The Study of Ionospheric Response to Precipitation Using Sounding Rocket Observations

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The Study of Ionospheric Response to Precipitation Using Sounding Rocket Observations

Abstract
Understanding the role that the ionosphere plays in phenomena such as the development of auroral arcs and ion outflow is basic to the investigation of these processes and critical to the advancement of the broader study of magnetosphere-ionosphere coupling. Sounding rockets present an optimal platform for such studies, allowing low-cost access to altitudes that are difficult to reach by other means. Additionally, these measurements are key to validating current models and furthering understanding of the near-Earth space environment. This thesis highlights two particular rocket-borne instruments that measure electron populations in the ionosphere: the Electron Retarding Potential Analyzer (ERPA) and the Electron PLASma (EPLAS) instrument. It also presents analysis of the first in situ measurements of the ionospheric feedback instability (IFI) occurring within the Alfvén resonator in the vicinity of an auroral arc, a phenomenon that may play a role in the upward acceleration of ions and contribute to upflow. Another study highlights correlations between electron temperature and density and ion upflows. Simulation results, validated by rocket observations, show that increased ionospheric density inhibits the strength of the ambipolar field considered necessary for Type-2 ion outflow. Despite this however, the simulations show that increased densities result in increased net upflow fluxes. New radar data shows that sunlight effects might play an important role in controlling upflows, as photoionization can change ionospheric densities by as much as an order of magnitude seasonally.

Keywords
aurora, ionosphere, magnetosphere, rocket, Aeronomy, Geophysics, Physics

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THE STUDY OF IONOSPHERIC RESPONSE TO PRECIPITATION USING SOUNDING ROCKET OBSERVATIONS

BY

IAN JAMES COHEN

B.A. in Astronomy & Physics with distinction, Boston University, 2010

DISSERTATION

Submitted to the University of New Hampshire
in partial fulfillment of
the requirements for the degree of

Doctor of Philosophy

in

Physics

May, 2015
This dissertation has been examined and approved in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Physics by:

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On April 28, 2015

Original approval signatures are on file with the University of New Hampshire Graduate School.
DEDICATION

I DEDICATE THIS WORK WITH LOVE AND GRATITUDE
TO THOSE WHO MADE IT POSSIBLE:

To LONI,
whose love and support got me through
graduate school and the life beyond

To MY PARENTS,
who never stopped encouraging me
to reach for the stars

To GRANDPA "RED" AND GRANDMA ANNETTE,
who unknowingly sparked my passion for space
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As with any great work of scientific research, this thesis is the result of the contributions of numerous collaborators across multiple institutions. In particular I would like to thank, Paul Riley and Mark Widholm from UNH for being outstanding electrical engineers with great patience and tolerance for the limitations of graduate student understanding. Special thanks must also be extended to some great unsung heroes: the remarkable engineers at NASA Wallops Flight Facility and the engineers and machinists of the UNH Space Science Center. I would also like to thank Craig Pollock, Ulrik Gliese, and the rest of the MMS Dual Electron Spectrometer (DES) team for welcoming and supporting me during my internship with them at GSFC. Additional collaborators
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ABSTRACT
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Ian James Cohen
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Understanding the role that the ionosphere plays in phenomena such as the development of auroral arcs and ion outflow is basic to the investigation of these processes and critical to the advancement of the broader study of magnetosphere-ionosphere coupling. Sounding rockets present an optimal platform for such studies, allowing low-cost access to altitudes that are difficult to reach by other means. Additionally, these measurements are key to validating current models and furthering understanding of the near-Earth space environment. This thesis highlights two particular rocket-borne instruments that measure electron populations in the ionosphere: the Electron Retarding Potential Analyzer (ERPA) and the Electron PLASma (EPLAS) instrument. It also presents analysis of the first in situ measurements of the ionospheric feedback instability (IFI) occurring within the Alfvén resonator in the vicinity of an auroral arc, a phenomenon that may play a role in the upward acceleration of ions and contribute to upflow. Another study highlights correlations between electron temperature and density and ion upflows. Simulation results, validated by rocket observations, show that increased ionospheric density inhibits the strength of the ambipolar field considered necessary for Type-2 ion outflow. Despite this however, the simulations show that increased densities result in increased net upflow fluxes. New radar data shows that sunlight effects might play an important role in controlling upflows, as photoionization can change ionospheric densities by as much as an order of magnitude seasonally.
Chapter 1

Introduction

The Earth is constantly being bombarded by highly energetic particles originating from the Sun and elsewhere in the near-Earth environment. This perpetual barrage and the resulting deposition of energy into the planet’s upper atmosphere can have significant effects, even if they are not readily apparent to the everyday life of its inhabitants. The most well-known result of this precipitation are the auroral displays often seen at high latitudes. These emissions are the most tangible manifestation of the interaction between our planet and our local star, the Sun.

At times it is hard for mankind to remember that we are ultimately dominated by the will of the Sun, that our existence is maintained by the workings of a spherical ball of plasma nearly ninety-three million miles away. Unfortunately, the Sun does not just provide sunlight and its accompanying warmth, but also spews millions of tons of radiated particles through phenomena such as solar flares and coronal mass ejections. Fortunately, Earth has a built-in protection for her inhabitants in the form of the planet’s magnetic field. This unseen shield carves out a relatively serene space in the solar system where life can thrive safe from harmful solar radiation. However, this “bubble” of safety, known as the magnetosphere, is still constantly buffeted by the solar wind and other solar phenomena. Understanding the reactions of the magnetosphere to solar drivers and the resulting effects on the Earth is crucial to our ultimate understanding of our home.

To truly understand the Earth and its local environment, one must study the system in its entirety and the interconnectivity between the different regions of space. Of particular importance
is understanding the coupling between the magnetosphere and the uppermost ionized layer of the atmosphere, known as the ionosphere. These two regions are intimately connected via currents and the convection of plasma. Determination of whether the ionosphere plays a more active or passive role in auroral dynamics remains a primary science question in magnetospheric physics. Originally it was believed that all magnetospheric plasma originated from the solar wind, but now it is commonly understood that the ionosphere is an important plasma source, particularly of O\(^+\) ions. This is extremely important to magnetospheric physics as the ionospheric plasma can change the Alfvén speed in the magnetotail and greatly affect reconnection rates. Understanding the mechanisms that drive and sustain ion upflow and outflow is key to ultimately understanding the dynamics of the ionospheric source.

This dissertation focuses on several aspects of magnetosphere-ionosphere coupling studies, specifically, the response of the ionosphere to auroral precipitation. Chapter 2 highlights the details of magnetosphere-ionosphere coupling, including overviews of those regions and their interconnectivity through current closure and plasma convection, aurora, and ion outflow. Particular emphasis is given to the specifics of the ionospheric Alfvén resonator (IAR) and the distinction between ion upflow and outflow processes.

Chapter 3 reviews two instruments developed by the Magnetosphere-Ionosphere Research Laboratory at UNH. The first is a combination Faraday cup and retarding potential analyzer known as the Electron Retarding Potential Analyzer (ERPA). The ERPA has flown on rocket missions for over a decade and has proven to obtain reliable in situ measurements of the thermal ionospheric electron temperature. This unique instrument allows for extremely low temperature measurements and recent results suggest that its utility might be expandable to include electron density observations as well. The second instrument is the Electron PLASma (EPLAS) instrument, which measures the energy and pitch-angle distribution of precipitating auroral electrons. A top hat electrostatic analyzer, the EPLAS descends from similar instruments with heritage reaching back nearly three
decades.

Chapter 4 presents observations of the ionospheric feedback instability (IFI) within the ionospheric Alfvén resonator (IAR) made by the Auroral Current and Electrodynamics Structure (ACES) rocket mission. When IFI occurs in the IAR, a resonant cavity within the ionosphere, it can generate ultra low frequency (ULF) waves that drive a ponderomotive force that evacuates plasma upwards, creating a density cavity at lower altitudes. The ACES-High rocket measured small-scale Alfvénic oscillations and a corresponding local density enhancement; together these observations agree with simulation results that suggest that IFI within the IAR may lead to ion upflow in the vicinity of auroral arcs.

Chapter 5 focuses on the impact of ionospheric density on ion upflow. A one-dimensional ionospheric model was run with precipitation characterized by observations from the Magnetosphere-Ionosphere Coupling in the Alfvén resonator (MICA) sounding rocket mission. Six simulations were run with varying initial ionospheric density profiles to study the relationship between ionospheric parameters (such as electron temperature and density) and ion upflow. The results indicate that higher densities result in increased O\(^+\) upflow, despite inhibiting the strength of the ambipolar electric field that is established by the precipitation. However, the higher densities decrease upflow speeds and extend the timescales for the development of upflow. This dependence on ionospheric density variation suggests that solar photoionization, which can increase ionospheric densities by as much as an order of magnitude on the dayside, may play an important role in controlling the strength of O\(^+\) upflows. New simulations were run on the dayside that show the direct effect of sunlight on upflow fluxes.

Chapter 6 concludes the thesis by summarizing the major results of this research, including its impact and importance in the study of magnetosphere-ionosphere coupling and the broader study of heliophysics. It also outlines the many new and remaining questions related to these studies and suggests possible future work.
Chapter 2

Magnetosphere-Ionosphere Coupling

The near-Earth environment is dominated by the planet’s magnetic field, which extends roughly 12 $R_E$ (Earth radii) towards the Sun [Schunk and Nagy, 2009] and over 200 $R_E$ away from it [Hughes, 1995]. This region is known as the magnetosphere [Gold, 1959] and its dynamics are complex, as it is constantly interacting with the charged uppermost layer of Earth’s atmosphere, known as the ionosphere. In addition to the effect of photoionization from solar ultraviolet radiation, the ionosphere is constantly being affected by the electromagnetic fields and near-constant precipitation of particles from the magnetosphere. Zhang et al. [2011] succinctly summarize that “[t]he Earth’s magnetosphere supplies energy to the ionosphere while the ionosphere dynamically responds by redistributing its plasma and ionization to affect the magnetospheric state.” It is the collision of these precipitating particles from the magnetosphere with the neutrals in the upper atmosphere that cause the impressive visual displays known as the aurora. Understanding the processes and dynamics of the coupling between these two regions as well as identifying the sources of the waves and particles that are created as a result is critical to modern magnetospheric research. In addition to better understanding of basic plasma physics concepts, our knowledge of magnetosphere-ionosphere (M-I) coupling is also key to improving model simulations that will help to visualize and one day predict the response of the near-Earth system to external influences such as
solar flares and coronal mass ejections (CMEs). The geomagnetic response to solar activity, known collectively as “space weather”, can have severe effects on the technology of modern civilization, from spacecraft and GPS systems to the power grid.

2.1 The Magnetosphere

The Earth’s magnetic field plays a critical role in the survival of life on Earth. Without it, Earth’s atmosphere would be ablated away by the solar wind and other energetic particles from the Sun, leading to the evaporation of the oceans and the suffocation and irradiation of the planet’s inhabitants. Luckily, Earth has a magnetic field driven by currents in its molten, electrically conducting iron and nickel outer core. The terrestrial magnetic field at the surface is approximately 0.5 G (50,000 nT); it is slightly stronger near the poles than near the equator.

If left undisturbed, the magnetic field of Earth would be very near to a simple dipole. However, because of the constant pressure exerted on it by the solar wind streaming from the Sun, the sunward side of the field (nose) is compressed while the anti-sunward direction (tail) is stretched, giving the magnetosphere the elongated shape shown in Figure 2-1. As the supersonic flow of the solar wind encounters the terrestrial magnetic field, it slows and transitions to subsonic speeds, producing the bow shock at the nose of the magnetosphere. The magnetopause is defined as the boundary between the realm of the interplanetary magnetic field (IMF) from the Sun and Earth’s magnetic field. The location of the magnetopause varies as the dynamic, magnetic, and thermal pressures within the magnetosphere act to balance these pressures within the solar wind. However, the primary drivers are the magnetic pressure within the magnetosphere and the dynamic pressure or momentum flux in the solar wind. This simplifies the equilibrium condition to

\[
\rho_{SW} u_{SW}^2 = \frac{B_{MS}^2}{2\mu_0},
\]  

(2.1)
where $\rho$ is the mass density, $u$ is velocity, $B$ is the magnetic field, $\mu_0$ is the permeability of free space, and the subscripts $SW$ and $MS$ refer to solar wind and magnetosphere, respectively. At the magnetopause, the unmagnetized incident solar wind ions and electrons experience differential gyration from the Lorentz force ($v \times B_{MS}$), giving rise to the Chapman-Ferraro currents [Chapman and Ferraro, 1932]. Between the bow shock and magnetopause is a region of subsonic flow being diverted around the Earth known as the magnetosheath. Just inside the magnetopause is a region known as the magnetospheric boundary layer, where magnetosheath plasma dominates. Figure 2-2 from Eastman [2003] shows the magnetospheric boundary layer and its four component regions: the plasma mantle, the cusps, the dayside boundary or entry layer, and the low-latitude boundary layer (LLBL).

The near-Earth, inner magnetosphere is home to two important particle populations. First, are the energized particles trapped on terrestrial magnetic field lines creating the radiation belts first
Figure 2-2: Sketch from Eastman [2003] showing the primary boundaries within the magnetosphere. 

... discovered by Van Allen et al. [1958]. The radiation belts are most commonly separated into two separate regions, the outer and inner belts, although new observations have shown the occasional existence of a third belt as well [Baker et al., 2013]. The outer belt generally spans from 3 to 7 $R_E$ and is comprised mostly of high energy electrons (up to and above 15 MeV); however, this outer belt is extremely dynamic and can change drastically during geomagnetic storms. Meanwhile, the inner belt extending from 1.5 to 2 $R_E$ is much more stable, containing 100s keV electrons, 10s of MeV protons, and heavier ions. The highly energetic and low-density ($\sim 10^{-5}$ cm$^{-3}$) radiation belts are contrasted by the cold ($\sim 1$ eV), dense ($\geq 10^{-3}$ cm$^{-3}$) plasma of the plasmasphere. The plasmaspheric particles originate from the ionosphere (as will be discussed in Section 2.5) and corotate with Earth [Burch et al., 2004; Gallagher et al., 2005]. The combination of the convection electric field and corotational electric field near Earth gives the plasmasphere the dusk-oriented teardrop shape shown in Figure 2-3. The sharp outer boundary of this cold plasma, known as the plasmapause, is generally located between 3-8 $R_E$, but can move considerably during times of high solar activity [Carpenter and Lemaire, 1997]. Particles within the the inner magnetosphere can be lost to the ionosphere via wave-particle interactions that include plasmaspheric hiss, chorus, and electromagnetic ion cyclotron (EMIC) waves (see Shprits et al. [2008] and references therein).
Figure 2-3: Figure from Lyons and Williams [1984] showing the equipotential contours that constrain the plasmasphere. The bulge seen at dusk in the net field results from the superposition of the convection and corotational electric fields in the near-Earth environment.

During typical conditions \( n_{sw} = 4 \times 10^6 \text{ m}^{-3}, \) \( v_{sw} = 400 \text{ km s}^{-1}, \) \( E_{sw} = 1 \text{ keV} \), the solar wind inputs an energy flux of 0.26 mW m\(^{-2}\) into the magnetosphere. While precipitating electron energy fluxes into the ionosphere are of the same order, the more dominant Poynting flux deposited by the magnetosphere into the ionosphere is of the order of 1-10 mW m\(^{-2}\). This implication that the magnetosphere collects solar wind kinetic or bulk energy flux, converts it to Poynting flux, and focuses it into the auroral ionosphere demonstrates the strong interconnectivity between the magnetosphere and ionosphere.

