The Role of High-Speed Plasma Flows in Plasmaspheric Refilling

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A model of time-dependent one-stream interhemispheric plasma flow is used to investigate plasmaspheric refilling. In the model the coupled time-dependent hydrodynamic equations (continuity, momentum and energy) of a two-ion (H\(^{\text{+}}\) and O\(^{\text{+}}\), quasi-neutral, currentless plasma are solved for a closed geomagnetic field line. For the present set of calculations an L = 2 field line was used. A steady state solution was found and used as the initial condition in subsequent simulations of the effect of density depletions. Density depletions were modeled by reducing the densities by an arbitrary factor above 2500 km altitude, while keeping the velocities and temperatures unchanged. Shock structures develop which move up the field line, meeting and reflecting at the equator. The reflected shocks are absorbed by the dense neutral atmosphere when they reach the model flux tube boundaries. After the upwelling streams collide, refilling occurs from the equator downward for 2 to 3 hours; thereafter there is steady refilling from the ionospheres upward.

INTRODUCTION

An important unresolved question in magnetospheric physics is that of refilling of plasmaspheric flux tubes following density depletions caused by magnetic storms [Park, 1970]. There have been questions as to whether the refilling starts from the equator downward or from the ionospheres upward [Banks et al., 1971]. To address this question, various models for interhemispheric flows on magnetic flux tubes have been used.

The models can be divided into one-stream and two-stream models. One-stream models have been developed by Moffet and Murphy [1973], Young et al. [1980], Khazanov et al. [1984], and Singh et al. [1986b]. Rasmussen and Schunk [1988] developed a two-stream model. One-stream models do not distinguish the streams coming from the two hemispheres, whereas two-stream models do. Thus in the one-stream models a shock wave system might be formed near the equator. In two-stream models the streams can interpenetrate and shocks do not automatically form. However, the interpenetrating streams can excite waves which can pitch angle scatter the ions, leading to ion trapping. Thus an important question is whether the collisionless interaction of the streams will result in shocks or ion trapping at the equator.

Banks et al. [1971] postulated that after flux tube depletion the resulting flows would be supersonic and that the collision of these streams would result in a pair of electrostatic shocks. Schulz and Koons [1972] developed a two-step mechanism for ion trapping: first, ions are trapped due to pitch angle scattering as a result of wave-particle interactions; when the density becomes sufficiently large, Coulomb collisions are effective in thermalizing the plasma. Schulz and Koons [1972] also suggested that shock formation was unlikely, because the interaction of the individual plasma streams with the background plasma will not excite waves, which would dissipate the energy of the ion streams; they did not consider the interaction of the plasma streams themselves. More recent simulations by Singh et al. [1986a, b] showed that in a collisionless plasma, shocks would develop if T\(_e\) > 3T\(_i\). Since T\(_e\) = T\(_i\) in the conjugate ionospheres, this would require preferential electron heating. Another potential mechanism for ion trapping is perpendicular ion heating.

The model developed by Moffet and Murphy [1973] solves the O\(^{\text{+}}\) and H\(^{\text{+}}\) continuity and momentum equations from the F region to the equator assuming low-speed, diffusion-dominated flow. This model was applied to flux tubes with L = 3 and 4. Bailey et al. [1978] extended this model to both hemispheres and used it to study the refilling of a flux tube with L = 3 following a magnetic storm. They found that it took as long as 6 days for such a flux tube to refill during sunspot minimum conditions.

The model developed by Young et al. [1980] includes the photoelectron two-stream equation, diffusion velocity solutions of the ion and electron momentum equations [St. Maurice and Schunk, 1977], continuity equations for ions, and the electron and ion energy equations. In this model the species temperature and velocity differences were assumed small, so that Burgers' [1969] linear collision terms could be used, and that stress and nonlinear acceleration terms could be neglected. It has O\(^{\text{+}}\), H\(^{\text{+}}\), electrons, and an arbitrary number of minor ions in a neutral atmosphere of O, \(\text{O}_2\), \(\text{N}_2\), and H. Steady state results indicated that there was downflow of H\(^{\text{+}}\) and O\(^{\text{+}}\) below 500 km, but counterstreaming of H\(^{\text{+}}\) and O\(^{\text{+}}\) above 500 km, with O\(^{\text{+}}\) moving up.

