LA-UR-97- 2176

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Title: **Plasmasphere Refilling: New Numerical and
Observational Tools**

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Submitted to: DOE Office of Scientific and Technical Information (OSTI)

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PLASMASPHERE REFILLING: NEW NUMERICAL AND OBSERVATIONAL TOOLS

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Abstract

This is the final report of a three-year, Laboratory-Directed Research and Development (LDRD) project at the Los Alamos National Laboratory (LANL). The outflow of plasma from the ionosphere and its interactions in the outer magnetosphere remain important problems in space physics. While outflow is a continuous process, it becomes even more important after geomagnetic substorms when magnetic field lines that have been vented of plasma are reconnected. The purpose of this project was to develop new computational, theoretical, and observational tools to study plasma dynamics and heating associated with the outflow and refilling processes. In particular, we have developed new numerical methods to model the transition from collisional plasma flow at low altitudes to collisionless behavior at high altitudes and incorporated them in a multi-species kinetic simulation model to model the outflow process. We have also investigated electromagnetic instabilities in the outer magnetosphere to understand their contribution to the heating of upflowing protons and minority ions. In addition, new observational techniques have been used to analyze geosynchronous plasma data and to assess the effect of the spacecraft potential on the observations.

1. Background and Research Objectives

In the inner reaches of the Earth's magnetosphere, inside a distance of 5 or so Earth radii, is a region that is the extreme high-altitude extension of the Earth's atmosphere. This region, called the plasmasphere, contains fairly dense (10's to 1000's of ions per cubic centimeter), relatively cold plasma that originated in the Earth's ionosphere, flowed upward and outward along geomagnetic field lines, and became trapped near the high-altitude magnetic equator. Plasma on flux tubes that comprise the plasmasphere approximately corotates with the Earth and is able to complete many circuits around the planet without

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being lost either back to the atmosphere or out to interplanetary space. Competing with the tendency to corotate is a generally sunward convection caused by a large-scale electric field imposed across the magnetosphere by the magnetized solar wind flowing past the Earth. Beyond the so-called plasmapause, this convection electric field dominates over the corotational electric field so that the cold plasma of ionospheric origin can no longer execute closed drift orbits and is eventually lost through the magnetopause into interplanetary space. The consequence of this loss is the erosion of the plasmasphere. Similarly, as the imposed electric field decreases, flux tubes which had not previously been able to execute a complete drift orbit may now do so, and the build-up of the cold plasma density takes place, leading to the so-called refilling of the plasmasphere.

The problem of the refilling of the plasmasphere is of fundamental interest in magnetospheric physics, and, in spite of two decades of study, there remain a number of unresolved first-order questions (see recent review [1]) related to the mechanisms that operate to loft plasma from the high-altitude ionosphere into the magnetosphere and to heat and trap the upflowing plasma in the magnetosphere. One important question is how the initially supersonic flows from each hemisphere interact when they meet at the magnetic equator. Originally, it was proposed that the interaction would lead to the formation of a pair of electrostatic shocks that would then propagate down and cause the flow to become subsonic [2]. Observations do at times show density jumps [3], but strong evidence for a shock-like interaction is still lacking. The other view is that the interaction involves more collisional (either Coulomb or wave-particle due to instabilities) processes that scatter and/or heat the plasma in the equatorial region, but do not lead to the formation of a shock [4]. There is good observational evidence for such heating [5], which can result from the interaction of the streaming plasma with a hot plasma component, whose origin is either the plasma sheet or the ring current.

The problem of refilling is particularly interesting because it involves fundamental issues of magnetosphere/ionosphere coupling. Traditionally there has been a separation of effort when considering magnetospheric and ionospheric plasmas. While this separation is partially due to their different location in space, on a more fundamental level the division is due to different physics: essentially collisionless processes in the magnetosphere versus primarily collisional processes in the ionosphere. In fact, of course, these two systems are coupled together, sometimes quite strongly. Plasmasphere refilling is one important example of this coupling. Unfortunately, the theoretical tools that have so far been brought to bear on the problem tend to be applicable only in either the low-altitude collisional regime or the high-altitude collisionless regime, with the connection to the alternate regime accomplished through largely *ad hoc* boundary conditions [6]. On the observational side,

previous measurements of refilling have been clouded by the lack of three-dimensional viewing, by problems with detecting low-energy plasma on a spacecraft that is charged positively with respect to the ambient plasma because of photoelectron emission, and by spacecraft ram effects.