2.2 The Ionosphere

As previously mentioned, the uppermost layer of the Earth’s atmosphere is a region of partially ionized gas known as the ionosphere. This ionized layer primarily results from ultraviolet radiation from the Sun and extends from roughly 60 to beyond 1,000 km in altitude.
The primary regions of the ionosphere are identified based on these plasma densities. The existence of the ionosphere was initially theorized nearly simultaneously in 1902 by Oliver Heavisides and Arthur Kennelly as an explanation for how radio waves could be transmitted across the Atlantic Ocean; both men correctly reasoned that an electrically conducting layer must exist in the atmosphere that reflects the waves and allows them to propagate long distances over the horizon. The first ionospheric layer discovered, extending from 90-150 km, was dubbed the E region due to the “electric” field component of the reflected radio waves. The F and D regions were discovered subsequently and named alphabetically; “A”, “B”, and “C” were reserved for future regions that were never discovered. The bottommost D region ranges from roughly 60-90 km. The F region, from roughly 150-500 km, is also known as the Appleton-Barnett layer after its discoverers who helped to experimentally confirm the existence of the ionosphere [Appleton and Barnett, 1925]; Appleton was awarded the 1947 Nobel Prize in Physics for this work.

Figure 2-4 shows the typical daytime composition of the upper atmosphere. The D and E regions are dominated by heavy molecular ions, while the F region is primarily O\(^+\). However, heavier molecular ions are still prominent in the lower part of the F region, so it is commonly broken into the F1 and F2 layers during daytime. The peak plasma density (10\(^{11}\) m\(^{-3}\)) occurs in the F region at around 250 km, so it is commonly referred to as the “F peak”. It defines the lower boundary of the so-called topside ionosphere. Above roughly 1000 km is the protonosphere where lighter ions (H\(^+\) and He\(^+\)) dominate and the plasma can be treated as fully ionized. At night, the lack of sunlight and the resulting photoionization causes depletion of the E region and disappearance of the D region. Although there are significant populations of charged particles in the ionosphere (up to 10\(^{10}\) m\(^{-3}\)), they are significantly outnumbered by the neutrals by several orders of magnitude. This means that collisions with neutrals plays a large role in the physics of the ionosphere.
2.2.1 Auroral Ionosphere

As mentioned earlier, the aurora occurs near the poles of the Earth where particles from the magnetosphere and solar wind are able to precipitate into the ionosphere along open magnetic field lines or perhaps in the outer regions of the closed field lines. The region where aurora most commonly occurs is known as the auroral zone (or auroral region), defined from 60° to 75° magnetic latitude [International Union of Geodesy & Geophysics, 1963]; however, further statistical studies showed that the geospatial distribution varies over the solar cycle [Stringer and Belon, 1967]. While the auroral zone is the defined region where aurora occurs most frequently, the auroral oval is a persistent observable auroral feature. These oval-shaped bands of commonly-occurring aurora are centered around the magnetic poles in both hemispheres and contain most of the aurora seen on Earth [Davis, 1992]. Figure 2-5 shows an image of auroral oxygen emissions in the northern hemisphere from the Dynamics Explorer (DE-1) satellite. The equatorward region of the auroral oval approximately overlaps with the boundary between open and closed field lines. The location of this boundary is determined by the dayside and nightside reconnection rates; it is commonly referred to as the polar cap boundary (PCB), open-closed field line boundary (OCFLB), or the open-closed boundary (OCB) [Siscoe and Huang, 1985; Cowley and Lockwood, 1992; Wild et al.,
Figure 2-5: Image from *Frank and Craven* [1982] showing Dynamics Explorer images of the 130.4 and 135.6 nm oxygen emissions in the northern hemisphere on November 8, 1981. The left side of the image shows the sunlit dayside ionosphere while the right side shows a majority of the auroral oval; both are overlaid on a geographic map.

2004. The region poleward of this boundary where the terrestrial magnetic field lines are open to solar wind plasma is known as the polar cap.

At the cusp introduced in Section 2.1, plasma flowing along field lines at the magnetosheath has direct access to the dayside ionosphere [*Russell*, 2000]. There is another region near the cusp in the dayside auroral ionosphere known as the cleft, where field lines connect to the aforementioned LLBL [*Farrell and Van Allen*, 1990]. Observations from DE-1 found that O\(^+\) ions were dominant at low energies (0-50 eV) in the polar cap region, but were not originating from the polar cap itself [*Waite et al.*, 1985]. *Lockwood et al.* [1985] later found a persistent source of many ionospheric species near the dayside polar cap boundary and *Moore et al.* [1986] confirmed that this source was co-located with the cleft. This phenomenon came to be known as the cleft ion fountain, where ionospheric ions are heated by wave-particle interactions, driven upward by the \( \nabla B \) force, and then convect across the polar cap toward the midnight sector due to magnetospheric electric fields. The energized particles continue to convect into the plasma sheet, while the lower energy particles fall back into the ionosphere [*Schunk and Nagy*, 2009]. The cleft ion fountain has been the focus of
many studies on ion outflow, a phenomenon to be discussed further in Section 2.5. In particular, observations from the SCIFER rocket mission showed its interior structure [Arnoldy et al., 1996] and the effect solar activity has on the outflow composition [Moore et al., 1996]. The electrons precipitating in the cleft region are soft (∼100 eV), allowing them to deposit a large fraction of their energy in the F region [Rees, 1969; Winningham, 1972; Whittle, 1976].

2.2.2 Conductivity

Ionospheric dynamics are dominated by electromagnetic fields and currents. For that reason, the ratio of current density to the electric field, known as the conductivity, is an important parameter when considering ionospheric phenomena. For instance, the integral of conductivity along a particular field line determines the load impedance into the ionosphere.

The derivation of conductivity (following Baumjohann and Treumann [1997]) begins with a single particle of charge $q$ in a magnetic field, which will feel both a Lorentz and Coulomb force, resulting in an equation of motion of the form

$$m \frac{dv}{dt} = q(E + v \times B). \quad (2.2)$$

In a collisional plasma, another frictional term must be added. Assuming that collisions occur at a frequency of $\nu_c$ between particles moving at velocities $v$ and $u$, the new equation of motion becomes

$$m \frac{dv}{dt} = q(E + v \times B) - m\nu_c(v - u). \quad (2.3)$$

When considering an idealized steady-state unmagnetized plasma ($B = 0$), where the electrons ($q = -e$) move at $v = v_e$ and collide with ions at rest ($u = 0$) at a collision frequency $\nu_{ei}$, then (2.3) can be simplified to

$$eE = -m_e\nu_{ei}v_e. \quad (2.4)$$
The moving electrons carry current, with a current density $\mathbf{J}$ defined as

$$\mathbf{J} = -en_e\mathbf{v}_e. \quad (2.5)$$

Equations (2.4) and (2.5) can be combined into Ohm’s Law to show that

$$\mathbf{J} = \frac{n_e e^2}{m_e \nu_{ei}} \mathbf{E}, \quad (2.6)$$

where the plasma conductivity is defined as

$$\sigma_0 = \frac{n_e e^2}{m_e \nu_{ei}}. \quad (2.7)$$

Ohm’s Law can also be expressed as the relative motion between ions and electrons, where

$$\mathbf{J} = n_e e(\mathbf{v}_i - \mathbf{v}_e) \quad (2.8)$$

When considering a magnetized plasma where collisional particles are again at rest ($\mathbf{u} = 0$), the equation of motion (2.3) for electrons can be written as

$$\mathbf{E} + \mathbf{v}_e \times \mathbf{B} = -\frac{m_e \nu_{ei}}{e} \mathbf{v}_e. \quad (2.9)$$

Inserting the definitions of $\sigma_0$ (2.7) and $\mathbf{J}$ (2.5) here yields

$$\mathbf{E} - \frac{1}{en_e}(\mathbf{J} \times \mathbf{B}) = \frac{m_e \nu_{ei}}{e^2 n_e} \mathbf{J}. \quad (2.10)$$

Assuming that the magnetic field is oriented along the z-axis ($\mathbf{B} = B \hat{\mathbf{e}}_z$), the solutions for the
current density can be found to be

\[ J_x = \sigma_0 E_x + \frac{\omega_{ce}}{\nu_{ei}} J_y \]

\[ J_y = \sigma_0 E_y - \frac{\omega_{ce}}{\nu_{ei}} J_x \]

\[ J_z = \sigma_0 E_z, \quad (2.11) \]

where \( \omega_{ce} \) is the electron cyclotron frequency or gyrofrequency that defines the period of the gyration of the electron around the magnetic field line [Baumjohann and Treumann, 1997]. It is defined as

\[ \omega_{ce} = -\frac{eB}{m_e}. \quad (2.12) \]

Combining the first two equations of (2.11) yields

\[ J_x = \frac{\nu_{ei}^2}{\nu_{ei}^2 + \omega_{ce}^2} \sigma_0 E_x + \frac{\omega_{ce} \nu_{ei}}{\nu_{ei}^2 + \omega_{ce}^2} \sigma_0 E_y \]

\[ J_y = \frac{\nu_{ei}^2}{\nu_{ei}^2 + \omega_{ce}^2} \sigma_0 E_y + \frac{\omega_{ce} \nu_{ei}}{\nu_{ei}^2 + \omega_{ce}^2} \sigma_0 E_x \]

\[ J_z = \sigma_0 E_z. \quad (2.13) \]

The components can be rewritten similarly to Ohm’s Law (2.6) in matrix notation as

\[ \mathbf{J} = \mathbf{\sigma} \cdot \mathbf{E}. \quad (2.14) \]

For the assumed field-aligned magnetic field along the z-axis, the conductivity tensor can be written as

\[ \mathbf{\sigma} = \begin{pmatrix} \sigma_P & -\sigma_H & 0 \\ \sigma_H & \sigma_P & 0 \\ 0 & 0 & \sigma_\parallel \end{pmatrix}. \quad (2.15) \]

The first tensor element, \( \sigma_P \), is know as the Pedersen conductivity and drives the Pedersen current,
which flows along the parallel component of the electric field \( E_\parallel \) and is perpendicular to the magnetic field. The second tensor element, \( \sigma_H \), is called the Hall conductivity and is associated with the Hall current that flows in the direction perpendicular to both the electric and magnetic fields (i.e. in the \(-E \times B\) direction). The final element, \( \sigma_\parallel \), is the parallel conductivity, which characterizes the field-aligned or Birkeland current governed by the parallel component of the electric field, \( B_\parallel \) [Baumjohann and Treumann, 1997]. These conductivities are defined generally as

\[
\begin{align*}
\sigma_P &= \frac{\nu_{ei}^2}{\nu_{ci}^2 + \omega_{ce}^2}\sigma_0 \\
\sigma_H &= -\frac{\omega_{ce}\nu_{ei}}{\nu_{ci}^2 + \omega_{ce}^2}\sigma_0 \\
\sigma_\parallel &= \sigma_0 = \frac{n_e e^2}{m_e \nu_{ci}}.
\end{align*}
\] (2.16)

If the magnetic field is not along the z-axis, then Ohm’s Law (2.14) can be generalized as

\[
J = \sigma_\parallel E_\parallel + \sigma_P E_\perp - \sigma_H \frac{(E_\perp \times B)}{B}.
\] (2.17)

In a partially ionized plasma like the Earth’s ionosphere, the charged electrons and ions collide with neutral particles at frequencies \( \nu_{en} \) and \( \nu_{in} \). Baumjohann and Treumann [1997] further show that by adding the consideration of ion-neutral collisions and incorporating the ion cyclotron frequency \( \omega_{ci} \), the generalized conductivities shown in (2.16) can be written as

\[
\begin{align*}
\sigma_p &= \left( \frac{\nu_{en}^2}{\nu_{en}^2 + \omega_{ce}^2} + \frac{m_e}{m_i} \frac{\nu_{in}}{\nu_{en}^2 + \omega_{ci}^2} \right) \frac{n_e e^2}{m_e} \\
\sigma_H &= -\left( \frac{\omega_{ce}}{\nu_{en}^2 + \omega_{ce}^2} + \frac{m_e}{m_i} \frac{\omega_{ci}}{\nu_{en}^2 + \omega_{ci}^2} \right) \frac{n_e e^2}{m_e} \\
\sigma_\parallel &= \left( \frac{1}{\nu_{en}} + \frac{m_e}{m_i} \frac{1}{\nu_{in}} \right) \frac{n_e e^2}{m_e \nu_{ci}}.
\end{align*}
\] (2.18)
2.2.3 The Ionospheric Alfvén Resonator

The IAR is a resonant cavity in the ionosphere, bounded at the bottom by a conducting layer of the ionosphere and at the topside by a sharp increase in the Alfvén speed. The IAR has been the focus of many studies involving modeling, in situ observations, and theory for nearly a half century. In the early 1960’s, researchers began to find narrow-band oscillations [Maple, 1959; Tepley, 1961] and resonant peaks in the observed energy spectra [Ness et al., 1962; Davidson, 1964; Santirocco and Parker, 1963; Smith et al., 1961] of natural and artificial geomagnetic micropulsations. These results were followed by theoretical calculations of the transmission and reflection of hydromagnetic waves in the ionosphere and exosphere [Jacobs and Watanabe, 1962; Field and Greifinger, 1965; Greifinger and Greifinger, 1965].

As Belyaev et al. [1990] note, although the term “ionospheric Alfvén resonator” was not introduced until Polyakov [1976], its existence was implicit in the work of Field and Greifinger [1965] who noted the resonant structure of the waves. Polyakov and Rapoport [1981] made the first attempt to characterize the IAR by calculating its natural frequencies, Q-factor, and excitation efficiency. Later studies fleshed out more of the IAR’s properties [Trakhtengerts and Feldstein, 1981, 1984, 1987a; Lysak, 1988; Rudenko, 1990; Young et al., 2012].

The first experimental evidence of the IAR was found by Belyaev et al. [1989a, 1990], who discovered spectral resonance structure (SRS) excited by lightning, which produced prominent minima and maxima in the averaged spectral intensity of the background noise of the atmosphere in the frequency range of 0.1 to 10 Hz. An explanation for SRS was generated by applying the effects of the IAR on electric emission excited by discharges from lightning in the Earth-ionosphere waveguide [Belyaev et al., 1989b]. Figure 2-6, from Belyaev et al. [1990], shows the correlation between the diurnal variation of the frequency interval $\Delta f$ between maxima of the SRS (a) and the inverse of the critical frequency of the F region (b). Their ability to explain this effect with the effects of the IAR confirmed its observation and existence. High-latitude evidence of the IAR
Figure 2-6: This figure from Belyaev et al. [1990] shows the correlation between the diurnal variation of the frequency interval $\Delta f$ between maxima of the SRS (a) and the inverse of the critical frequency of the F region (b). Their ability to explain this effect with the effects of the IAR confirmed its observation and existence.

was later found via SRS signatures as well [Belyaev et al., 1999; Bosinger et al., 2002]. IAR measurements have also been made by satellites in the auroral region [Grzesiak, 2000; Chaston, 2002] and recently in the equatorial region [Simões et al., 2012]. In recent years, probes of the IAR have been conducted by using radar to artificially stimulate the ionosphere [Streltsov et al., 2011; Yeoman et al., 2008].

