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TOPSIDE IONOSPHERE

Peter M. Banks, et al

California University

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Principal Investigator: Peter M. Banks
Associate Professor
(Telephone: (714) 453-2000 Ext. 2676)

Co-Investigator: Robert W. Schunk
Assistant Research Physicist
(Telephone: (714) 453-2000 Ext. 2550)

Department of Applied Physics and Information Science
University of California, San Diego
La Jolla, California 92037

The main findings and conclusions of our research have been published in three scientific papers. The first paper entitled "Behaviour of Ion Velocity Distributions for a Simple Collision Model" has been published in Planetary and Space Science. From this study we have found that whenever there are large relative drifts between the interacting species in the gas mixture, the velocity distribution functions are non-Maxwellian. Although this research was specifically conducted for the auroral E-region, where perpendicular electric fields drive the ambient ions NO^+, O_2^+ and O^+ through the neutrals with speeds approaching 1 km sec^{-1}, the main conclusion of this research can be applied to the topside polar ionosphere, where large relative H^+ - O^+ drifts of the order of several km sec^{-1} have been detected.

The consequence of a non-Maxwellian H^+ velocity distribution function is that the usual Euler and Navier-Stokes hydrodynamic equations, which are derived assuming a Maxwellian or near Maxwellian distribution function and which have been used in previous studies of the topside polar ionosphere, may not be appropriate. In order to obtain a more general set of transport equations, we have used a 13-moment approximation of the distribution function. The resulting system of transport equations contains a continuity, momentum, internal energy, pressure tensor and heat flow equation for each species in the gas mixture. The application of this general system of transport equations to the polar E-region, F-region, topside ionosphere and neutral atmosphere is discussed in a paper entitled "Transport Equations for Aeronomy", which has been accepted for publication in Planetary and Space Science.

Because the 13-moment system of flow equations corresponds to a system of coupled, nonlinear, partial differential equations, it was important to determine the character of the flow before we attempted a numerical solution of this general system. To accomplish this, we obtained a numerical solution of the coupled continuity, momentum, and energy equations for H^+, O^+, and electrons. Although this reduced system of equations is not as general as the 13-moment system, it is still more general than systems considered in previous model studies of the topside polar ionosphere. The results of this investigation have been presented in a paper entitled "Temperature and Density Structure of Thermal Proton Flows", which has been accepted for publication in the Journal of Geophysical Research.

It should be noted that due to the premature cancellation of the ARPA model program, we have not been able to achieve our final goal of obtaining a numerical solution of the 13-moment system of transport equations for the topside polar ionosphere. However, this research will continue under NSF support.

A brief summary of the three publications that resulted from our research follows:

Behaviour of Ion Velocity Distributions for a Simple Collision Model

For application to studies of the high latitude ionosphere, we have calculated ion velocity distributions for a weakly-ionized plasma subjected to crossed electric and magnetic fields. An exact solution to Boltzmann's equation has been obtained by replacing the Boltzmann collision integral with a simple relaxation model. At altitudes above about 150 km, where the ion collision frequency is much less than the ion cyclotron frequency, the ion distribution takes the shape of a torus in velocity space for electric fields greater than 40 mV m^{-1}. This shape persists for 1 to 2 hours after application of the electric field. At altitudes where the ion collision and cyclotron frequencies are approximately equal (about 120 km), the ion velocity distribution is shaped like a bea.. for large electric field strengths. This bean-shaped distribution persists throughout the lifetime of ionospheric electric fields. These highly non-Maxwellian ion velocity distributions may have an appreciable effect on the interpretation of ion temperature measurements.

Transport Equations for Aeronomy

By taking moments of Boltzmann's equation, we have obtained a general system of transport equations for a multiconstituent gas mixture. This system of equations contains a continuity, momentum, internal energy, pressure tensor, and heat flow equation for each species. The system of equations has been closed by using Grad's 13-moment approximation of the distribution function to express higher-order moments in terms of lower-order moments. The closed system of equations can be applied to both collision-dominated and collisionless plasmas, and provides a continuous transition between the two regimes. In the collision-dominated limit, the pressure tensor and heat flow equations yield the usual Navier-Stokes expressions for the viscous stress tensor and heat flow vector. In addition, the momentum equation yields thermal diffusion and thermo-electric transport coefficients that correspond to the second approximation of Chapman and Cowling. In the collisionless limit, the closed system of transport equations can be shown to reduce to the well-known Chew-Goldberger-Low equations.