One goal of this LDRD project has been to build a numerical model that links together collisionless magnetospheric and collisional ionospheric plasmas on a kinetic scale in a unified manner. The numerical model is being used to address important, and largely unresolved, issues related to plasmaspheric refilling. Associated with the numerical model is a theoretical study of the microphysics of particle trapping and heating near the magnetic equator. In conjunction with this theoretical work, we also conduct a study of *in situ* observations of refilling ion flows obtained by recently-launched LANL plasma instrumentation on three spacecraft in geosynchronous orbit. Synchronous orbit often lies within the refilling region, and the three-dimensional plasma instrumentation on board these spacecraft is well suited to viewing the field-aligned ion flows since it avoids the main deficiencies that have plagued earlier measurements. These observations provide validation to the numerical work as well as guidance with regard to appropriate questions to investigate theoretically.

2. Importance to LANL's Science and Technology Base and National R&D Needs

In addition to making significant progress toward solving some of the outstanding questions about plasmaspheric refilling, this LDRD project has much broader significance for a number of critical problems. First of all, we have improved numerical techniques and a theoretical methodology that has application to many other problems involving magnetosphere/ionosphere coupling. Central to the computational problem is how to link the different physics regimes together. One goal of our project is to demonstrate that one can bridge the gap between magnetospheric and ionospheric physics on ion scales appropriate to the problem. A second area of global interest concerns the effects of nuclear weapon detonations in the upper atmosphere on the ionosphere and magnetosphere. Again, this is an area where collisional and collisionless plasma physics have traditionally been treated independently. Research in developing new physics/computation tools that could be applied to address issues of survivability of space assets, treaty verification, and communications links remains an important part of the Laboratory's technology base.

3. Scientific Approach and Accomplishments

The goal of this project is to improve Laboratory numerical, theoretical, and observational tools to address issues related to the fundamental and long-standing problem of plasmasphere refilling and associated physical processes. The computational model developed as part of this project goes beyond capabilities that exist at present in the space community to follow the initially collisional flow from the ionosphere as it becomes collisionless at higher altitudes. Related theoretical analysis is used to study what collisionless processes contribute to the heating of upflowing protons and minority ions in the outer magnetosphere. In addition, new observational techniques are used to analyze geosynchronous plasma data and to assess the effect of the spacecraft potential on the observations. The data are also used to verify the theoretical results and to suggest observational issues to be addressed by the calculations.

One of the most challenging aspects of this project has been to develop new computational methods to treat the transition from collisional plasma flow at low altitudes to collisionless behavior at higher altitudes. While numerical methods exist [7,8] to include collisional processes in kinetic calculations, these algorithms, which involve pairing particles in each computational cell and then scattering them off each other elastically so that energy and momentum are locally conserved, tend to be somewhat arbitrary and inefficient. We have developed a new technique to model collisional processes that avoids these difficulties [9]. Our method treats Coulomb collisions between particles of different species ("interspecies collisions") through a collision field, which is designed so that energy and momentum are automatically conserved. Efficiency is achieved by making the collision field a quantity defined on the computational grid, so that the collisional force can be treated on equal footing with the Lorentz force. Collisions between particles of the same species ("intraspecies collisions") are treated in a different manner, a more Monte Carlo-like approach based on a Langevin equation. Careful analysis of this approach [10] shows its flexibility and utility, but also its inherent tendency to lose energy over many collision times. This problem can be remedied by renormalizing the particle distribution so that energy is strictly conserved. Together, the inter-species and intra-species collision methods allow a full range of phenomena, from strongly collisional to collisionless, to be modeled by the same numerical algorithm so that problems in which the collisionality changes rapidly in time or space are handled in a seamless manner.

Using these collision models, we have developed a multi-species kinetic simulation code for modeling the outflow of ions from the polar ionosphere. The model gives an accurate description of the ionosphere and all relevant collision processes above 200 km. The code includes the particle collision algorithm described previously [9] that allows the

interaction of multi-species ions. The model is one-dimensional, but has a tilted dipole coordinate system, thereby allowing for asymmetric illumination of the ionosphere and includes corotation as well as convection. A number of test problems have been carried out to benchmark the code, and comparisons have been made with fluid code results [11]. As a realistic test, the code has been used to study the effect of ions accelerated out of the ionosphere due to the ponderomotive force by Alfvén waves propagating into the ionosphere [11]. Alfvén waves with frequencies of several Hertz are often observed in the auroral zone. As an Alfvén wave penetrates into the inhomogeneous ionosphere, the absorption of the wave results in a gradient of the electric field of the wave, and hence gives rise to a ponderomotive force that can affect the outflow of the plasma. In our case, we specify the electric field magnitude of the wave and its frequency at some altitude, as well as the time interval over which the Alfvén waves are present. Figure 1 shows the effect of a ponderomotive event of 10-minute duration on the outflow of ions. Plotted are the density (left panel) and flow velocity (right panel) profiles versus altitude of H^+ and O^+ ions corresponding to equilibrium profiles (solid curves) compared with those occurring after the event (dashed curves). Evidently, the effect of the Alfvén waves has been to increase the flow speeds of both the hydrogen and oxygen ions significantly and thus to accelerate more ions to higher altitudes [11].