Despite its history, disagreements persist between the locations of the upper and lower boundaries of the IAR. Limits for the location of the topside boundary range from roughly 0.5 $R_E$ [Yeoman et al., 2008] to 1 $R_E$ [Streltsov and Lotko, 2008; Simões et al., 2012] to $10^4$ km [Trakhtengerts and Feldstein, 1991]. Some place the bottom boundary in the E region [Trakhtengerts and Feldstein, 1991], while others claim it is in the F region [Yeoman et al., 2008]. However, the range of eigenmodes of the IAR are widely agreed upon to be in the order of a few seconds [Lysak and Song, 2002]. Streltsov et al. [2011] explain that this broadness may be attributable to the dependence of the resonator’s frequency on various parameters (resonator size, plasma density, ion composition within the resonator, and the strength of the background magnetic field), which can vary signifi-
cantly over the wide range of latitudes and geomagnetic conditions that the IAR has been studied in. As *Polyakov and Rapoport* [1981] explain, the ionosphere below the F region is optically thin and does not exhibit resonant properties at frequencies below $\sim 0.2$ Hz. Likewise, above $\sim 1$ Hz, the reflection coefficient for the topside boundary of the IAR becomes small.

The speed at which waves propagate in a plasma, known as the Alfvén speed, is defined as:

$$v_A = \frac{B_0}{\sqrt{\mu_0 \rho_0}},$$

(2.19)

where $B_0$ is the magnetic field, $\mu_0$ is the magnetic permeability, and $\rho_0$ is the density. Equation (2.19) shows the density-dependence of the Alfvén speed. This is significant, because of the exponential decrease in ionospheric density above the F region peak (see Figure 2-4). The exponential decay of the ionospheric density means that the dielectric topside boundary of the IAR is lossy [Pokhotelov et al., 2000]. *Polyakov and Rapoport* [1981] calculated the maximum value of the $Q$-factor to be $Q_{max} \simeq 10$, higher than that of the magnetospheric Alfvén resonator (also known as the field-line resonance, comprising of the magnetic field line bounded by the ionosphere in each hemisphere). Following the work of *Trakhtengerts and Feldstein* [1991], we can express the Alfvén speed dependence on altitude, $v_A(z)$, as

$$v_A^2(z) = \frac{v_{A0}^2}{\epsilon^2 + e^{-z/h}}$$

(2.20)

with $\epsilon \ll 1$. With this model, the Alfvén speed is equal to the ionospheric Alfvén speed, $v_{A0}$, at the lower boundary of the IAR ($z = 0$) and increases exponentially until it reaches the magnetospheric Alfvén speed, $v_{AM} = v_{A0}/\epsilon$. Then, $\epsilon \ll 1$ reflects the fact that the Alfvén speed in the ionosphere is much (10-100 times) lower than that in the magnetosphere [Lysak, 1991].

For a wave to reflect, the gradient of the index of refraction needs to be large relative to the wavelength of the medium [Belyaev et al., 1990]. *Greifinger and Greifinger* [1973] and *Polyakov*
[1976] showed that this condition can be satisfied in the regions above and below the F region density peak for waves of frequency 0.1-10 Hz. The existence of this lower IAR, below the magnetospheric Alfvén resonator creates a two-scale stratification where small-scale waves \( \lambda_{\perp} \geq 1 \text{ km} \) appear enclosed in larger-scale waves [Trakhtengerts and Feldstein, 1991].

The IAR may also have some influence in the acceleration of precipitating electrons that are responsible for Alfvénic auroral arcs. Small-scale components of the electric and magnetic fields observed by Stasiewicz et al. [1997] and Chaston [2002] could be produced by magnetospheric waves entering into the IAR and reflecting multiple times with a period of 1 Hz and might play a role in accelerating precipitating particles [Chaston, 2002; Lysak and Song, 2002]. Low-altitude density cavities found in the vicinity of auroral arcs [Doe et al., 1993; Shepherd et al., 1998; Aikio et al., 2004] help to trap the waves and the resulting small-scale structure is driven by phase mixing that arises from the gradients in the Alfvén speed near their boundaries [Lysak and Song, 2008; Haerendel, 2011].

### 2.3 Convection and Current Structure

Currents and the convection of plasma are primary means of coupling and energy transfer between the magnetosphere and ionosphere. Figure 2-7 shows the interaction between southward IMF and the Earth’s magnetic field. Magnetic reconnection occurs as the IMF encounters the terrestrial magnetic field, connecting the magnetic field lines of the Earth to those of the Sun [Dungey, 1961]. Though this reconnection occurs regardless of the orientation of the IMF, it happens more easily when it is oriented southward (i.e. opposing the northward orientation of the Earth’s magnetic field). The newly formed “reconnected” field lines allow current (particles) from the Sun and interplanetary medium to flow through the magnetosphere and into the polar ionosphere; such currents are a common driver of the aurora to be discussed in Section 2.4. Since these reconnected field lines extend through the magnetosphere into the IMF, they continue to be carried away from
Figure 2-7: Evolution of a southward-oriented interplanetary magnetic field line it encounters the magnetosphere. Magnetic reconnection occurs at the near the nose, connecting terrestrial magnetic field lines to the Sun and allowing access of solar plasma into the magnetosphere. In the tail, reconnection occurs again, bringing flow back upstream towards the planet. Also shown are the corresponding locations of the field line footprints in the polar ionosphere; note that “depolarizing”, Earthward-moving field lines (6,7,8) correspond to the auroral oval. [Hughes, 1995]
the Sun by the solar wind as the anchored footprints of these field lines are dragged from noon to midnight across the polar ionosphere. The effects of this convection on the ionosphere are summarized in Figure 2-9.

Downstream in the tail, the elongated field lines create pressure gradients that drive currents and move plasma towards the equatorial region. Here, the oppositely directed field lines (step 5 in Figure 2-7) give rise to a neutral current sheet in the equatorial region that separates the northern and southern lobes of the tail. In this neutral current sheet, where $|B| \sim 0$, reconnection can occur again, reestablishing a field line with both ends connected to the Earth. This newly formed field line then relaxes during "dipolarization", accelerating its plasma back towards the planet’s poles via field-aligned currents (FAC) in the northern and southern plasma sheath boundary layer (PSBL). After encountering the ionosphere, these particles mirror between the hemispheres, eventually thermalizing to join the other particles trapped on terrestrial field lines in the central plasma sheet (CPS) [Hughes, 1995].

As the particles in the central plasma sheet move Earthward, the electrons and ions gyrate in different directions establishing the ring current that flows opposite to the Earth’s rotation. These near-Earth distances, from roughly 2-10 $R_E$, are populated with 10-100s keV electrons, protons, He$^+$ from the solar wind, and O$^+$ from the ionosphere. A partial ring current also flows at distances just beyond the ring current, particularly in the dusk region. The partial ring and tail currents are closed through the ionosphere via field-aligned Birkeland currents, as shown in Figure 2-8. There exist two regions of these particular field-aligned currents (FACs) that flow into the polar ionosphere: Region 1 (R_1) and Region 2 (R_2). The poleward Region 1 currents flow to and from the tail current, while the equatorward Region 2 currents connect the polar ionosphere to the partial ring current. The currents in the two regions are connected via Pedersen currents (see Section 2.2.2) that flow through the auroral zone and across the polar cap in the ionosphere. These Region 1 currents overlap on the dayside with the cleft region discussed earlier in Section 2.2.1) [Cowley,
Figure 2-8: (a) Diagram of the currents and electric fields that connect the ionosphere and magnetosphere. Region 1 and Region 2 field-aligned currents flow into and out of the auroral ionosphere from the tail current ($J_T$) and partial ring current ($J_{PR}$), respectively, closing in the polar ionosphere via Pedersen currents ($J_0, J_{pc}$). (b) Another depiction showing the three-dimensional geometry of fields and currents in the MI system. From Kelley [2009].
Figure 2-9: Schematic of the electrodynamic coupling between the magnetosphere and ionosphere [Strangeway et al., 2000a]. A newly reconnected field line convecting over the Earth “pulls” the field line in the polar ionosphere, where the plasma motion must overcome the frictional drag. The stretching field lines generate a $\delta B$ that drives perpendicular currents ($J$), which provide a $J \times B$ force and close through field-aligned currents. The electric field ($E$) created by the moving field lines opposes the current at the magnetopause and generates electromagnetic energy which is transmitted through Poynting flux ($S = E \times \delta B/\mu_0$) and dissipated in the ionosphere.

1981]. Figure 2-9 shows an example of the electrodynamic coupling between the magnetosphere and ionosphere.

2.4 Aurora

The beautiful light displays known as the aurora are by far the most commonly known and easily visible manifestation of space weather and the interconnectivity of the Sun-Earth system. Though they have been observed by humans for thousands of years, modern scientific understanding of the aurora stems from the 1896 suggestion by Kristian Birkeland that the aurora is caused by electrons originating from the Sun and guided into the atmosphere by Earth’s magnetic field; he was subsequently able to prove that concept through laboratory experiments [Jones, 1974].

While all auroral emissions are caused by precipitating particles colliding with the atmosphere, there are several different auroral classifications. The most commonly known type of aurora is discrete aurora, usually consisting of highly structured auroral arcs and bands within the auroral
Discrete aurora is driven by electric fields created along magnetic field lines at high altitudes (>3000 km) that accelerate electrons into the atmosphere [Kelley, 2009]. Davis [1992] describes an auroral arc as a uniform arc extending from horizon to horizon, while bands tend to have more irregular curvature, often containing kinks and bends. These arcs are on the order of 10 km wide and associated with upward field-aligned current regions, where downward precipitating electrons collide with the atmosphere and excite it. Discrete auroral arcs and bands can be homogeneous or significantly dynamic with rapidly-moving vertical striped structures called rays that appear to dance along the arc. Discrete aurora is typically created at altitudes around 100-150 km by precipitating primary electrons with energies around 10 keV (see Figure 2-11).

Another primary type of aurora is diffuse aurora, which as the name implies, is generally less structured than discrete aurora. Common throughout the polar cap and at equatorward regions of the auroral oval, diffuse aurora is created by particles accelerated into the polar ionosphere from the central plasma sheet (CPS) during the magnetospheric convection discussed in Section 2.3. Of particular interest in recent studies is pulsating aurora. Generated by chorus waves, pulsating
aurora is characterized by well-defined patches generally extending tens of kilometers that pulsate regularly at periods of 8-10 seconds [Nishimura et al., 2010; Lessard, 2012]. Brown et al. [1976] showed that pulsating aurora originates from lower altitudes and higher energy particles than diffuse aurora (Figure 2-11). See Lessard [2012] for a complete review of pulsating aurora. Of note is also proton or hydrogen aurora, which is caused by the precipitation of plasma streams rich in hydrogen ions (protons) from the outer Van Allen radiation belt and nightside plasma sheet. Relative to the types of aurora created by precipitating electrons, proton aurora is very dim and rather unimpressive visually [Davis, 1992].

Following Kirchoff’s second law of spectroscopy, the color of aurora is determined by the atomic structure of the gases in the atmosphere. The brightness of aurora is measured in units of Rayleighs, defined as a column emission rate of $10^{10}$ photons per square meter per column per second [Hunten et al., 1956]; the lower limit of auroral visibility for the human eye is roughly 1 kR. Davis [1992] contains a complete explanation of the International Brightness Coefficient (IBC) that governs classification of auroral brightness. The most common auroral emission is created when an oxygen atom relaxes from its second excited state to the first; this transition is responsible for green aurora at 558 nm. Transitions of the oxygen atom from the first excited state to the ground state are
also responsible for red auroral emissions at 630 and 636 nm. The dominance of green in auroral
displays can be attributed to oxygen being the most abundant ion in the upper atmosphere (see
Figure 2-4) and the sensitivity of the human eye, which is only 1/5 as sensitive to the red part of
the spectrum as the green [Davis, 1992]. More energetic precipitation penetrates to lower altitudes
where it ionizes molecular nitrogen, generating blue/violet emissions around 391 and 428 nm.

2.5 Ion Outflow

It was originally believed that magnetospheric plasma was supplied entirely by the solar wind
because ionospheric plasma could not escape the planet’s gravitational pull [Andr´e and Yau, 1997].
Evidence of ions escaping along open magnetic field lines from the upper atmosphere via the polar
wind was first confirmed by the Explorer 31 and ISIS-2 satellites [Hoffman, 1970; Brinton et al.,
1971] and later supported by observations from the Akebono satellite [Abe et al., 1993]. Further
evidence for the role of the ionosphere as a plasma source came when satellite observations showed
significant magnetospheric quantities of He$^+$ and O$^+$ ions with energies greater than 1 keV [Shelley
et al., 1972]. It is now accepted that the ionosphere is an important source to the magnetosphere
[Chappell, 1988; Kronberg et al., 2014], with evidence of ionospheric plasma found in the lobes [e.g.,
Sharp et al., 1981], plasma sheet [e.g., Mukai et al., 1994], and ring current [Hamilton et al., 1988].
Figure 2-12 from Yau et al. [1988] shows typical outflow rates on the order of $10^{26}$ s$^{-1}$ for H$^+$ and
O$^+$ across the auroral and polar cap regions [Yau and Andr´e, 1997; Strangeway et al., 2005].

This broadly termed “ion outflow” of light thermal ions (H$^+$, He$^+$) and light and heavy energized
ions (H$^+$, He$^+$, O$^+$, N$^+$, NO$^+$, O$_2^+$, N$_2^+$) can be attributed to multiple processes occurring in the
polar and auroral ionosphere [Schunk, 2000]; these include both bulk flows affecting the full ion
distribution and flows where only portions of the distribution are energized. However, with the
exception of H$^+$, these ions require an additional energization source such as solar heating, ion
neutral frictional heating, or wave-particle interactions to reach escape velocity [Schunk and Nagy,
Figure 2-12: Energetic H$^+$ and O$^+$ outflow rates from the auroral and polar cap regions as a function of $K_p$ magnetic index at three solar radio flux ($F_{10.7}$) ranges [Yau et al., 1988].

2009]; this leads to the differentiation between ion “upflow” or “upwelling” processes that move ions to higher altitudes and “ion outflow”, the liberation of ions into the magnetosphere from the ionosphere. This collective outflow is extremely important to magnetospheric physics because O$^+$ ions in the magnetotail can change the Alfvén velocity and affect reconnection rates [Shay and Swisdak, 2004; Hesse and Birn, 2004].

In the auroral region, observed energetic upflowing ion (UFI) populations are separated into two categories based on the location of the peak of the velocity distribution; those with a peak along the magnetic field line are called ion beams [Shelley et al., 1976] while those at an angle to the magnetic field are ion conics [Sharp et al., 1977]. Ion beams are generally seen at altitudes above 5000 km, while ion conics have been observed as low as 500 km [Klumpar, 1979; Yau et al., 1983]. Ion beams and ion conics typically have energies from 10 eV to a few keV [Yau and André, 1997]. A special subset of ion conics with peak pitch angles at or near 90° are known as transversely accelerated ions (TAIs); these have been seen in association with aurora as low as 400 km [Yau et al., 1983; Arnoldy et al., 1992]. Giles et al. [1994] showed that these UFI distributions evolve as they move upward in altitude; for instance, ion conics increase in energy with altitude [Peterson
et al., 1992; Miyake et al., 1993, 1996]. Furthermore, the outflowing mass distributions can vary significantly depending on the solar EUV flux during different seasons and throughout the solar cycle [Yau et al., 1985].