The Young et al. [1980] model is restricted to low flow speeds because the diffusion velocity equations are derived using the assumption that the inertial terms can be neglected. In addition, for the high-altitude portions of the flux tube the diffusive equilibrium approximation is made. Because of this, shocks cannot be self-consistently simulated using this model.

Using the Young et al. [1980] model, Richards et al. [1983] studied the flow of H\(^{\text{+}}\), He\(^{\text{+}}\), and O\(^{\text{+}}\) on a flux tube, which passed through Millstone Hill, for solstice conditions at noon local time. They initially depleted the flux tube by a factor of 2, and considered both symmetric and asymmetric poleward neutral winds. Their results included H\(^{\text{+}}\) - He\(^{\text{+}}\) counterstreaming in the summer hemisphere during the refilling phase for both symmetric and asymmetric winds. Steady state results showed flow of both H\(^{\text{+}}\) and He\(^{\text{+}}\) from the winter to the summer hemisphere for symmetric winds, and H\(^{\text{+}}\) - He\(^{\text{+}}\) counterstreaming along the entire flux tube for asymmetric winds.
Khazanov et al. [1984] developed a one-stream model which included $O^+$, $H^+$, and electrons. This model had the continuity, momentum, and energy equations, the temperatures were allowed to be anisotropic, and the electron inertia term was neglected. It also had a kinetic equation for superthermal electrons. This model had very large time steps, ranging from 10 to 15 minutes near sunrise and sunset to 1 hour during the night. Refilling of flux tubes with $L$ values from 2 to 5.6 was studied. They found that for $L \geq 3.5$ the refilling occurs with supersonic speeds and is very different from diffusive equilibrium; for such flux tubes the refilling time is much greater than a typical magnetically quiet period.

Singh et al. [1986b] developed a one-stream time-dependent hydrodynamic model which assumed an isothermal gas of $H^+$ ions, with $T_e = T(H^+)$; no other ion species were included. In this model the electrons were assumed to obey a Boltzmann relation between the electron number density and electric potential, which in effect means that the electrons were assumed to be in diffusive equilibrium. This assumption and the lack of an energy equation imply that this model cannot self-consistently simulate shocks. Also, the boundaries of the model flux tube are at high altitudes (~2000 km) where the neutral densities are not high enough to absorb the downward moving shocks, which results in unphysical shock reflections from the flux tube boundaries. Results were found for $L = 4$ and 6.6. Refilling was simulated after a density depletion in the form

$$N = \left( \frac{\sin \lambda}{\sin \lambda_0} \right)^{2n}$$

where $N$ and $N_0$ are the $H^+$ number densities at magnetic latitudes $\lambda$ and $\lambda_0$, respectively; here $\lambda_0$ is the magnetic latitude corresponding to the ionospheric base. Results were given for $n = 2$ and 8.

Rasmussen and Schunk [1988] developed a two-stream version of the Singh et al. model, modeled refilling after a density depletion of the form

$$N = \left( \frac{\sin \lambda}{\sin \lambda_0} \right)^4$$

and compared the results with those of the one-stream model for $L = 4$. This model also has high flux tube boundaries (~2000 km altitude) and prescribes boundary conditions which result in unphysical shock reflections from the flux tube boundaries. Results were given both with and without $H^+ - H^+$ collisions; the results were about the same, but streams were reflected at higher altitudes when collisions were included. Initially, the streams interpenetrate. Shocks develop after the density fronts have passed the equator, travel toward the conjugate hemispheres, and reverse direction. The subsequent motions of the shocks give results which are similar to those of one-stream models. They find that refilling starts from the equator downward.

The purpose of this paper is to present results which have been found using a time-dependent hydrodynamic one-stream model. It is an adaptation, for closed field lines, of a model for polar wind flows developed by Gombosi et al. [1985]. This model takes into account the effects of ionization, charge exchange, recombination, collisions, and heat conduction and allows for external heat sources; it includes $O^+$ and $H^+$ ions and electrons. No diffusive equilibrium assumptions are used and it includes an energy equation for each species, which means that shocks can be self-consistently modeled. A flux tube with $L = 2$ was used because then the density at the equator is large enough that Coulomb collisions are effective in thermalizing and coupling the streams from the conjugate hemispheres. The boundaries of the flux tube are at 200 km altitude, which is low enough that shocks are not reflected from the boundaries. Steady state results were found and used as initial conditions in subsequent simulations of the effect of flux tube depletions, which were simulated by dividing the ion densities by an arbitrary factor above 2500 km altitude. Although $L = 2$ flux tubes are not usually depleted, this study should be useful for clarifying the stages of the refilling process at higher $L$ values.