General collision terms for the 13-moment system of equations have only been calculated for Maxwell molecule interactions, where the inter-particle force varies inversely as the fifth power of the particle separation. These Maxwell molecule collision terms are given in the paper. For other interparticle force laws, the appropriate collision terms have only been calculated for low-speed flows, where the species drift velocity differences are much smaller than the species thermal speeds. For low-speed flows, we present collision terms for hard sphere interactions, Coulomb interactions, resonant charge exchange interactions and electron-neutral interactions.

We have applied the 13-moment system of equations to the E-region, F-region, topside polar ionosphere, and neutral atmosphere in order to determine the importance of viscous stresses and heat flow. By using an order of magnitude analysis, we have found that

(1) At high latitudes, electric fields directed perpendicular to the geomagnetic field set up viscous stresses in the plasma, and these stresses affect the altitude distribution of E- and F-region ions.

(2) The usual Navier-Stokes expressions for the viscous stress tensor and heat flow vector that have been extensively used in neutral gas studies may not be appropriate. The 13-moment pressure tensor and heat flow equations contain additional terms that appear to be the same order of magnitude as the usual Navier-Stokes terms. These additional terms are definitely important if the scale length for variation of the neutral atmosphere is small. Small scale lengths may occur, for example, at the edges of auroral arcs.

(3) The transport coefficients that are commonly used in studies of the mid-latitude F-region and topside ionosphere are valid provided the electron density does not become too small. The lower limit for the electron density is of order 10^4 cm^{-3} in the F-region and 10^3 cm^{-3} in the topside ionosphere.

(4) In the topside polar ionosphere, viscous stresses and heat flow are likely to have a significant effect on H^+ densities and temperatures if the upward flow of H^+ reaches its critical flux.

Temperature and Density Structure of Thermal Proton Flows

We have obtained self-consistent solutions of the coupled continuity, momentum, and energy equations for H^+, O^+, and electrons. Using reasonable values for the various input parameters, we have obtained theoretical density, drift velocity, and temperature profiles for a variety of boundary conditions covering the range of ionization inflow to polar wind outflow. The main conclusion of our paper is that the Joule heating that is associated with the outward flow of H^+ from the topside polar ionosphere is sufficient to maintain a large $H^+ - O^+$ temperature difference. Typically, the H^+/O^+ temperature ratio varies between 1 and 3.

The ion density profiles we have obtained depend on a number of parameters that are currently not well known. Examples of these parameters are the neutral oxygen and hydrogen densities, the charge exchange rate coefficients, and the downward electron heat flux. By separately varying the magnitude of the different input parameters, we have been able to determine the extent to which each input parameter affects our theoretical densities and temperatures. From such a study we have found that:

(1) A change in the plasma temperature at 500km has a significant effect on the ion density and temperature profiles. An increase in the plasma temperature results in enhanced H^+, O^+ and electron temperatures at all altitudes.

(2) A factor of 20 change in the magnitude of the downward electron heat flux at 4000km has a small effect on H^+ and O^+ densities. The effect on the ion temperatures, however, is not small. An increase in the magnitude of the downward electron heat flux results in enhanced H^+ and O^+ temperatures.

(3) In general, an increase in the atomic hydrogen density results in enhanced H^+ densities, drift velocities and temperatures. A factor of 2 increase in N(H) results in approximately a factor of 2 increase in the

H^+ escape flux.

(4) A factor of 2 increase in the charge exchange rate coefficients is roughly comparable to a factor of 2 increase in the atomic hydrogen density.

(5) Model atmospheres with low exospheric temperatures yield high H^+ and O^+ temperatures and large H^+ escape fluxes.

(6) Unusually low O^+ densities yield unusually high H^+/O^+ temperature ratios.