A significant source of bulk plasma flow comes from the polar ionosphere via a constant stream of particles (particularly H\(^+\) and He\(^+\)) known as the polar wind. The outflow rate from the polar wind is significant, as high as \(\sim 1 \times 10^{25} \text{s}^{-1}\) across the polar cap at solar maximum [Yau and André, 1997]. The term “polar wind”, coined by Axford [1968], is broadly applied to the outflow of ions across the polar cap, but the processes that drive this outflow are separated into two categories. The classical polar wind, first theorized by Bauer [1966] and Dessler and Michel [1966] and later formalized by Banks and Holzer [1969], is driven by thermal processes in the lower ionosphere. The ions in this classical polar wind travel up to higher altitudes along the open magnetic field lines; as they do so, the collisional, chemically-dominated, subsonic flow of heavy (O\(^+\)) ions transitions to a collisionless, diffusion-dominated, supersonic flow of light (H\(^+\)) ions. Additional processes shown in Figure 2-13 may contribute to the nonclassical polar wind; these include escaping photoelectrons, cusp ion beams and conics, hot magnetospheric electrons such as the polar rain, wave-particle interactions, centrifugal acceleration, and anomalous resistivity along auroral field lines [Schunk and Nagy, 2009].

Another significant source is the bulk upflow of thermal ions at auroral latitudes, which has been observed by rocket [Lockwood and Titheridge, 1981], satellite [e.g., Heelis et al., 1984; Loranc et al., 1991], and ground-based radar [e.g., Wahlund et al., 1992]. Initially there was much debate about the mechanisms driving these bulk thermal upflowing ions (TUI), mostly centered on convective heating versus heating from auroral precipitation. Liu et al. [1995] showed that the precipitation of soft (<1 keV) auroral electrons can be a primary driver of these upflows, playing a larger role than the frictional heating and perpendicular ion temperature enhancements generated by convection [Loranc et al., 1991]. Wahlund et al. [1992] first separated TUI into two types: thermal
plasma outflows (Type-1) and outflow due to enhanced field-aligned electric fields (Type-2). Type-1 outflows, caused by ion frictional heating, are generally seen absent of auroral precipitation and feature enhanced ion temperatures and perpendicular electric fields in an expanded F region. Moore et al. [1999] showed increased outflow response to an interplanetary shock created by a coronal mass ejection (CME); they suggested that the outflow was caused by the resulting fluctuations in the solar wind dynamic pressure. However, Strangeway et al. [2000b] argued that the outflows resulted from field-aligned currents driven by reconnection with a y-directed IMF near the cusp. Type-2 outflows, on the other hand, are driven by auroral precipitation and subsequently occur above auroral arcs; this type of outflow is associated with enhanced electron temperatures, weak parallel electric fields, and decreased topside electron density. Type-2 outflows generally result in larger ion fluxes and occur more frequently than Type-1 outflow [Wahlund et al., 1992].

Figure 2-14 from Strangeway et al. [2005] shows a flow chart showing the two principal pathways
for generating ionospheric outflows. The left-hand side shows the flow of electromagnetic energy, via
the Poynting flux, which increases ion frictional heating, increases the ionospheric scale height, and
results in Type-1 outflow. The right-hand side of the chart shows the particle energy flow carried
by soft electron precipitation, which generates an ambipolar electric field that also increases the
ionospheric scale height and results in Type-2 outflow. While little observational evidence
has been obtained regarding the ionospheric ambipolar field, it is well understood theoretically.
Soft (<1 keV) auroral electron precipitation, which is most efficient at imparting energy into the
ionosphere, energizes the ambient ionospheric electrons through collisions. The heated ionospheric
electrons then move upwards, establishing a “vertical component” of the electric field, as results from the ambipolar diffusion process detailed by Ferraro [1964].
CHAPTER 3

ROCKET INSTRUMENTATION

3.1 Electron Retarding Potential Analyzer (ERPA)

The determination of electron temperature in the ionosphere is crucial to understanding several key phenomena related to the study of magnetosphere-ionosphere coupling. In particular, accurate determination of electron temperature is critical to understanding the processes that drive type-2 ion outflow. EISCAT and VHF radar observations have shown that enhanced ion outflow correlates with enhanced electron temperature \cite{Ogawa2000}. Precipitating auroral electrons heat the background ionospheric electrons, driving an ambipolar field that accelerates ions and facilitates outflow \cite{Wahlund1992, Strangeway2005}. Electron temperatures may also correlate with field-aligned currents, playing an important role in forming density cavities in the vicinity of auroral arcs \cite{Zhang2003}.

While much is understood about electron temperatures in the E and F regions \cite{Schunk1978}, obtaining measurements of this parameter has proven much more difficult at higher altitudes \cite{Lund2012}. Typical ground-based radar observations are limited due to the low densities and correspondingly lower spatial and temporal resolution at higher altitudes. Obtaining in situ measurements is also difficult since the cold temperatures result in small gyroradii that pose challenges for classic electrostatic analyzers. To address this issue, M. Widholm (UNH Space Science Center) developed the rocket-borne Electron Retarding Potential Analyzer (ERPA) by combining elements
of a Faraday Cup and a retarding potential analyzer. First flown on the Svalbard EISCAT Rocket Study of Ion Outflow (SERSIO) rocket mission in 2004 [Frederick-Frost et al., 2007], the ERPA instrument has amassed over a decade of successful flight heritage on multiple sounding rocket missions.

From the start, the ERPA has made significant scientific contributions. On the SERSIO flight, the ERPA combined with other plasma instruments to show evidence of a relationship between electron heating and soft auroral precipitation. In 2008, the SCIFER-2 rocket was launched into a series of poleward moving auroral forms (PMAFs) and observed elevated electron temperatures at very high altitudes (>1400 km). Analysis of ERPA data from that event showed that those elevated temperatures propagated to very high altitudes after only ~100 seconds following the onset of auroral precipitation [Lund et al., 2012], consistent with earlier model predictions [Rees and Jones, 1973; Jones and Rees, 1973; Whittleker, 1977]. On the 2009 Auroral Current and Electrodynamics Structure (ACES) rocket mission, observations from the ERPA and other instruments helped to validate model predictions of ionospheric feedback instability (IFI) inside the ionospheric Alfvén resonator (IAR) [Cohen et al., 2013]. Most recently, ERPA data from the Magnetosphere-Ionosphere Coupling in the Alfvén Resonator (MICA) mission have helped to shed light on the large-scale [Zettergren et al., 2014] and fine-scale (K. A. Lynch et al., Observations of gradient-generated auroral ionospheric response effects as seen by the MICA sounding rocket, Journal of Geophysical Research, in preparation, 2015) ionospheric response to auroral precipitation.

3.1.1 Instrument Description

The ERPA measures ambient thermal ionospheric electrons in the energy range from a small fraction of an eV to 3 eV with a resolution of 0.06 eV. Like a true retarding potential analyzer, it measures the distribution of electron energy by sweeping a retarding potential across a selection screen of very fine conductive mesh. As the voltage sweeps across the selection screen, electrons with energies less
than the retarding potential are rejected, while those with higher energies enter the instrument’s optics and are recorded by the detector anode. Figure 3-1 shows a diagram of the ERPA’s optical assembly [Frederick-Frost et al., 2007]. The current collected by the anode is measured by a low noise electrometer circuit. As Figure 3-1 indicates, the entrance face of the analyzer is held at a fixed +4 V relative to payload ground to accelerate electrons into the entrance in the presence of a negative payload potential. Issues arising due to gyroradius effects are mitigated by the small dimensions of the instrument (roughly 5 cm in diameter) and ensuring that the instrument is oriented parallel to the magnetic field. However, results from the SCIFER-2 rocket, which experienced significant coning, showed no temperature modulation, leading to the conclusion that misalignment with the field has negligible effect on ERPA observations. Figure 3-2 shows a covered ERPA instrument mounted on the sub-payload of the MICA rocket.

Unfortunately due to its sensitivity to very low energy electrons, it is very difficult to determine normal instrument characteristics, such as field of view or geometric factor, for the ERPA. Since the ERPA is a thermal plasma instrument, the field of view is generally considered to consist of the plasma in a 10 cm wide cylinder extending upwards from the instrument sensor. Since it is nearly impossible to sort out effects due to stray fields, care is taken on rocket payloads to ensure that the ERPA is placed in a region that is removed from objects that might alter the local plasma characteristics and affect the ERPA’s measurements. Figure 3-3 shows a model of the potential distribution near the ERPA with -1.5 V payload potential and +4 V bias on the entrance face. The light green area is the neutral plasma potential, the dark blue is the negative payload potential, and the red is the positively biased ERPA. The trace shows a path of a 0.01 eV electron as it moves from its gyration in the background plasma and accelerates along the magnetic field toward the ERPA. The electrons from the external plasma are accelerated into the ERPA by the +4 V bias, but are then decelerated after crossing the entrance screen as they approach the selection screen. The selection screen sweeps from +2 V to -2 V in sixty-four steps of 1 ms duration. Once
Figure 3-1: This diagram (adapted from Frederick-Frost et al. [2007]) shows the optics of the Electron Retarding Potential Analyzer (ERPA), which consists of four nickel mesh screens and a series of concentric brass collimators. The selection screen (green) probes the full electron energy distribution by sweeping from -2 V to +2 V in sixty-four steps of 1 ms duration. The front face and back end of the optics (blue) are both held at +4 V, which accelerates electrons into the instrument. Once an electron of sufficient energy passes through the selection screen it is then reaccelerated toward the anode.

An electron with sufficient energy passes through the selection screen it is accelerated toward the anode. As the selection voltage nears the payload potential, the net energy gained relative to the plasma goes to zero, similar to a Langmuir probe. When the selection voltage is more positive than the payload potential, the ERPA collects the full energy range of electrons. As the sweep becomes more negative, the lower energy electrons are rejected. Since the thermal energy spectrum only extends to a few tenths of an eV, the sweep goes sufficiently negative (by design) to reject all the electrons. To see how many electrons were collected at each energy, the change in current at each step is computed to give a differential energy spectrum. The differential spectrum is analyzed instead of the measured current to remove any flat background due to high energy auroral electrons.
Figure 3-2: A photograph of a covered ERPA instrument mounted on the sub-payload of the MICA rocket launched from Poker Flat, Alaska in February 2012.

Figure 3-3: A model of the potential distribution near the ERPA with -1.5 V payload potential and +4 V bias on the entrance face. The light green area is at the neutral plasma potential, the dark blue is the negative payload potential, and the red is the positively biased ERPA. The trace shows a path of a 0.01 eV electron as it moves from its tight spiral in the neutral plasma and accelerates along the magnetic field toward the ERPA.
3.1.2 Temperature calculation

The ERPA’s primary data product is a measurement of electron temperature. Since each sweep is composed of a ramp up and ramp down in voltage, it results in two energy spectra every 128 ms. The average of these two spectra is fit to a Maxwellian differential spectrum to determine the electron temperature. Following Langmuir theory, when the probe potential is less than the plasma potential ($V_L < V_p$) only a fraction of electrons can overcome the potential and access the probe. Then the retarding current is defined as

$$I_e(V) = -Ae n_e \sqrt{\frac{2k_B T_e}{m}} \exp \left( \frac{e(V - V_p)}{k_B T_e} \right),$$

(3.1)

where $A$ is the surface area of the detector, $e$ is the elementary charge, and $n_e$ is the electron density. The high thermal velocity of the electrons dismisses the need to consider ram effects and allows for the assumption that the high energy tail of the differential spectrum follows the Maxwellian expression above. This simplifies the calculation, allowing the temperature to be determined by taking the logarithm of the electron retarding current and differentiating it with respect to voltage. This is mathematically equivalent to the slope of the logarithm of the differential spectrum plotted versus sweep voltage and yields

$$\frac{d \ln I_e}{dV} = \frac{d}{dV} \left( \ln \left( -Ae n_e \sqrt{\frac{2k_B T_e}{m_e}} \right) \left( \frac{e(V - V_p)}{k_B T_e} \right) \right) = \frac{e}{k_B T_e}.$$

(3.2)

The algorithm I wrote to calculate the electron temperature calculates the differential spectra for each sweep and locates the peak of the average spectrum. It then selects a range of points from the high energy tail of the spectrum that does not extend into the region where the signal level drops into the noise and performs a least squares fit. The slope of that best-fit line ($\alpha$) is then proportional to $1/k_B T_e$. Inverting the line’s slope parameter and dividing by Boltzmann’s constant gives the temperature. Since the temperature calculation depends only on the slope parameter ($\alpha$),
it can be produced without knowing the density or payload potential. Figure 3-4 shows an example of this process: white is the logarithm of the tail of the differential spectrum, red indicates the points selected for fitting, and green shows the result of the least squares fit.

3.1.3 Evaluating Error Sources

Direct comparisons of ERPA in situ data to ground-based radar observations have shown good agreement [Frederick-Frost et al., 2007]; however, it is difficult to accurately determine error sources and uncertainty levels for the ERPA. Potential systematic error sources include misalignment to the background magnetic field, modulation of misalignment due to coning of the rocket, flux dependencies, and digitization determined by the resolution of the steps during the sweep. As stated previously, payload potential does not affect the width or shape of the differential spectrum. However, as previously mentioned, data from SCIFER-2 indicate that misalignment to the background magnetic field and modulation due to coning have minimal or no effect. Flux dependency is also of minimal significance since it is most prevalent at high energies where the counts drop off into
the noise; since we do not include this region in our fit, it does not affect our temperature calculation. The largest source of uncertainty listed above is digitization resolution, which is determined by the resolution or number of steps made in each sweep. While this is without a doubt the most significant source of uncertainty, the nature of our temperature calculation diminishes its impact on the final temperature result. Since the least squares fit only takes into account the short downward-sloped linear range of the logarithm of the differential spectrum, the resolution of the voltage sweep is related to, but also negligible compared to, the uncertainty introduced by the fit. The statistical uncertainty of the fit ($\sigma$) then becomes the most significant source of uncertainty in the temperature calculation.

Another potentially significant, but difficult to quantify source of error comes from the inconsistency and energy dependence of the ERPA’s solid angle, which is not part of the temperature analysis. In principle, this has the largest effect on low energy electrons near 0 eV that have a tendency to be accelerated into the instrument at greater angles, thereby widening the field-of-view. This means that counts on either end of the distribution exhibit the most error. The error associated with the higher energy counts on the tail is due to the lack of signal and statistical error, while the lower energy counts can be affected by the the field-of-view effect. While quantifying the effect of this error source is extremely difficult, we do our best to minimize it by fitting to a range of points near the center of the linearly sloped region of the differential spectrum’s logarithmic tail. This limits the fit to a smaller number of points, as mentioned, but the uncertainties associated with the fit and the limited number of points are contained within $\sigma$.

3.1.4 Density Measurements

While the optics of the ERPA operate like a retarding potential analyzer, the front face of the instrument, which is held at +4 V (see Figure 3-1), acts like a Langmuir probe that collects plasma as it builds up a charge sheath. Following basic Langmuir probe theory (as discussed in
Figure 3-5: Plot of the electron density seen by the multiple Needle Langmuir Probes (m-NLP) instrument [Bekkeng et al., 2010] versus the current collected by the front plate of the ERPA on the sub-payload of the MICA rocket mission. Two very distinct fits were found for the up leg (black) and down leg (red). The best fit lines shown here were used to calculate the expressions used to convert ERPA skin current to electron density (Equation 3.3).