**MODEL**

**Governing Equations**

The model includes the time-dependent coupled continuity, momentum, and energy equations for $O^+$ and $H^+$ ions and the energy equation for electrons. As a result of the strong geomagnetic field, only motions along magnetic field lines are important; field line curvature effects are neglected. Quasi-neutrality is assumed and no field-aligned electric currents are allowed so that

$$n_e = n(O^+) + n(H^+)$$

$$u_e = u(O^+)n(O^+) + u(H^+)n(H^+)$$

With these constraints the governing equations become

$$\frac{\partial}{\partial t} \left( \text{AP}_e \right) + \frac{\partial}{\partial x} \left( \text{AP}_e u_i \right) = \text{AE}_i$$

$$\frac{\partial}{\partial t} \left( \text{AP}_e u_i \right) + \frac{\partial}{\partial x} \left( \text{AP}_e u_i^2 + \frac{1}{\gamma_i - 1} \text{AP}_i \right) = A\text{E}_i + AQ_i$$

$$\frac{\partial}{\partial x} \left( \text{AP}_e u_i^2 + \frac{1}{\gamma_i - 1} \text{AP}_i \right) = A\text{E}_i + AQ_i$$

$$\rho_e \frac{\partial T_e}{\partial t} = \left( \gamma_e - 1 \right) m_e \frac{\partial}{\partial x} \left( \text{AE}_i \right)$$

$$-\rho_e u_e \frac{\partial T_e}{\partial x} - T_e S_e + \frac{\gamma_e - 1}{A} \frac{\partial (\text{AE}_i)}{\partial x}$$

$$+ \frac{m_e}{k} \left( \gamma_e - 1 \right) Q_e + \frac{\text{AE}_i}{\partial x}$$

where $\text{AE}_i = \left( \frac{\text{EP}_i}{\gamma_i - 1} \right)$ and $\text{AQ}_i = \left( \frac{\text{EP}_i}{\gamma_i - 1} \right)$. The governing equations are solved numerically using a finite difference method. The results are presented in the form of density, velocity, and temperature profiles along the field lines. The model is validated by comparing the results with those obtained from other models and with observations.
In these equations, \( t \) is time, \( r \) is distance along magnetic field lines, \( B \) is the magnetic field strength, \( A - B^{-1} \) is the cross-sectional area of a flux tube, \( m \) is the particle mass, \( \rho \) is the mass density, \( n \) is the number density, \( u \) is the field-aligned flow velocity, \( p \) is the pressure, \( T \) is the temperature, \( e \) is the electron charge, \( k \) is Boltzmann's constant, \( \gamma \) is the specific heat ratio, \( c \) is the heat conductivity, \( S \) is the net mass production rate, \( E_i \) is the polarization electric field, \( g \) is the component of the gravitational acceleration parallel to the magnetic field line, \( \delta E/\delta t \) is the energy exchange rate, and \( Q \) is the external heating rate. The subscript \( i \) refers to either of the ions, whereas the subscript \( e \) refers to the electrons.

In this model the collision terms are assumed to have the following form:

\[
\frac{\delta M_s}{\delta t} = \sum t s m_s n_s \nu_s \left( u_i - u_s \right)
\]

\[
\frac{\delta E_s}{\delta t} = \sum t s m_s n_s \nu_s \left[ 3k\left(T_i - T_s \right) + m_i \left( u_i - u_s \right)^2 \right]
\]

In these equations the summations run over all species, and the neutral velocity is assumed to be zero; \( \nu_s \) is the momentum transfer collision frequency of species \( s \) with species \( t \). The velocity-dependent correction factors due to Schunk [1977] have been approximated by one. This approximation is not expected to influence the results significantly because at the altitudes used in the model the relative drifts and momentum transfer collision frequencies are small.

The neutral atmosphere model used was MSIS-86 [Hedin, 1987]; this includes \( N_2, O_2, O, \) and \( H \). It is important to note that this model is not symmetric about the magnetic equator. Also, in the present set of calculations the neutral atmosphere was not allowed to vary with time. The \( O^+ \) ions are produced by photoionization, whereas the \( H^+ \) ions are created by charge transfer only. \( O^+ \) is removed by chemical reactions with \( N_2 \) and \( O_2 \); \( H^+ \) is removed by charge transfer with \( O \). The ion-ion, ion-neutral, and ion-electron collision frequencies and the heat conductivities used in this model were taken from Raitt et al. [1975].