Additional modifications are needed to use the computer model to study the much more difficult problem of the dynamics of the plasmasphere refilling process. These modifications involve deriving and implementing the proper boundary conditions at the magnetic equator and, more significantly, including an improved, self-consistent electron energy equation, so that the correct outflow is produced and maintained as the ionospheric ions reach the equator. These elements have not been completely implemented and tested before the termination of this project, but work is continuing on this problem nonetheless.

As part of this project, we have also pursued the problem of how the upflowing ionospheric ions can be trapped in the magnetosphere. Ions in the outer magnetosphere typically are observed to consist of a hot component with temperature of order 10 keV and a cool constituent with temperature of order a few eV, which is presumably ionospheric in origin. The hot component often is observed to have temperatures perpendicular to the magnetic field larger than temperatures in the parallel direction; this anisotropy leads to growth of the electromagnetic proton cyclotron anisotropy instability. The turbulent electric and magnetic fields from this instability scatter the cool ionospheric component and contribute to plasmaspheric refilling by heating the cool ions in the perpendicular direction, leading to the trapping of "warm" (~ 10 eV) ions at high altitudes. One-dimensional hybrid (particle ions, fluid electrons) computer simulations have been used to obtain scaling

relations for the temperature of warm protons heated by this instability and for the temperature anisotropy of the hot proton population [12,14]. Figure 2 shows data from geosynchronous orbit and the corresponding scaling relation for the hot proton anisotropy versus plasma beta of the hot component. Consistent with theory, the data points all lie below the scaling relation, which is essentially the threshold condition for instability. The next step was to examine warm proton properties as observed by Los Alamos instrumentation at geosynchronous orbit [17]. The results of this data analysis showed that the predicted scaling relation provide an approximate upper bound for a selected set of observed warm proton temperatures. This result is consistent with the hypothesis that the proton cyclotron instability is an important mechanism for trapping ionospheric protons that reach the outer magnetosphere. Moreover, this same mechanism is capable of heating minority ions (helium, oxygen). The scaling of the helium ion heating rate has also been obtained [15].

With respect to the observations, we have made considerable progress in exploring the effects of spacecraft charging on the measurement of low-energy plasmaspheric ions. We have modeled the spacecraft using the NASCAP modeling code to derive the electrostatic potential structure around the detector under realistic magnetospheric conditions, and we have examined ion trajectories that indicate there is an asymmetry in the sunlit/shadowed measurement that depends on the ambient hot electron population, as well as the cold ion density. This asymmetry probably distorts the measured distributions and will need to be accounted for when we examine the very-low-energy ion anisotropies. We are also exploring whether or not this asymmetric sheath can account for the striking north/south asymmetries we commonly observe in the magnetic-field-aligned flows of ionospheric ions during times of plasmasphere refilling. Because the combination of marginal energy resolution and asymmetric sheath focusing effects makes it difficult to deal quantitatively with ion observations very near the instrument potential (i.e., the lowest energy particles), we have focused our attention on the slightly warmer population ($> \sim 10$ eV) that seems to be more characteristic of refilling intervals. We are currently especially interested in a population that appears primarily in the dayside trough region and shows a strong perpendicular anisotropy that may be indicative of the trapping action of the ion cyclotron instability.

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Figure 1. The density and flow speed profiles from 200 to 2500 km before (solid curves) and after (dashed curves) a 10-minute ponderomotive acceleration event modeled with a one-dimensional kinetic polar outflow code [11], showing how the effect of Alfvén waves is to greatly increase the flow of both hydrogen and oxygen ions.

Figure 2. The hot proton temperature anisotropy as a function of hot proton beta (= ratio of thermal to magnetic pressure). The circles represent individual observations from Los Alamos instrumentation on geosynchronous spacecraft 1989-046 during 11-20 November 1993. The dashed curve is the scaling relation that gives an upper bound to the anisotropy [14]. Consistent with theory, the data points all lie near or below the threshold condition.