Section 3.1.1), one would assume that electron density could be determined using the electron saturation current measured by the face of the ERPA.

A scaling factor must be applied to obtain electron density values from the current collected by the front plate of the ERPA. In an attempt to determine this coefficient, J. Heavisides (UNH Space Science Center) compared this current with density measurements from other instruments on two different rocket missions (MICA and ACES). Figure 3-5 plots the electron density seen by the multiple Needle Langmuir Probes (m-NLP) instrument [Bekkeng et al., 2010] versus the current collected by the front plate of the ERPA on the sub-payload of the MICA rocket mission. Two very distinct slopes were seen for the up leg (red) and down leg (black), which led to the calculation of two separate expressions to convert the ERPA front plate current ($I_{front\,plate}$) to electron density.
Figure 3-6: Comparison of the electron densities measured by the ERPA and the multiple Needle Langmuir Probes (m-NLP) instrument from the MICA rocket mission. The ERPA density was calculated by applying a scaling factor to the current collected by the front plate of the instrument. The bottom panel shows the percent difference between the measurements made by the two instruments. The first half of the flight (up leg) shows very good agreement, but wake effects are believed to cause the growing disagreement during the second half (down leg) of the flight.

These can be expressed as

\[
\begin{align*}
up \; leg \ : \ n_e &= (1.69 \times 10^{10} \times I_{\text{front \ plate}}) + 5.12 \times 10^{10} \\
\text{down \ leg} \ : \ n_e &= (4.07 \times 10^{10} \times I_{\text{front \ plate}}) - 1.56 \times 10^{10}.
\end{align*}
\] (3.3)

Figure 3-6 shows a comparison of the electron densities obtained from the ERPA using these scaling expressions (top panel) and those measured by the multiple Needle Langmuir Probes (m-NLP) instrument (middle panel) on the MICA mission. The bottom panel shows the percent difference between the measurements made by the two instruments. Data from the two instruments
agree fairly well for the first half (up leg) of the flight; the increasing disagreement seen during the second half (down leg) of flight is believed to be caused by wake effects on the payload. Density data from the ERPA on the ACES-High rocket do not agree with the density measurements made by the HF antenna. It is unclear why this would be true, but may be related to the instrument’s location on the payload. The ERPA was front-mounted on the sub-payload for the MICA mission, but deployed on a boom on the main payload on ACES-High.

3.2 Electron PLASma (EPLAS) Instrument

Another critical measurement for auroral studies is the energy determination of precipitating particles. Where the ERPA measures the thermal response of the background ionospheric electrons, the Electron PLASma (EPLAS) instrument measures the energy and pitch angle distribution of the incoming energetic electrons (from 6 eV to 18 keV for the 2015 Rocket Experiment for Neutral Upwelling 2 (RENU2) mission). Figure 3-7 shows a cross-section of the EPLAS instrument, which is composed of three electrodes (inner, center, and outer). Top hat electrostatic analyzers (ESAs), like the EPLAS, work based on application of the Lorentz force. A positive voltage is applied to the inner electrode causing electrons to curve towards it. However, only electrons of certain energies at a given voltage will have the correct trajectory to make it through the gap between R_1 and R_2 in Figure 3-7; this gap width (Δ_1) plays an important role in the determination of the instrument’s geometric factor. Hence, controlling the voltage on the inner electrode allows for determination of the energy of the electrons incident on the detector. The azimuthal symmetry of the top hat ESA and its accompanying electronics also allow for determination of the pitch-angle (or azimuthal) distribution of the incoming particles.

The EPLAS has a long heritage of flight on rocket missions. Its predecessor, the Hemispheric Electrostatic Energy and Pitch angle Spectrometer (HEEPS) ion instrument, a top hat electrostatic analyzer similar to that described by Carlson et al. [1983], was first flown on the Topaz3 mission.
Figure 3-7: Cross-section view of the top hat electrostatic analyzer optics of the Electron PLASma (EPLAS) instrument. $R_1$ is the diameter of the inner electrode where voltage is applied to divert the incoming electrons; the inner electrode is “stretched” from hemispheric by the distance $L$. $R_2$ is the diameter of the center electrode, which determines the gap width $\Delta_1$, which plays an important role in the determination of the geometric factor. In this coordinate system, electrons enter the field of view between the outer and center electrode in the y-z plane and are diverted into the gap and to the detector located downstream in the x-direction by the Lorentz force applied by the voltage on the inner electrode.

[Pollock, 1987; Pollock et al., 1988]. Later, the HEEPS-E was designed to measure energetic electrons. Both the original ion HEEPS and the HEEPS-E have evolved and flown on multiple rocket missions spanning over two decades [Kintner et al., 1996; Arnoldy et al., 1999; Lynch et al., 1999; MacDonald et al., 2006; Frederick-Frost et al., 2007; Mella et al., 2011]. A sister instrument, a magnetic mass spectrometer known as the BEEPS, was also developed that introduced the capability of distinguishing ion composition by mass [Lynch et al., 1999]. For RENU2, the HEEPS-E instrument was renamed the EPLAS and redesigned, eliminating some of the changes made as the instrument evolved from its original design. A particular emphasis was put on simplifying the mechanical design of the mount and deployment system.
3.2.1 Geometric Factor

Of paramount importance during the redesign process for RENU2 was determination of the instrument’s geometric factor. The geometric factor \( G \) is a coefficient determined by the design of the instrument that relates the number of particles transmitted by the analyzer to the ambient flux into it. It can be simplistically defined as

\[
G = \frac{C}{j},
\]

(3.4)

where \( C \) is the number of particles per second transmitted by the analyzer and \( j \) is the ambient flux in particles per square centimeter per square radian per second per keV [Chase, 1973].

Collinson et al. [2012] presents a more rigorous derivation, beginning with the concept of an “instrument response function” \( R \), first introduced by Johnstone et al. [1987]. This function describes the response of the instrument to a given particle flux, taking into account both the optics and non-optical elements (i.e. detection efficiency). The response determined only from the optics is known as the “physical geometric factor”. The instrument response function \( R_{ijk}(v, v_0, x, t) \), where the indices \( ijk \) indicate the angular pixel, energy bin, and deflection state, respectively, is then defined such that the number of particles detected for a given mass to charge ratio \( C_{ijk} \) is

\[
C_{ijk} = -\int_0^\tau dt \int dA \cdot \int_{v-} d\mathbf{v} \mathbf{v} R_{ijk}(\mathbf{v}, v_0, x, t) f(\mathbf{v}, x, t),
\]

(3.5)

where \( \tau \) is the period of accumulation, \( f(\mathbf{v}, x, t) \) is the particle distribution function, \( \mathbf{v} \) is the single-particle velocity space coordinate, and \( dA \) is a differential area element of the detector aperture [Johnstone et al., 1987]. The subscript \( v- \) indicates integration over the velocity space region where \( v \cdot dA < 0 \) and \( v_0 \) is a vector parameter describing the instrument response function that maximizes at \( \mathbf{v} = v_0 \). Following Collinson et al. [2012], this can be converted into generalized spherical-polar
coordinates and under special conditions rewritten as

\[
C_{ijk} \equiv \frac{2\tau A_{ij}}{m^2} \int_0^\infty dE \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} d\theta \cos^2\theta \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} d\phi \cos\phi \bar{R}_{ijk}(E, \theta, \phi; E_0, \theta_0, \phi_0) f(E, \theta, \phi),
\]

(3.6)

where \( \bar{R}_{ijk} \) is the space-time averaged detector response and \( E_0, \theta_0, \) and \( \phi_0 \) are the spherical polar coordinates corresponding to the vector \( v_0 \). The generalized geometric factor \( (G) \) can then be defined as

\[
G_{ijk} \equiv \frac{A_{ij}}{E_0^2} \int_0^\infty dE \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} d\theta \cos^2\theta \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} d\phi \cos\phi \bar{R}_{ijk}(E, \theta, \phi; E_0, \theta_0, \phi_0).
\]

(3.7)

If the flow \( (f(E, \theta, \phi)) \) is constant over the instrument aperture, then Collinson et al. [2012] shows that (3.6) can be rewritten as

\[
C_{ijk} \equiv \frac{2\tau A_{ij}}{m^2} f(E, \theta, \phi) \int_0^\infty dE \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} d\theta \cos^2\theta \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} d\phi \cos\phi \bar{R}_{ijk}(E, \theta, \phi; E_0, \theta_0, \phi_0).
\]

(3.8)

Plugging in the definition for the geometric factor from (3.7) yields

\[
C_{ijk} \approx \frac{2E_0^2}{m^2} G_{ijk} \tau f(E, \theta, \phi),
\]

(3.9)

which allows a more generalized definition of the geometric factor

\[
G_{ijk} \approx \frac{C_{ijk}}{\tau J(E, \theta, \phi, x)}
\]

(3.10)

that relates the number of particles detected \( (C_{ijk}) \) to the differential energy flux \( (J(E, \theta, \phi, x)) \) as stated in Equation (3.4).

The geometric factor is an important parameter when designing an instrument because it relates how much of the incoming particles pass through the optics to the sensor and subsequently has
a strong effect on the instrument’s count rate. For example, opening the polar angle acceptance or aperture of an instrument will increase the geometric factor and allow for a higher count rate, but may cause saturation if the incoming fluxes are too large. Increasing the geometric factor also decreases the instrument’s energy resolution, so determining the ideal geometric factor requires finding the correct balance between achieving the desired energy resolution and the ability to acquire sufficient counts.

The determination of the geometric factor can be difficult to ascertain due to the many factors that can affect it, so many geometric factor determination studies for modern instruments include both laboratory calibration and modeling efforts [Collinson et al., 2012]. Carlson et al. [1983] introduced the top hat electrostatic analyzer, detailing the relationship between the normalized geometric factor \((G/R_1^2)\) and other analyzer parameters, but did not review the process used to determine the geometric factor itself. Young et al. [1988] introduced the stretched inner electrode as is used in the EPLAS while remaining consistent with the parametric relationships presented by Carlson et al. [1983]. They followed the definition of the geometric factor expressed by Gosling et al. [1978] as

\[
G = A_e \left( \frac{\Delta \alpha}{\Delta E} \right) \int_{\Delta \beta} \cos \beta \, d\beta, \tag{3.11}
\]

where \(A_e\) is the approximate aperture area, \(\Delta \alpha\) is the elevation angle, \(\Delta E/E\) is the energy resolution, and \(\Delta \beta\) is the desired pitch angle resolution.

Previously, the desired geometric factor of the HEEPS-E instrument had been determined using data collected from multiple missions during its extended flight heritage. To determine the geometric factor of the EPLAS for RENU2, simulations were conducted using ion optics simulation software (SIMION). A simple two-dimensional model of the instrument was created by taking a cross sectional view and rotating it around the axis of symmetry (the \(x\)-axis in Figure 3-7). Since the physical dimensions of the instrument had already been determined, the calculation of the physical geometric factor required the determination of three parameters via simulation: the
energy resolution ($\Delta E/E$), the elevation angle acceptance ($\Delta \alpha$), and the pitch angle acceptance ($X'$) needed to determine the aperture area ($A_c$). Figure 3-8 shows the results from the three simulations run to determine these parameters: $\Delta \alpha = 4.5^\circ$, $\Delta E/E = 0.122 \text{ eV/eV}$, and $X' = 3.4$ mm. The aperture area $A_c$ is calculated by multiplying the determined pitch angle acceptance $X'$ by the gap width $\Delta_1$ between the radii of the center and inner electrodes (0.196 cm). For RENU2, the desired pitch angle resolution was $10^\circ$, which can be substituted for the integral over $\Delta \beta$. Plugging these values into Equation (3.11), we arrive at

$$G_{10^\circ} = (0.196 \text{ cm})(0.34 \text{ cm})(0.079 \text{ rad})(0.122 \text{ eV/eV})(0.175 \text{ rad})$$

$$= 1.12 \times 10^{-4} \text{ sr} - \text{ cm}^2 - \text{ eV/eV},$$

which is the same as the physical geometric factor of the similarly dimensioned HEEPS used on the SCIFER rocket [Arnoldy et al., 1996]. Expanding this over the full $360^\circ$ field-of-view of the instrument yields a total physical geometric factor of $4.32 \times 10^{-3} \text{ sr-cm}^2-\text{eV/eV}$. 

Figure 3-8: Results from the SIMION simulations of the EPLAS instrument to determine the parameters necessary to determine the geometric factor: (a) the elevation angle ($\Delta \alpha$), (b) the energy resolution ($\Delta E/E$), and (c) the pitch angle acceptance ($X'$).
Chapter 4

Rocket Observations of the Ionospheric Feedback Instability (IFI)

The following chapter is reprinted here from the Journal of Geophysical Research: Space Physics and is cited elsewhere in this thesis as “Cohen et al. [2013]”. Although part of a collaborative effort, I was responsible for interpreting the data, performing the polarity analysis, drawing the conclusions, and writing the text below. Significant contributions came from co-authors, particularly S. Kaeppler, in the preparation and presentation of the data in Figure 4-4. Likewise, the new model presented in Section 4.3 was developed and conducted by another co-author, A. Streltsov.

4.1 Background

The ionospheric feedback instability (IFI) was first introduced by Atkinson [1970] as a system model to explain the processes that drive auroral arcs. The model, illustrated qualitatively in Figure 4-1, assumes a change in ionospheric conductivity to start. This perturbation of the conductivity creates electric fields in the ionosphere that then map to the magnetosphere. A flux tube in the magnetosphere would then see a time-varying magnetospheric electric field which drives polariza-
Figure 4-1: This illustration, modified from Atkinson [1970], shows a qualitative model of the ionospheric feedback instability (IFI). The model starts in panel A with an assumed change in ionospheric conductivity. This perturbation of the conductivity creates electric fields in the ionosphere that then map to the magnetosphere. A flux tube in the magnetosphere would then see a time-varying magnetospheric electric field which drives polarization currents that produce field-aligned currents (FACs) to close the current loop. The upward FAC is characterized by downward precipitating electrons that cause the ionospheric conductivity variations that are assumed at the start, thereby closing the feedback loop.
tion currents that produce field-aligned currents (FACs) to close the current loop. The upward FAC is characterized by downward precipitating electrons that cause the ionospheric conductivity variations that are assumed at the start, thereby closing the feedback loop.

After its introduction, the IFI was studied further by Sato [1978] who found a global, large-scale (tens of km) feedback instability with growth time on the order of several minutes, associated with field line resonance. Lysak [1986] built on this work by including a self-consistent change in ionospheric conductivity that resulted in the development of a feedback instability with a wave period of 1 Hz, much quicker than previously investigated instabilities. In later work, Lysak [1988] came up with a simple resonant cavity to explain this fast IFI (to be distinguished from the “slow” feedback instability that results from the field line resonance). Lysak [1991] then connected the work of Trakhtengerts and Feldstein [1981] and Lysak [1988] by eliminating restrictions on ionospheric conductivity and showed that the IFI can develop quickly in the IAR discussed in Section 2.2.3 and lead to structuring of auroral currents as Trakhtengerts and Feldstein [1987b] had suggested. The sharp Alfvén speed gradients that form the topside boundary of the IAR can greatly enhance the IFI. Numerical simulations by Pokhotelov et al. [2002] showed that both the fast and slow IFI developed when using a realistic Alfvén speed profile (which naturally included the existence of the IAR).