In the model an \( L = 2 \) flux tube connects two external reservoirs, each at an altitude of 200 km; these reservoirs represent photochemically controlled regions of the ionosphere. The ions in the stationary reservoirs are assumed to be in chemical and thermal equilibrium with the neutral atmosphere, while the electron temperature in the reservoirs is assumed to be 1000 K. Since the reservoirs are at 200 km altitude, the neutral species densities are high enough that downward propagating shocks are absorbed at the boundaries rather than reflected from them. An equatorial downward, field-aligned electron heat flux of \( 1.4 \times 10^{32} \) erg cm\(^{-2}\) s\(^{-1}\) is used to simulate energy deposition from the magnetosphere. For this work the model was run assuming equinox conditions during solar minimum (September 22, 1988) and no external heating.

**Dipole Magnetic Field**

In this model the magnetic field is assumed to be dipolar, with the magnetic field strength given by

\[
B = \frac{M}{r} \sqrt{1 + 3 \sin^2 \lambda}
\]

where \( \lambda \) is magnetic latitude. On such field lines the geocentric radius and the magnetic latitude are related by

\[
r = LR_e \cos^2 \lambda
\]

where \( R_e \) is the radius of the Earth and \( L \) is the ratio of the equatorial flux tube radius and the Earth's radius.

An expression can be derived for the path length along the field line:

\[
s - s_0 = -\frac{LR_e}{2\sqrt{3}} \left[ w\sqrt{1 + w^2} + \log\left( w + \sqrt{1 + w^2} \right) \right]
\]

where \( w = \sqrt{3} \sin \lambda \). Here \( s_0 \) is determined so \( s(90^\circ) = 0 \); it represents the pathlength at the equator.

**Method of Solution**

The equations are solved using a combined Godunov scheme/Crank-Nicholson method with dimensional splitting. In this method the Godunov scheme is applied to the ion conservation equations but without heat conduction terms in order to get updated values of the ion velocities, densities, and pressures. Then the Crank-Nicholson method is applied to

\[
\frac{\partial T_i}{\partial t} = \frac{1}{\rho_i AR_i} \frac{\partial}{\partial r} \left( A X_i \frac{\partial T_i}{\partial r} \right)
\]

for the ions and to the full electron energy equation in order to get corrected values of the ion and electron temperatures. The Godunov and Crank-Nicholson operations are reversed on the next time step in order to get second-order accuracy in time.

The cells are spaced evenly along the flux tube. The magnetic latitude corresponding to each cell is determined using the expression for path length in terms of magnetic latitude; this is done iteratively using Newton's method.

The cell length is approximately 10.5 km and the time step is 0.05 s. The cell length was picked to be about half the scale height of the \( H^+ \) ions at 200 km altitude so that supersonic flows would not develop at the boundaries of the model flux tube. The time step had to be less than the limiting time scales of the differential equations.

**RESULTS**

**Steady State**

Figures 1a and 1b show the steady state altitude profiles for the northern and southern hemispheres. The six panels in each
Fig. 1. Steady state solution for (a) the northern and (b) the southern hemisphere. The six panels display flow velocity, hydrodynamic Mach number, particle flux (normalized to a reference altitude of 1000 km), number density, pressure, and temperature profiles between 200 km and 6500 km altitude.
figure display flow velocity, hydrodynamic Mach number, particle flux, number density, pressure, and temperature between 200 km and 6500 km altitude. It should be noted that positive flows are upward in the northern hemisphere but downward in the southern hemisphere. An important result is counterstreaming of O\(^+\) and H\(^+\) ions, with O\(^+\) moving up, between about 700 km and 1000 km altitude in the southern hemisphere and about 700 km and 1200 km altitude in the northern hemisphere; this is in agreement with the results of Young et al. [1980]. The magnitudes of the counterstreaming fluxes are not identical; usually, the H\(^+\) flux is greater than the O\(^+\) flux. The counterstreaming is a result of the O\(^+\) moving up to replace O\(^+\) that is lost in charge exchange reactions with H at higher altitudes, while the H\(^+\) that is created there moves down. Counterstreaming in steady state was predicted by Young et al. [1979], with the sum of the fluxes being zero for symmetric flux tube conditions but nonzero for nonsymmetric conditions. This effect is largely masked by diurnal variations, but has been observed at twilight over Arecibo by Vickrey et al. [1976, 1979].

