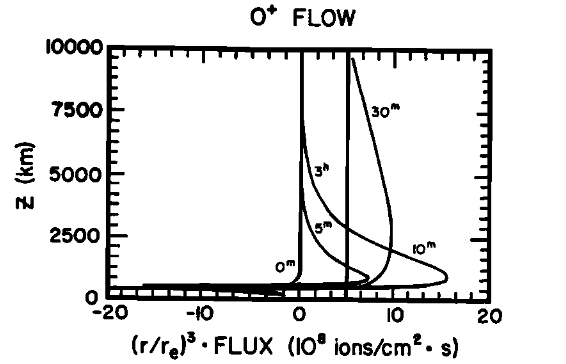

Fig. 3. Temporal evolution of O^+ fluxes in an ion heated ionosphere.

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/cm^2/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^o 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 $5 \cdot 10^8$ 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 $3 \cdot 10^7$ 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 $5 \cdot 10^8$ 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 upwelling 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

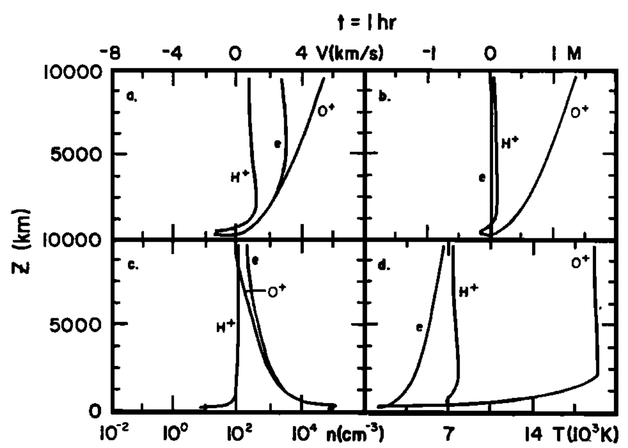

Fig. 2. Same as Figure 1 one hour after ion heating was initiated.

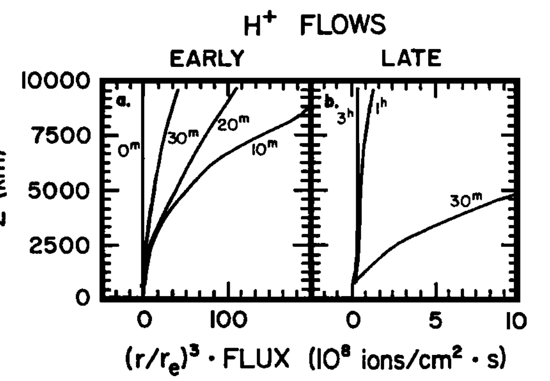

Fig. 4. Temporal evolution of H^+ fluxes in an ion heated ionosphere.

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 temporarily 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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