Over the last few decades, numerous studies have focused on the interaction of IFI inside the IAR [Pokhotelov et al., 2000; Lysak and Song, 2002; Streltsov and Lotko, 2004]. They found that it develops rapidly when the background ionospheric conductivity, $\Sigma_{P0}$, is (a) low ($\Sigma_{P0} < 10$ mho), and (b) comparable to the Alfvén conductivity ($\Sigma_A \equiv 1/\mu_0 v_A$) above the ionosphere. As Pokhotelov et al. [2000] note, the most peculiar features of IAR are observed in the auroral zone, where the structure of currents and electric fields is controlled by interaction and propagation of ultra-low-frequency (ULF) waves in the topside ionosphere. This connection of IFI with ULF waves within the IAR has been the focus of several numerical studies [Streltsov and Lotko, 2004, 2008]. It was
found that in the IAR, small-scale waves with perpendicular wavelengths $\leq 10$ km (at 100 km altitude) and frequencies of 0.1 to 1.0 Hz can be generated and amplified by the IFI [Streltsov and Lotko, 2008]. Recent rocket data have shown the first in situ measurements of multiple observational characteristics of IFI in the altitudes within the IAR in the vicinity of a discrete auroral arc [Cohen et al., 2013].

Two key observational characteristics of the IFI are low-altitude plasma density depletions and small-scale electromagnetic waves located in the vicinity of discrete auroral arcs. Observations from sounding rockets, ground-based radars, and satellites have shown evidence of plasma density
depletions in the ionosphere and the low-altitude magnetosphere adjacent to magnetic FAC regions [Doe et al., 1993; Shepherd et al., 1998; Aikio et al., 2004]. Streltsov et al. [2011] shows two examples of strong ionospheric density depletion in a localized region next to the region where it is enhanced by auroral precipitation. The significant presence of intense ULF waves in the downward current channels has also been demonstrated by a number of observations from satellites [Paschmann et al., 2003; Mishin et al., 2003] and on the ground [Streltsov et al., 2010].

Later theoretical studies of ionospheric feedback built upon the model proposed by Atkinson [1970] and supplied quantitative information about structure in the vicinity of auroral arcs, caused by interactions between pairs of downward and upward magnetic FACs and the ionosphere [Streltsov and Lotko, 2003a,b, 2008]. Streltsov and Lotko [2003b] present results from a numerical study of the origin and spatiotemporal properties of such intense, small-scale electromagnetic structures observed in the vicinity of discrete auroral arcs by low-altitude, polar-orbiting satellites. Their results show that these small-scale EM structures can be produced inside the aforementioned ionospheric Alfvén resonator (see Section 2.2.3). Streltsov and Lotko [2003b] presents three primary effects of FAC in creating and maintaining the resultant IFI: a) the removal of electrons from the ionosphere in the downward FAC locally decreases the ionospheric conductance and lowers the threshold for IFI, b) a Pedersen current closing the FAC enhances the perpendicular electric field in the E-layer and creates even more favorable conditions for the IFI, and c) a resistive layer in the lower magnetosphere is produced by the FAC that provides a well-defined upper boundary for the IAR, confining the small-scale feedback-amplified Alfvén waves.

The hypothesis that low-altitude density cavities in the downward current channels can be caused by small-scale, intense shear Alfvén waves, thus linking the two characteristics of the IFI, was investigated numerically by Streltsov and Lotko [2008] and Sydorenko et al. [2008]. In particular, Streltsov and Lotko [2008] produced numerical results based on a reduced two-fluid MHD model that self-consistently describes shear Alfvén waves, ion parallel dynamics, effects of the ionospheric
E region activity, and the magnetosphere-ionosphere feedback instability. These numerical simulations were performed in a dipole magnetic field geometry with realistic parameters of the ambient plasma. Figure 4-3 shows the results of the numerical model by Streltsov and Lotko [2008]. Panel A shows the geometry of the initial conditions, where two oppositely directed (upward and downward) FACs are launched. Panel B shows the formation of the small-scale EM structures within the downward FAC region. The small-scale structure is seen throughout most of the return current region, with a higher population at the boundary between the upward and downward FACs. Panel C shows how the upward evacuation of plasma from low altitudes causes a density cavity with a density enhancement above it. The dashed line traces a rough estimate of the trajectory of the ACES-High rocket. At the apogee altitude of ACES-High, the rocket would miss the plasma density cavity predicted by the model and fly through the density enhancement that is created above the cavity. Panel D shows the ion outflow velocity. Streltsov and Lotko [2008] showed that the ponderomotive force created by the IAR alone can cause a decrease of up to 96% of the background magnitude of plasma density between the E and F Regions. They also reasoned that the density depletion would cover a large part of the downward FAC region. The cavity formation presented by Streltsov and Lotko [2008] generally agrees with, but has a much lower observed ion temperature than, the ground-based radar observations by Aikio et al. [2004]. Temporal aspects of the feedback process depend on parameters of the background ionospheric plasma (density, temperature, recombination rate, etc.) and on the magnitude of the large-scale electric field in the ionosphere. Streltsov and Lotko [2008] showed that for typical parameters of the magnetosphere-ionosphere system in the auroral zone (plasma density $3 \times 10^4$ cm$^{-3}$; Pedersen conductivity $\sim 2$ mho; perpendicular electric field $\sim 100$ mV/m; and the parallel current density $\sim 10$ $\mu$A/m$^2$), the instability reaches saturation within sixty seconds.

The model did not reproduce the elevated ion temperature in the cavity nor include the effects of this heating on the ion parallel motion since it included only an isothermal treatment of
Figure 4-3: Results from numerical simulations by Streltsov and Lotko [2008]. Panel A shows the geometry of the initial conditions, where two oppositely directed (upward and downward) FACs are launched. Panel B shows the formation of the small-scale EM structures within the downward FAC region. Panel C shows how the upward evacuation of plasma from low altitudes causes a density cavity with a density enhancement above it. Panel D shows the ion outflow velocity. The dashed line traces a rough estimate of the trajectory of the ACES-High rocket.
the ion population. The simulation results also show that the ratio between the height integrated ionospheric Pedersen conductivity, $\Sigma_P$, and the Alfvén conductivity in the near-Earth magnetosphere defined as $\Sigma_A = 1/\mu_0 \nu_A$ (where $\nu_A$ is the Alfvén speed as defined in Equation 2.19, $B_0$ is the background magnetic field, and $\rho$ is the mass density) is an important parameter for the production of the necessary small-scale, intense ULF waves at low altitudes. Theoretical studies have shown that the maximization of the growth rate of IFI occurs when $\Sigma_P \approx \Sigma_A$ [Lysak, 1991; Pokhotelov et al., 2001; Lysak and Song, 2002]. Streltsov et al. [2011] explain that when $\Sigma_P \approx \Sigma_A$ a “matching impedance” condition exists between the ionosphere and magnetosphere where waves can propagate from one layer into the other, with the condition determined by the mass density near the ionosphere- a parameter that may fluctuate as ions move along the magnetic field lines.

4.2 Observations

The ACES rockets were launched into a dynamic multiple-arc aurora from Poker Flat Research Range in Alaska on January 29, 2009. The two-rocket mission was designed to investigate the three-dimensional current geometry of the auroral environment. The apogee of the ACES-High rocket (365 km) was such that it allowed the instrument payload to pass through both the upward and downward current regions of a discrete arc at an altitude where collisional effects between ions and neutrals has a negligible influence on the electrodynamics of the system. The ACES-High scientific payload was equipped with a fluxgate magnetometer, a pair of Electron Retarding Potential Analyzers (ERPAs), a pair of Langmuir probes cross calibrated with an HF receiver, double probes to measure the perpendicular DC electric field and low frequency wave activity, and a top hat electrostatic analyzer for the electrons. Further details regarding observations made by the ACES mission can be found in Kaeppler et al. [2012].

Figure 4-4 shows data from the ACES-High rocket as it passed, in a northward/poleward trajectory, through a stable auroral arc at roughly 350 km altitude (just above the F peak) at approxi-
Figure 4-4: Data from the ACES-High rocket as it passed, in a northward/poleward trajectory, through a stable auroral arc at roughly 350 km altitude (just above the F peak) at approximately 1 km/s on the morning of January 29, 2009. Panel A shows the average brightness of several pixels within a given latitude/longitude range of the payload footprint, which peaks around 09:53:41 UTC. This peak indicates the location of the visible discrete auroral arc associated with the upward current region as shown in panel B, which shows the FAC. Panel C shows the field-aligned pitch-angle distribution of the electron flux at 164 eV. Panel D depicts the differential electron energy flux in the range of 80-500 eV, providing clear evidence of a broad energy distribution characteristic of Alfvénic precipitation. Panels E and F display the meridional and zonal electric fields. Panels G, H, and I show the electron temperature, high frequency power spectrum and electron density, respectively.
mately 1 km/s on the morning of January 29, 2009. Panel A shows the average brightness of several pixels within a given latitude/longitude range of the payload footprint. To obtain this trace, the spacecraft’s coordinates and the coordinates of the individual pixels of the all-sky imager assuming emissions at 110 km were converted to Altitude Adjusted Corrected Geomagnetic (AACGM) coordinates. Then the coordinates of the all-sky grid were matched with the coordinates of the payload and an the average brightness was taken over a range of +/- 0.02 in latitude and +/- 0.05 in longitude of the payload footprint. The small periodic peaks that occur from 09:54:00 UTC onward are the result of noise from the video recording device. This device created a visible bar of brightness that can be seen scrolling down the field of view in each subsequent frame. The peak in this panel, at around 09:53:41 UTC, indicates the location of the visible discrete auroral arc associated with the upward current region as shown by the FAC measurements in panel B. The FACs were derived from magnetometer data by taking the spatial derivative and implementing Ampere’s Law, assuming that the spacecraft is moving fast relative to the current structures to allow the application of the Taylor Hypothesis and convert temporal into spatial structures. Finally, a median filter (of approximately 0.5 seconds) was applied to the output current data to get the overall FAC structure. Note that the field-aligned currents measured were on order of 10’s of µA/m², on the lower end of the range of 10-127 µA/m² predicted by Streltsov and Lotko [2008].

Panel C shows the pitch-angle distribution of the electron flux at 164 eV. Panel D depicts the differential electron energy flux in the range of 80-500 eV. Panels E and F display the meridional and zonal electric fields. This study primarily focuses on the region between 09:53:56 UTC and 09:54:19 UTC. This time period outlines a decrease in electron flux, bounded by strong signatures of Alfvénic precipitation (characterized by a field-aligned population over a broad distribution of energy from 0 to a few hundreds of eV). The electron flux recorded here is similar to the time dispersed signatures from the model and data presented by Kletzing and Hu [2001]. They showed that time-dispersed signatures of this type could be generated by propagating Alfvénic pulses along
realistic field lines. Observation of these features by ACES-High suggests that use of the Alfvén resonator model is appropriate to understand our data.

Associated with this Alfvénic activity are electromagnetic perturbations seen in panels E and F. It is important to note that although these perturbations look to have roughly 1 Hz frequency, we cannot necessarily characterize them as such due to limitations in temporal and spatial information. Although we cannot make strong conclusions about the spatial characteristics of the waves, we use the term “small-scale” to refer to these waves that appear to be localized in a region of roughly 10 km, comparable to the length scales of interest for FAC (of order 1-10 km). Note that both the EM wave magnitude and electron flux are greater at the poleward event than the equatorward one. Panels G, H, and I show the electron temperature, high frequency (HF) power spectrum, and electron density derived from the HF, respectively. These results do echo the predictions of enhanced electron density in the downward current region at altitudes above \( \sim 340 \text{ km} \) caused by the upward movement of the ionosphere in response to the ponderomotive force created by the intense ULF waves \cite{Streltsov and Lotko, 2004, 2008; Streltsov et al., 2011}. However, the overall densities observed are relatively low. The electron temperature in Panel G, obtained by the ERPA instrument, confirms that the density enhancement occurs in a return current region with a characteristic temperature of a cold ionosphere (fractions of an eV).

4.3 Model Response

As evidenced in Figure 4-4E-F, the intense small-scale electromagnetic waves seen at the boundaries of the downward FAC region by ACES-High are not present throughout the FAC region, as was predicted by the original simulations from Streltsov and Lotko \cite{2008}. In response to this new data, the model was reconfigured and new simulations were run. The physical model, its numerical implementation, and simulation domain used in this study are similar to the ones described in detail by Streltsov and Marklund \cite{2006} with a few minor parameter changes.
As in Streltsov and Marklund [2006], this domain of this model is comprised of a dipolar flux tube, bounded by the ionosphere at the bottom and extending to the equatorial plane. Here, the simulation domain is bounded in latitude by the \( L = 6.35 \) and \( L = 6.65 \) dipole magnetic shells and the magnetic field at the \( L = 6.5 \) (center) shell at the equator is 112.9 nT. As illustrated in Figure 4-4 of Streltsov and Lotko [2003a], at the equatorial plane a cylindrical extension is added on top of the dipole part of the model domain allowing a “buffer” zone which eliminates the effects of the artificial reflections from the magnetospheric end of the domain on the electrodynamics of the low-altitude region during the “buffer” time. In this model, the cylindrical extension is 27.8 \( R_E \), the Alfvén speed in the cylinder is 3176.9 km/s, and the plasma density at the equatorial magnetosphere is 0.6 cm\(^{-3}\). This model’s “buffer” time, as the wave propagates through the cylindrical extension, of \((2 \times 27.8 \ R_E \times 6371.2 \ km) / 3176.9 \ km/s = 111.5 \ s\). Unlike the model used by Streltsov and Marklund [2006], the model introduced here also includes correction to the Alfvén speed at low altitudes due to the presence of heavy ions (\( O_2^+ \) and \( NO^+ \)) in the ionosphere.

The results from the new simulations are shown in Figure 4-5. Note, as previously detailed, that this simulation decoupled the FAC regions by including only a single downward FAC region, as opposed to the two oppositely directed FACs included in the simulations by Streltsov and Lotko [2008]. Note that the small-scale oscillations seen in the results from the new model are on the order of 10 \( \mu \)A/m\(^2\), of the same order as the field-aligned current measured by ACES-High (see Figure 4-4B). The small-scale oscillations are better visualized in the FACs since the differentiation done to obtain them serves as a high-pass filter, eliminating the large-scale, smooth characteristics of the magnetic field. As Panels C and D of Figure 4-5 show, the intense small-scale oscillations are only seen near the boundaries of the downward current region. This is similar to the observations made by ACES-High, but differ from the results of Streltsov and Lotko [2008] where the oscillations were seen strongly at the boundary between the upward and downward current regions and existed throughout most of the downward current region. The electron precipitation and electromagnetic
Figure 4-5: Results from a new model similar to the one described in detail by Streltsov and Marklund [2006] with a few minor parameter changes. This simulation included only a single downward FAC region, as opposed to the two oppositely directed FACs included in the simulations by Streltsov and Lotko [2008]. The small-scale electromagnetic oscillations seen in the results from the new model are on the order of 10 μA/m², of the same order as the field-aligned current measured by ACES-High (see Figure 4-4B).
waves are generated near the boundaries of the large-scale downward current (see Panels C-F of Figure 4-4) because the strongest small-scale magnetic FACs are generated by the interaction between the large-scale downward current and the ionosphere. The fact that the results of the new model are in much better agreement with the data obtained by ACES-High seems to imply that the FAC regions may in fact be decoupled from one another.