The results are not symmetric about the magnetic equator; this is due to the asymmetry of the neutral atmosphere model. As an example, the O\(^+\) flux at 1000 km is about twice as large in the northern hemisphere than in the southern hemisphere. There is also an asymmetry in the fluxes above 1000 km. In the northern hemisphere the H\(^+\) flux is upward above about 1200 km and falls to near zero by 5000 km altitude. In the southern hemisphere the H\(^+\) flux is upward above 1000 km and falls to near zero above 6000 km. Below about 700 km the fluxes of both ions are downward, but now the O\(^+\) flux is much greater than the H\(^+\) flux, which is practically zero. The O\(^+\) flows down to replace O\(^+\) which is lost in reactions with O\(_2\) and N\(_2\) at lower altitudes. Above 1500 km, the O\(^+\) flux is practically zero, since the velocities and densities are very small there.

The temperatures of the ions and electrons are comparable for most latitudes. \(T_e\) is greater than \(T(O^+)\) for all points on the flux tube; \(T(H^+)\) is greater than \(T_e\) for altitudes between 1000 km and 2500 km. In that altitude region the hydrogen ions are heated as a result of frictional interactions with the O\(^+\) ions and the neutral species; however, there is also thermodynamic cooling of the H\(^+\) ions, since \(T(H^+)\) is greater than \(T(O^+)\) and the neutral temperature.

**Density Depletions**

Next the effect of density depletions of varying strength was modeled. In order to simulate such conditions the steady state densities for all species were reduced by a given factor above 2500 km altitude; however, the temperatures and velocities were not changed. The density depletion was also assumed to be instantaneous. This type of initial profile was used in order to simulate refilling after a strong magnetic storm; because of it shock structures clearly develop. These structures move upward because the ion and electron gases expand into the low-density regions. We chose to study twofold and fivefold density depletions. The model was allowed to run for 5 hours of simulated time in each case.

![Graph](image-url)

**Fig. 2.** Initial condition for the twofold density depletion case. The six panels display flow velocity, hydrodynamic Mach number, particle flux (normalized to a reference altitude of 1000 km), number density, pressure, and temperature profiles between \(-40^\circ\) and \(+40^\circ\) magnetic latitude.
In the case of a twofold density depletion the result was similar to a sonic disturbance. This is an acoustic disturbance which moves with the local sound speed and can be treated as a perturbation. The propagation speed of the H\(^+\) shock is about 10.7 km/s. The initial propagation speed of the O\(^+\) shock is 1.8 km/s but by 30 minutes this increases to 2.1 km/s. This occurs because the O\(^+\) velocity increases behind the shock, which implies that the shock velocity must increase because of mass flux conservation relationships. Both of these shocks are supersonic with respect to the ion acoustic speed (~12.2 km/s).

Figures 2 through 5 show the initial conditions and results at \(t = 5, 12.5,\) and 60 minutes in this case. The six panels in each figure display flow velocity, hydrodynamic Mach number, particle flux, number density, pressure, and temperature as a function of latitude. For both ions the flow velocity is always subsonic. Figure 3 shows clearly defined shock structures in the velocity profiles; the Mach number profiles show that the H\(^+\) shocks outrun the O\(^+\) shocks. This occurs because the H\(^+\) ions are 16 times lighter. The H\(^+\) shocks meet at about 12.5 minutes; this is shown in Figure 4. Note the equatorial H\(^+\) temperature increase, due to collisional heating. This figure also shows that the O\(^+\) temperature decreases behind the O\(^+\) shocks, due to adiabatic cooling. Figure 5 shows the O\(^+\) shocks meeting at 60 minutes; the O\(^+\) density and temperature increase at the equator. For both ions the shocks reflect after meeting. Note that the reflections must occur because of the one-stream nature of the model, but this is physically reasonable for a flux tube with \(L = 2\) since the plasma on such a flux tube is collision dominated at the equator. The refilling occurs from the equator downward, between the downward moving reflected shocks. All the shocks have decayed and there is steady refilling by 165 minutes; there are upward H\(^+\) fluxes in both hemispheres since the equatorial H\(^+\) densities are still lower than their steady state values.

For a fivefold density depletion the result was similar to a blast wave. In this case the blast wave is the result of a strong discontinuity in the density of the medium; the disturbance moves into the low-density region with a speed which exceeds the local sound speed of the upstream medium. Figures 6 through 11 show the initial conditions and results at \(t = 6, 11, 14, 25,\) and 27.5 minutes for this case. Again shocks develop which move upward; this can be seen in Figure 7, which also shows that the H\(^+\) shocks again outrun the O\(^+\) shocks. This time the propagation speed of the H\(^+\) shock is about 12.5 km/s; the propagation speed of the O\(^+\) shock is initially 1.8 km/s but by 30 minutes has increased to 2.8 km/s. The O\(^+\) shock speed increases because the O\(^+\) velocity increases behind the shock, which implies that the shock velocity must increase because of mass flux conservation relationships. The H\(^+\) shocks are supersonic, but the O\(^+\) shocks are subsonic, with respect to the ion acoustic speed (~11.7 km/s). However, in this case the flow velocities become supersonic. The H\(^+\) flow velocities approach the sonic velocity at 1 minute, and then its Mach number decreases, but the O\(^+\) ion gas definitely becomes supersonic with its Mach number reaching a maximum of 1.5 at 17.5 minutes. The H\(^+\) shocks meet at 11 minutes, as shown in Figure 8. Note the H\(^+\) density and pressure enhancement at the...
Fig. 4. Solution for $t = 12.5$ minutes in the twofold density depletion case. The six panels display flow velocity, hydrodynamic Mach number, particle flux (normalized to a reference altitude of 1000 km), number density, pressure, and temperature profiles between $-40^\circ$ and $+40^\circ$ magnetic latitude.

Fig. 5. Solution for $t = 60$ minutes in the twofold density depletion case. The six panels display flow velocity, hydrodynamic Mach number, particle flux (normalized to a reference altitude of 1000 km), number density, pressure, and temperature profiles between $-40^\circ$ and $+40^\circ$ magnetic latitude.
Fig. 6. Initial condition for the fivefold density depletion case. The six panels display flow velocity, hydrodynamic Mach number, particle flux (normalized to a reference altitude of 1000 km), number density, pressure, and temperature profiles between -40° and +40° magnetic latitude.

Fig. 7. Solution for t = 6 minutes in the fivefold density depletion case. The six panels display flow velocity, hydrodynamic Mach number, particle flux (normalized to a reference altitude of 1000 km), number density, pressure, and temperature profiles between -40° and +40° magnetic latitude.
Fig. 8. Solution for $t = 11$ minutes in the fivefold density depletion case. The six panels display flow velocity, hydrodynamic Mach number, particle flux (normalized to a reference altitude of 1000 km), number density, pressure, and temperature profiles between $-40^\circ$ and $+40^\circ$ magnetic latitude.

Fig. 9. Solution for $t = 14$ minutes in the fivefold density depletion case. The six panels display flow velocity, hydrodynamic Mach number, particle flux (normalized to a reference altitude of 1000 km), number density, pressure, and temperature profiles between $-40^\circ$ and $+40^\circ$ magnetic latitude.
Fig. 10. Solution for $t = 25$ minutes in the fivefold density depletion case. The six panels display flow velocity, hydrodynamic Mach number, particle flux (normalized to a reference altitude of 1000 km), number density, pressure, and temperature profiles between $-40^\circ$ and $+40^\circ$ magnetic latitude.

Fig. 11. Solution for $t = 27.5$ minutes in the fivefold density depletion case. The six panels display flow velocity, hydrodynamic Mach number, particle flux (normalized to a reference altitude of 1000 km), number density, pressure, and temperature profiles between $-40^\circ$ and $+40^\circ$ magnetic latitude.
equator. Also note the H⁺ temperature increase near the equator. This figure also shows that the O⁺ temperature decreases behind the O⁺ shocks, due to adiabatic cooling. After this the shocks reflect and the H⁺ ions start refilling from the top, as can be seen in Figure 9. The O⁺ maximum flow velocity decreases after 17.5 minutes due to increased collisions with the refilling hydrogen ions. Figure 10 shows results after 25 minutes; the downward propagating H⁺ shocks have almost reached the flux tube boundaries, as can be seen in the density and Mach number profiles. Figure 11 shows results after 27.5 minutes; now the Mach number profile shows that the H⁺ shocks were not reflected but instead have been absorbed by the denser lower atmosphere and their energy dissipated due to ion-neutral collisions.