4.4 Analysis

4.4.1 Field Polarity

Figure 4-6 shows the electric and magnetic field measurements taken by ACES-High as it passed through the upward and downward current regions. Of particular interest are the small-scale electromagnetic waves seen at the equatorward and poleward boundaries of the downward current region, appearing at roughly 09:53:58 UTC and 09:54:15 UTC. If the small-scale EM waves observed by ACES-High are standing waves, formed by reflections at the boundaries of the IAR, then we would expect to see a 90° phase shift between the electric and magnetic fields that is characteristic of standing waves. To analyze the polarity of the EM waves, a Hilbert transform was applied to the magnetic field component of the wave, introducing a 90° phase shift at all frequencies. Figure 4-7 shows a comparison of the electric field component (dashed line) with the Hilbert transformed magnetic field component (solid line) which illustrates a phase difference of roughly 20°. Since a 90° phase shift was introduced to the magnetic component of the wave by the Hilbert transform, the waves would show no phase difference if they were precisely 90° out of phase with one another before the transform. The analysis shows that the electric and magnetic components of the Alfvénic wave observed have a phase difference that is not equal to 90° and are not pure standing waves.

Knudsen et al. [1992] compared observations of fields measured by auroral sounding rockets and data from polar-orbiting satellites (including HILAT) to limiting-case models to explain low-frequency field fluctuations seen by low-altitude spacecraft. They found that the sounding rocket
Figure 4-6: The electric and magnetic field measurements taken from ACES-High as it passed through the upward and downward current regions associated with a stable auroral arc at roughly 1 km/s. Particularly of interest were the small-scale electromagnetic waves seen at the equatorward and poleward boundaries of the downward current region, appearing at roughly 09:53:58 UTC and 09:54:15 UTC.
Figure 4-7: Comparison of the electric field component (dashed line) with the Hilbert transformed magnetic field component (solid line) shows an apparent phase difference of roughly 20°. Since a 90° phase shift was introduced to the magnetic component of the wave by the Hilbert transform, the waves would show no apparent phase difference if they were precisely 90° out of phase with one another before the transform. This analysis shows clearly that the electric and magnetic components of the Alfvénic wave observed have a phase difference that is neither 0°, 90°, nor 180°.

data were in excellent agreement with the standing Alfvén wave model, while the data from the satellites were in better agreement with the static current model. They proposed two explanations, based around the movement and trajectory of the rocket, for the inconsistencies. Clemmons et al. [2000] reported in their measurements of ULF waves from the Polar satellite that the electric and magnetic field signatures were nearly in phase, differing by only about 20°, similar to the phase difference seen in our analysis. They claim that such a wave is actually best characterized as a traveling wave with a small admixture of a standing wave. ACES-High observed a phase difference between the electric and magnetic fields that was not equal to 90°, most likely attributable to the IAR’s imperfections as a resonant cavity. The observed phase difference suggests that these waves are not true standing waves, but most likely a standing wave mixed with a traveling wave as Clemmons et al. [2000] described.
4.4.2 Electron Flux, Density, and Temperature

The electron density data plotted in panel I of Figure 4-4 show density values of $1.3-1.8 \times 10^4$ cm$^{-3}$, which are 3-10 times less than the lowest densities seen at 350 km in the EISCAT radar data from Aikio et al. [2004] and an order of magnitude lower than the results of the numerical model presented by Streltsov et al. [2011]. The results from both of these studies, and the predictions from Streltsov and Lotko [2008], predict that at an altitude of 350 km ACES-High should have flown through the density enhancement region produced by the evacuation of plasma from the cavity that is created below it. ACES-High did see a local enhancement of electrons in the heart of the downward current region, but the overall densities measured were still up to an order of magnitude lower than expected. Panel C of Figure 4-3 shows the expected variation of density predicted by Streltsov and Lotko [2008]. Despite the overall low density values, the localized enhancement shown around 09:54:04 UTC in Panel I of Figure 4-4 amounts to an increase of about 50% that agrees with the percent change predicted in the simulation results.

The lack of electron flux seen in Panels C and D of Figure 4-4 in the time range between 09:53:59 and 09:54:13 UTC may be attributed to the upwelling of a cold electron population. Panel G clearly shows that the drop in electron temperature corresponds well with the lack of electron flux in Panels C and D and the local density enhancement seen in Panel I. The strong Alfvénic precipitation, of largely downward moving electrons, seen around 09:53:58 and 09:54:14 UTC appear to be intense enough to influence the net FAC. It is important to note that the stronger field perturbation, that seen around 09:54:14 UTC, actually occurs in a region of upward FAC (looking at Panel 4-4B). This is contrary to the model results of both Streltsov and Lotko [2008] and the new model presented here, which both predicted the small-scale waves inside the downward current region. However, this apparent offset between the FAC measurements and the fields may be attributable to a mix of temporal and/or spatial effects, either realistic or a result of the rocket’s quick movement through the region.
The presence of intense small-scale EM waves, observed in Panels E and F of Figure 4-4 and in more detail in Figure 4-6, was stated previously as one of the observational characteristics of the IFI. These small-scale currents are generated in the ionosphere by the IFI, which is driven by the perpendicular electric field in the ionosphere. This field is produced by the closure of the larger-scale FAC through the ionosphere and it maximizes on the boundaries of the magnetic FAC. This effect is described in detail by Streltsov and Marklund [2006] whose discussion of measurements performed by Cluster satellites did not focus on small-scale structures inside the IAR, and selected parameters of the magnetosphere-ionosphere system that do not include the presence of the IAR. However, their simulations explicitly show large-amplitude electric fields in the ionosphere on the boundaries of the downward current. In a later study, simulations by Streltsov and Karlsson [2008], which had a downward current regions with upward currents on each side, yielded results that again showed small-scale structures existing throughout the downward current region, but with much greater intensity at the boundaries between the currents; the magnitude of the currents from Streltsov and Karlsson [2008] are similar to those seen by ACES-High. The model results from Streltsov and Lotko [2008] also predicted the small-scale structures to exist throughout most of the return current region, with greatest intensity at the equatorward edge of the downward current region. However, the data from ACES-High do not show the small-scale structures persisting throughout the downward FAC region, but only existing in localized regions near the boundaries of the return current region.

4.5 Conclusions

The ACES-High rocket obtained data as it passed through the upward and downward FAC regions associated with a discrete auroral arc in January 2009. Data from this rocket show evidence of small-scale electromagnetic waves in the downward FAC region, as predicted by the model of Streltsov and Lotko [2008] with some notable differences. The ACES-High data found the small-
scale electromagnetic waves existing in localized areas (roughly 10 km) near the equatorward and poleward boundaries of the downward current region, not existing throughout a majority of the return current region. The magnitude of the waves shown in the data is on the lower end of the range predicted by the model. The data from ACES-High show evidence of downward-moving Alfvénic precipitation associated with the small-scale structure. The region between the Alfvénic precipitation lacks significant electron flux.

Analysis of the phase difference between the electric and magnetic fields of these small-scale waves and comparison with studies made by Clemmons et al. [2000] and Knudsen et al. [1992] have led to the conclusion that these oscillations are standing waves, either wholly or partially, created by reflection within the Alfvén resonator. The electron densities measured in the downward FAC region are up to an order of magnitude lower than would be expected compared to data from Aikio et al. [2004] and simulation results [Streltsov and Lotko, 2008; Streltsov et al., 2011]. However, the enhancement does correlate to a roughly 50% increase in density, which agrees with the predictions made by Streltsov and Lotko [2008]. The measured increase in electron density inside the downward FAC region suggests that ACES-High flew through the area of enhanced density that Streltsov and Lotko [2008] predicted would be caused by the upward evacuation of plasma from the cavity created below.

In response to these data from ACES-High, simulations were run using a model similar to that used by Streltsov and Markland [2006], which decouples the FAC regions by launching only a single downward FAC region as opposed to an opposing pair (as done by Streltsov and Lotko [2008]). Results from this new simulation agree very well with the observations from ACES-High, showing small-scale electromagnetic waves with appropriate magnitudes appearing at the equatorward and poleward boundaries of the downward FAC region.

In summary, this paper shows:

1. The ACES-High sounding rocket obtained the first in situ measurements of small-scale Alfvénic
wave structures, evidence of the IFI, near the boundaries of the return current region associated with a discrete auroral arc.

2. These observations agree with the Streltsov and Lotko [2008] model that small-scale EM waves would be seen in the downward FAC region adjacent to a discrete auroral arc and there would be an enhancement in plasma density at altitudes directly above the cavity as a result of plasma being evacuated upwards. However, contrary to model predictions, the small-scale wave structures are only seen in localized areas of about 10 km near the boundaries of the return current region and not throughout it.

3. ACES-High observed increased density with a temperature characteristic of a cold ionosphere in the return current region, however this density is still up to an order of magnitude lower than expected from simulations and other observations [Streltsov and Lotko, 2008; Aikio et al., 2004]. This enhancement is consistent with the theory and results from Streltsov and Lotko [2008] that plasma is evacuated upwards from lower altitudes to create a density cavity, another observational characteristic of the IFI, near a discrete auroral arc.

4. A new model, based on that by Streltsov and Markland [2006], which decouples the FAC regions by launching only one downward current, has produced results very similar to the observations seen by ACES-High.


Chapter 5

Ion Upflow Dependence on Ionospheric Density and Solar Photoionization

The following chapter is a preprint of a paper of the same title to be submitted to the Journal of Geophysical Research: Space Physics. Although the model presented here was created and run by co-author R. Varney, I was responsible for the analysis and interpretation of the results. I was also integral to driving the thought process of the study itself and generated the text and conclusions below. Data from the EISCAT Svalbard radar was contributed by co-author K. Oksavik and calculation of the altitude of the terminator presented in Figure 5-9A was performed by J. Heavisides.

5.1 Background

It is now commonly understood that the ionosphere and magnetosphere are intimately coupled through the passage of currents and convection of plasma. Of particular importance to the magnetosphere-ionosphere system is the outflow of ionospheric plasma into the magnetosphere. Although it was originally believed that heavy ionospheric plasma could not achieve enough energy to escape the planet’s gravitational pull, satellite observations soon showed evidence of significant
quantities of such ionospheric plasma in the near-Earth environment [Hoffman, 1970; Brinton et al., 1971; Shelley et al., 1972].

This global outflow of plasma occurs through different processes at high and mid-latitudes. In the polar cap, plasma is liberated through the classical polar wind, a thermal process by which light ions (H\(^+\) and He\(^+\)) are carried out of the ionosphere along open field lines [Banks and Holzer, 1969]. This mechanism can also be affected by non-classical processes in the polar cap involving photoelectrons, cusp electrons, wave-particle interactions, and the polar rain [Schunk and Sojka, 1997]. With the exception of H\(^+\), the ions liberated by outflow processes require a secondary energization source to achieve escape velocity. This creates the distinction between ion upflow processes, which initially move ions to higher altitudes, and secondary ion outflow processes that provide sufficient energy for the ions to escape Earth’s gravity. Of particular note in this paper is the response of thermal upflowing ions (TUI). Wahlund et al. [1992] first separated TUI into two types: thermal plasma upflows (Type-1) and upflow due to enhanced field-aligned electric fields (Type-2). Strangeway et al. [2005] later built upon this classification, differentiating the types by energy transport: electromagnetic for Type-1 and particle for Type-2. New results show that upflowing/backscattered secondary electrons can also augment the self-consistent ambipolar electric field and contribute to ion upflow in the same way that photoelectrons do (private communication, A. Glocer, 2015).

5.2 Rocket Data

Observations from rocket missions on both the dayside and nightside have found evidence of varying electron temperature and density (as summarized in Table 5.1). These contrasting measurements associated with soft or more energetic precipitation and observed at different altitudes, motivate questions regarding the relationship between electron temperatures and densities and, ultimately, the role these ionospheric parameters might have on ion upflow. In particular, this study focuses
Table 5.1: Table showing the variation in observations of electron temperature and densities obtained during rocket missions at different altitudes on the nightside and dayside. Density measurements presented for SERSIO were obtained by the EISCAT Svalbard radar.

On Type-2 upflow initiated by the precipitation of soft electrons, which can deposit a significant amount of energy into the auroral ionosphere. This energy deposition can have many effects on the ionosphere and subsequently on the magnetosphere-ionosphere system. For example, Strangeway et al. [2005] and many other authors have concluded that the establishment of a vertical ambipolar field by the deposition of energy from soft electron precipitation is a significant driver of Type-2 ion upflow. However, despite its importance in generating Type-2 upflow, very little is known about the development of the ambipolar field itself. In theory, precipitating electrons collisionally heat ionospheric electrons, which adiabatically expand upward in an attempt to cool. The movement of the electrons creates a field-aligned ambipolar electric field that is thought to accelerate ions, generating upflow. Likewise, Clemmons et al. [2008] and Zhang et al. [2012] proposed processes by which soft electron precipitation may play a role in heating neutrals and contribute to neutral upwelling. In both cases, precipitation can lead to important ionospheric dynamics affecting both
magnetospheric and ionospheric regions and processes.

Of particular interest in Table 5.1 is the order of magnitude variation in electron density measurements made by MICA and ACES-High. These missions had similar apogees and auroral characteristic energies, which would lead one to expect similar ionospheric response and resulting parameters. The higher temperatures seen at elevated altitudes by SCIFER-2 and SERSIO are most likely due to softer (lower energetic) dayside precipitating electrons that do not penetrate as deeply into the ionosphere and therefore deposit energy at higher altitudes. These varying observations of electron temperature and density from the dayside and nightside at different altitudes make it difficult to develop a cohesive understanding of the dynamics of ionospheric response to auroral precipitation and the role they might play in processes such as ion outflow.

These rocket observations, particularly on the nightside, are critical and unique measurements of ionospheric parameters at the ionospheric footprint of the Earth’s magnetic field lines. As such, the obvious variation in observations led to questions about how conditions near the ionospheric field line footprint might impact and relate to ion upflow dynamics at higher altitudes. A one-dimensional ionospheric simulation based off the model by Varney et al. [2014] was employed to investigate the potential impact that these varying low altitude parameters might have on upflow dynamics at higher altitudes along the field line.

5.3 Model Description

The single field line ionosphere/polar wind model introduced by Varney et al. [2014] solves the dynamics of thermal ions, thermal electrons, and suprathermal electrons on a single open field line between 97 and 6300 km altitude. The thermal ions use the 8-moment transport equations for H\(^+\), He\(^+\), and O\(^+\)(^4S), and photochemistry only for N\(^+\), NO\(^+\), O\(_2\)\(^+\), N\(_2\)\(^+\), O\(^+\)(^2D), and O\(^+\)(^2P). In the 8-moment approximation the heat flow vector is treated at the same level as the density, velocity, and pressure. This inclusion captures the thermal diffusion effect (i.e. heat flow effects on the
ion velocities through collisions) and the diffusion thermal effect (i.e. velocity effects on the heat flows through collisions). The 8-moment approximation does not include temperature anisotropy or any other higher order moments of the distribution function. As such, this approximation is not valid above 3000 km [Robineau et al., 1996]. Tests with the model have demonstrated that the results below 2000 km are insensitive to the location of the upper boundary as it is moved between 3000 and 8000 km. Thus this fluid model is still appropriate for investigations of the ionosphere below 2000 km. It should be noted that the model uses a thermosphere generated by NRLMSISE-00 [Picone et al., 2002] and neutral upwelling effects are not included.