Figures 12 through 15 show results at t = 45, 60, 90, and 150 minutes in the fivefold density depletion case. The O⁺ shocks meet at 45 minutes, as shown in Figure 12. This figure also shows a strong O⁺ density and pressure enhancement at the equator and an equatorial O⁺ temperature increase. The flux profiles in this figure also show counterstreaming of O⁺ and H⁺ ions between about 1100 km and 4900 km altitude. The O⁺ shocks reflect, and after this the O⁺ ions start refilling from the top; this is shown in Figure 13. These reflected shocks move down and merge with reverse shocks which are moving up from the ionospheres. By 90 minutes these have almost completely merged and are moving up. As can be seen in Figure 14, at this time there is a relative O⁺ density decrease between these shocks, but the equatorial O⁺ density is still higher than before the first pair of O⁺ shocks met at 45 minutes due to the initial refilling of O⁺ ions. These have met and reflected by 150 minutes, since there is a small bulge at the equator in the O⁺ density profile in Figure 15 which is characteristic of reflected shocks, and thereafter the O⁺ ions refill from the top. By 195 minutes all the shocks have decayed, and there is steady refilling; again there are upward H⁺ fluxes in both hemispheres. These upward fluxes are expected, since the equatorial H⁺ density is still lower than the steady state value.

The secondary O⁺ shocks which can be seen in Figure 13 are reverse shocks which are moving up. This is a result of the initial O⁺ density discontinuity, which leads to a fast shock moving up and a slow rarefaction wave moving down in the rest frame of the plasma. However, since the O⁺ ions flow upward, the rarefaction wave is slowly transported up. This rarefaction wave then interacts with the reflected shock which is moving down, leading to the formation of the reverse shock. These secondary shocks heat the O⁺ ions, as can be seen in the O⁺ temperature profile in Figure 13. Such secondary shocks are not seen in the H⁺ velocity profile because the reflected H⁺ shocks overun the rarefaction waves before they can steepen into shocks.

In both the twofold and the fivefold depletion cases the temperature of a particular ion species increases sharply at the equator when the upward moving shocks for that ion collide. This is due to heating caused by the collision of the upwelling streams. Also, when the shocks meet, the ion flow velocity becomes very small and hence the density must increase. In both these cases the initial, upward moving shocks propagate at speeds which are greater than those reported by Singh et al.

![Fig. 12. Solution for t = 45 minutes in the fivefold density depletion case. The six panels display flow velocity, hydrodynamic Mach number, particle flux (normalized to a reference altitude of 1000 km), number density, pressure, and temperature profiles between -40° and +40° magnetic latitude.](image-url)
Fig. 13. Solution for $t = 60$ minutes in the fivefold density depletion case. The six panels display flow velocity, hydrodynamic Mach number, particle flux (normalized to a reference altitude of 1000 km), number density, pressure, and temperature profiles between $-40^\circ$ and $+40^\circ$ magnetic latitude.

Fig. 14. Solution for $t = 90$ minutes in the fivefold density depletion case. The six panels display flow velocity, hydrodynamic Mach number, particle flux (normalized to a reference altitude of 1000 km), number density, pressure, and temperature profiles between $-40^\circ$ and $+40^\circ$ magnetic latitude.
CONCLUSIONS

In this paper the results of a time-dependent, one-stream, multispecies, hydrodynamic model for interhemispheric flow have been presented. This model includes O\(^+\) and H\(^+\) ions and electrons. A steady state solution was found and used in simulations of the effect of density depletions. Since the streams from conjugate hemispheres are not distinguished in this model, a shock pair must form at the equator when the upwelling streams collide. However, since an \(L = 2\) flux tube was used, the equatorial density should be high enough that Coulomb collisions are effective in thermalizing the streams, thus leading to the formation of a shock pair.

An important steady state result was counterstreaming of O\(^+\) and H\(^+\) ions between 700 km and 1000 km altitude. These counterstreaming fluxes are not equal in magnitude. This is in agreement with the prediction of Young et al. [1979], since the neutral atmosphere model is not symmetric about the magnetic equator. Also, the results are not symmetric about the magnetic equator.

The effect of an instantaneous density depletion was simulated by dividing the steady state densities by an arbitrary factor above 2500 km altitude, while leaving the velocities and temperatures unchanged. For this work, twofold and fivefold density depletions were studied. The density discontinuities lead to shock fronts which propagate up the field line. These shocks meet and reflect at the equator; thereafter refilling occurs between the reflected shocks. Shocks develop in the velocity profile for both ions, but the H\(^+\) shocks outrun the O\(^+\) shocks since the H\(^+\) ions are 16 times lighter. In both cases the model was allowed to run for 5 hours of simulated time. By this time all the shocks have decayed and there is steady refilling. Also, by this time there are upward H\(^+\) fluxes in both hemispheres since the equatorial H\(^+\) densities are still lower than the steady state values. The equatorial O\(^+\) densities at this time are higher than the steady state values, but the O\(^+\) fluxes are very small except near the lower boundaries.

The result of the twofold depletion was similar to a sonic disturbance. In such a case the disturbances should move with the ion acoustic speed. However, the propagation speed of the H\(^+\) shock was 10.7 km/s, which is much faster than the maximum propagation speed of 1.5 km/s reported by Singh et al. [1986b]. In addition, the flow velocities were always subsonic. The H\(^+\) shocks meet at 12.5 minutes and then reflect; the O\(^+\) shocks meet at 60 minutes and then reflect. There is steady refilling by 165 minutes.

The fivefold depletion resulted in a blast wave. In this case the disturbances move faster than the ion acoustic speed. In addition, the flow velocities can become supersonic. The H\(^+\) Mach number approaches 1 after 1 minute and then decreases. The O\(^+\) Mach number reaches a maximum of 1.5 by 17.5 minutes; thereafter the Mach number and flow velocity decrease due to increased collisions with the refilling hydrogen ions. In this case the H\(^+\) shocks meet at 11 minutes and then reflect,
while the O\textsuperscript+ shocks meet at 45 minutes and then reflect. The reflected O\textsuperscript+ shocks merge with shocks which are moving up from the ionospheres and continue to move up. These shocks have met and reflected by 150 minutes. The downward moving reflected H\textsuperscript+ shocks are absorbed in the denser regions of the neutral atmosphere. In this case there is steady refilling by 195 minutes.

In both of the density depletion cases the refilling occurs from the equator downward after the upwelling streams from each hemisphere collide, and this continues for 2 to 3 hours. Thereafter there is steady refilling from the ionospheres upward.

In comparison with the results of Singh et al. [1986f], in both cases the shock speeds are much higher and the maximum H\textsuperscript+ outflow speeds are much lower. The shock speeds are higher because of the discontinuity in the initial conditions for our work. The H\textsuperscript+ outflow speeds are lower because of the higher neutral densities at the equator on an L = 2 flux tube as compared to an L = 4 flux tube. Rasmussen and Schunk [1988] found that on an L = 4 flux tube the streams from conjugate hemispheres interpenetrate at first but that there is refilling from the equator downward after about 4 hours. In our work the refilling starts immediately after the upward moving shocks meet, but our results are for an L = 2 flux tube where the equatorial densities are high enough so that the plasma is collision dominated. In both of these earlier works the plasma is assumed to be isothermal with T(H\textsuperscript+) = T\textsubscript{e}, whereas our model includes an energy equation for each species. Our results indicate that the temperatures depend on latitude and change dramatically as the shocks move up the field line, meet, and reflect. In addition, the species' temperatures can be significantly different. Finally, the flux tube boundaries in our model are low enough that shocks are not reflected from them, whereas in these earlier works the boundaries are at higher altitudes (~ 2000 km) and shocks are reflected from them.

Limitations of the model include the inability to distinguish the streams from conjugate hemispheres and the restriction to isotropic temperatures. As discussed in the introduction, the streams could interpenetrate if the collision frequency was low enough. The assumption of isotropic temperatures is also serious, since the presence of a strong magnetic field allows anisotropicity if the collision frequencies are small enough. These are not serious limitations for an L = 2 flux tube, since the plasma is still collision dominated at the equator. However, for flux tubes with higher L values the plasma becomes collisionless above a certain altitude, and these limitations would then be more serious.

Since the original submission of this paper the model has been adapted for an L = 4 flux tube. A steady state solution was found assuming only electron heating near the equator; this solution was used in studies of the effect of H\textsuperscript+ heating near the equator. The steady state solution was similar to that found in the L = 2 case; however, counterstreaming of O\textsuperscript+ and H\textsuperscript+ ions was not observed, and the O\textsuperscript+ temperature is much lower than the H\textsuperscript+ temperature. The L = 4 model uses much more computer time, and so refilling studies have not been done using it. We intend to publish these results in a later paper.

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