The thermal electrons are governed by quasineutrality, current continuity ($\nabla_{||} \cdot \mathbf{J}_{||} = 0$), and a time dependent electron energy equation that includes heating from suprathermal electrons, heat flows associated with thermal conduction, and the thermoelectric effect. A steady-state linearized kinetic solver is used for the suprathermal electron population. This solver is a version of the photoelectron model introduced by Varney et al. [2012] with the addition of ambipolar electric field effects. The suprathermal electron solution is used to compute a thermal electron heating rate and ion production rates through impact ionization. All of the plasma populations are connected through the self-consistent ambipolar electric field. As explained in the appendix of Varney et al. [2014], this field is computed in such a way that it implicitly includes the augmentation of the field by suprathermal electron effects. For the tests shown here, the suprathermal energy grid has been extended up to 10 keV to allow for simulations of more energetic precipitation than were originally considered by Varney et al. [2014]. For all of the simulations presented here, the suprathermal electron solver is recalled every 1 s as opposed to every 180 s as was done for the simulations presented by Varney et al. [2014].

The upper boundary of the model uses Neumann boundary conditions for the ions and upflowing suprathermal electrons, thus allowing outflow through the top of the model. The model runs require a specification of the downflowing suprathermal electron distribution (i.e. precipitation), an electron
Figure 5-1: Initial ionospheric density profiles for the six nightside simulation runs.

For the simulations discussed here, the precipitation is a Maxwellian distribution placed in the loss cone, the electron temperature gradient is zero, the potential difference is zero, and the FAC is set using the net suprathermal electron flux at the upper boundary such that the suprathermal electrons carry all of the upwards FAC.

5.4 Model Results

To investigate the effect of ionospheric density on upflow, six simulations were run using initial density profiles with F-peaks ranging from $6.8 \times 10^{10}$ to $2.16 \times 10^{11}$ m$^{-3}$ (see Figure 5-1). In all six simulations, the model was allowed to run for 48 hours starting at 09:00 UT on 17 February 2012 (near the launch of the MICA rocket) to establish “normal” ionospheric conditions over Poker Flat. The parameters established by that run at 05:48 UT on 19 February 2012 were then used as initial conditions for the runs presented here. Unfortunately, the energetic electron instrument on MICA experienced a malfunction; however, the precipitating electron characteristics were estimated by
a new method that combines the determination of energy flux from all-sky observations of 427.8 nm emission with characteristic energies ascertained from scanning Doppler imaging (SDI) measurements (D. L. Hampton et al., Detailed regional auroral electron energy deposition estimations using measurements of E-region temperature and N$_2^+$ first-negative emissions: A MICA case study, *Journal of Geophysical Research*, in preparation, 2015). As a result, these runs introduce 360 s of constant Maxwellian precipitation with a characteristic energy of 1750 eV and a number flux of $2.6 \times 10^{12}$ m$^{-2}$s$^{-1}$ mapped to 6300 km altitude.

To ensure that the results were reasonable, the electron temperature at 300 km in the simulations was compared with the observations from MICA. As shown in Figure 5-2, the simulation temperatures ranged from approximately 1000 to 2350 K during the precipitation, in very good agreement with the 2200 K seen by MICA at apogee. Figure 5-2 also shows a clear inverse relationship between electron density and temperature, which agrees with observations by *Brace and Theis* [1978].

Although the MICA mission did not obtain in situ observations above 326 km, simulation
Figure 5-3: Comparison of the evolution of electron temperature at 1470 km for the six simulation runs during active precipitation. The color of each line corresponds to the initial density profile of that simulation, as shown in Figure 5-1.

results of the thermal evolution at very high altitudes (Figure 5-3) were considered for comparison to the higher altitude observations from SCIFER-2 and SERSIO. Comparison of Figures 5-2 and 5-3 shows that the simulation did not result in much variation in temperature between very high and F region altitudes. Overall these temperatures are much lower than those measured by the dayside rockets. This is most likely attributable to the more energetic precipitation of the MICA event, which would penetrate to lower altitudes and have less soft precipitation to directly heat higher altitudes. However, Figure 5-3 does show that the time required to reach the peak temperature for each run increases with density. In other words, the timescale for electron heating at higher altitudes increases with density. SCIFER-2 observed spikes in electron temperature at very high altitudes (>1400 km) and Lund et al. [2012] were able to determine that a ~100 second “cooking time” was required to reach those elevated temperatures after the onset of precipitation. The simulation results in Figure 5-3 show “cooking times” to reach maximum temperature that range from approximately 60-240 s, which are of the order of 100 s and consistent with the observations from SCIFER-2.
Because of its importance in the generation of Type-2 upflow, the effect of density variations on the ambipolar electric field were studied as well. Figure 5-4 shows the evolution of the ambipolar electric field ($E_a$) versus altitude during the 360 s of precipitation for each of the six simulation runs. Notice how the ambipolar field weakens as the background density increases. Given this result and the ambipolar field’s role in driving Type-2 upflow one would expect that increased density would inhibit upflow in the simulations. As expected, Figure 5-5 shows that the upflow velocity decreases as the density increases. However, despite the weakened ambipolar field and decreased upflow speeds, the overall upflow fluxes shown in Figure 5-6 increase with density. Here, the O$^+$ number flux ($n_{O^+} v_{O^+}$) is plotted versus altitude at one minute intervals during the 360 s of precipitation for each of the runs.

Several effects are immediately evident from these results. First, there is an obvious change in upflow behavior above and below the F-peak (approximately 275 km, as shown in Figure 5-1). Notice that this is approximately the same altitude above which the bulk of the ambipolar field is established, as shown in Figure 5-4. It is approximately at the F-peak where ionospheric dynamics switch from being chemistry-dominated (below) to being transport-dominated (above). At altitudes below the F-peak, the plasma attempts to respond to the energy deposited by the precipitation via transport, but this response is overshadowed by chemistry effects. For this reason, this study will focus on the effects at F region and topside altitudes above roughly 350 km, where appreciable upflow is shown to result from the precipitation. Secondly, at these higher altitudes the runs with increased densities show more significant upflow. Finally, notice that upflow in the lower density runs starts to move to higher altitudes faster than the higher density runs. This is understandable due to the longer heating timescales and slower upflow velocities seen at higher densities.
Figure 5-4: The strength of the ambipolar electric field \( (E_a) \) versus altitude during the 360 s of precipitation for each of the six simulation runs.
Figure 5-5: The strength of the ambipolar electric field ($E_a$) versus altitude during the 360 s of precipitation for each of the six simulation runs.
Figure 5-6: Comparison of the evolution of O\(^+\) number flux \((n_{O^+}v_{O^+})\) at one minute intervals during the phase of active precipitation across the six simulation runs. The colors correspond to colors of the initial density profiles for each run, as shown in Figure 5-1.
5.5 Discussion

The simulation results indicate that at these F region and topside altitudes, increased density results in increased upflow of O⁺. While Skjæveland et al. [2014] were unable to show any correlation between electron density and ion upflow in observations of PMAFs and associated ion upflows from the European Incoherent Scatter (EISCAT) Svalbard radar, they did show a strong correlation between upflow and electron temperature. However, their study did not distinguish between Type-1 and Type-2 upflows, while this study exclusively focuses on the latter.

It seems counterintuitive that enhanced ionospheric density would correlate with increased upflow since Figure 5-4 shows that an increase in density decreases the strength of the ambipolar field. However, the momentum equation for the dominant ion species can be expressed as

\[
\frac{\partial}{\partial t}(m_i n_i v_i) + \nabla \cdot (m_i n_i v_i v_i) = -\nabla (k_B n_i T_i) + n_i e E_a + \frac{\delta M}{\delta t}, \tag{5.1}
\]

where \(m_i, n_i, v_i\) are the ion mass, density, and velocity, respectively; \(T_e\) and \(n_e\) are the electron temperature and density; \(e\) is the elementary charge; \(k_B\) is the Boltzmann constant; \(E_a\) is the ambipolar field; and \(\delta M/\delta t\) includes the remaining collisional terms. The ambipolar field can be expressed as

\[
E_a = \frac{-1}{en_e} \nabla (k_B n_e T_e), \tag{5.2}
\]

where \(n_e\) is the thermal electron density, not the total electron density. Substituting this into (5.1), the momentum equation becomes

\[
\frac{\partial}{\partial t}(m_i n_i v_i) + \nabla \cdot (m_i n_i v_i v_i) = -\nabla (k_B n_i T_i) - \frac{n_i}{n_e} \nabla (k_B n_e T_e) + \frac{\delta M}{\delta t}. \tag{5.3}
\]

All of the terms in the momentum equation are proportional to the ion density, so it is not surprising that density variation has a noticeable effect on the ionospheric dynamics. The final term is the
acceleration rate per volume, which scales as the ambipolar field times the electron density. The ambipolar field could also be described as the acceleration felt by each particle and while that field might decrease when density is increased, resulting in lower O\(^+\) velocity, the increased number of particles of the higher density runs result in greater net number flux (upflow). So while increased density impedes the strength of the ambipolar field, that weaker field is acting on a larger number of particles and still results in increased upflow fluxes. Figure 5-7 summarizes the effect of increased plasma density in upflow generation.

To summarize, enhanced ionospheric plasma density in the model results in:

- Lower ionospheric electron temperatures
- Longer ionospheric heating timescales
- Weaker ambipolar electric field
- Lower O\(^+\) upflow speeds
- Longer upflow timescales
5.5.1 The Role of Solar Photoionization

Of the many natural effects that can affect ionospheric density, the most significant is solar photoionization [e.g., Moen et al., 2008]. Figure 5-8 elucidates the seasonal ionospheric density variation caused by solar photoionization. It shows data from the 42-meter EISCAT Svalbard radar taken during the International Polar Year (IPY), which spanned parts of 2007, 2008, and 2009 [Ogawa et al., 2011]. More explicitly, Figure 5-9 shows the EISCAT data from the IPY (B) plotted versus the lowest illuminated altitude (or altitude of the terminator for the flux tube) over the EISCAT Svalbard radar (A). This data presents the electron density values observed each day from 08:30-09:30 UT (near magnetic noon) between 190-290 km (approximately around the F-peak). The histogram shows the occurrence rate (%) in each of the 20 bins created between $1 \times 10^{10}$ and $1 \times 10^{12}$ m$^{-3}$. Note the obvious similarity in the shape of the two plots. The relatively constant density seen throughout the summer months can be attributed to the full illumination of the Arctic Circle and the entirety of the flux tubes over Svalbard.

The effect of solar photoionization on outflow driven by the polar wind has been investigated both observationally [Kitamura et al., 2011] and in simulations [Glocer et al., 2012]. Wang and Luhr [2013] focused on auroral latitudes using data from the Defense Meteorological Satellite Program (DMSP) satellites. Their observations showed increased ion fluxes during the darker winter months, which disagrees with the conclusion that increased ionospheric densities lead to increased upflow. However, it must be underscored that Wang and Luhr [2013] only looked at Type-1 upflow events associated with subauroral polarization streams (SAPS).

Several statistical studies have specifically looked at the seasonal variation of ion upflows [Yau et al., 1985; Keating et al., 1990; Foster, 1997; Ogawa et al., 2011], but none have highlighted the impact of electron density. In particular our results agree very well with those by Yau et al.
Figure 5-8: Data from the 42-meter EISCAT Svalbard radar taken during the International Polar Year (IPY) clearly showing the seasonal effect of solar photoionization on ionospheric density.
Figure 5-9: The top panel (A) shows the lowest illuminated altitude (or altitude of the terminator on the flux tube) over the EISCAT Svalbard radar for each day from March 2007 through February 2008, the same time period shown in Figure 5-8. The bottom panel (B) shows the electron density values observed each day by the 42-meter EISCAT Svalbard radar (located at 78° N) from 08:30-09:30 UT (near magnetic noon) between 190-290 km (approximately around the F-peak). The histogram shows the occurrence rate (%) in each of the 20 bins created between $1 \times 10^{10}$ and $1 \times 10^{12}$ m$^{-3}$.

[1985], who presented satellite observations of increased O$^+$ upflow occurrence during the summer and suggested a connection to solar EUV flux. Ogawa et al. [2011] also showed an increase in upflow flux during summer months, but a simultaneous decrease in upflow occurrence. However, this decrease might be due to limitations in their definition of an upflow event. To allow for identification of an upflow event in their EISCAT data, they required that the upflow velocity reach 100 m/s at three or more consecutive heights along the radar profile. However, Figure 5-5 clearly shows that increased density can reduce the upflow velocity, which may have led to less upflows reaching the velocities necessary to be considered as an event in their analysis. Figure 5-10 summarizes the additional understanding of the physics behind the observed seasonal dependence of ion upflows resulting from this study.

Additional simulation runs were performed to directly study the effect of sunlight on ion upflow. These new runs used the same precipitation characteristics and exposure time as the initial runs,
but introduced the precipitation during the different times of the day (0900, 1200, 1500, and 1800 local time, respectively). Figure 5-11 shows the evolution of the O\(^+\) number flux \((n_{O^+}v_{O^+})\) for each of the four daytime simulations. Note that the number flux increases throughout the day as photoionization from sunlight increases the densities along the flux tube; it then decreases again as the sun begins to set in the evening.

### 5.6 Conclusions

Understanding the ionospheric response to auroral precipitation is key to understanding the very fundamentals of magnetosphere-ionosphere coupling. However, varying rocket measurements of ionospheric parameters such as electron density and temperature have motivated new questions of how the conditions at the ionospheric footprint of magnetic field lines affect the magnetospheric dynamics at higher altitudes. In particular, this study investigated the potential correlations between electron temperature and density and ion upflow. To do this, a one-dimensional ionospheric simulation based off the model by Varney et al. [2014] was run with precipitation characterized by ground-based observations made during the MICA sounding rocket mission. To understand the effects of ionospheric density on upflow, six simulations were run with ionospheric density profiles peaking from \(6.8 \times 10^{10}\) to \(2.16 \times 10^{11}\) m\(^{-3}\).
Figure 5-11: Comparison of the evolution of O$^+$ number flux ($n_{O^+}v_{O^+}$) at one minute intervals during 360 s of active precipitation at four different local times.
The simulation results showed good agreement with MICA observations at F region altitudes (300 km), but much lower temperatures at higher altitudes (1470 km) than those seen on the dayside by the SCIFER-2 rocket. The simulation also showed that electron density affected the timescales for high altitude heating. In general, the simulations showed enhanced electron temperatures at very high altitudes within several minutes, which agrees well with observations by Lund et al. [2012]. Furthermore, the simulations demonstrated that increased density inhibits the strength of the ambipolar field that is established as a result of precipitation. However, the simulations also show that despite the weakened ambipolar field, upflow fluxes are still enhanced at higher densities because more ions are present to be influenced by the field. Moreover, at higher densities the associated upflow timescales are increased and upflow velocities are inhibited.

The simulation results suggest that the density and temperature are inversely related (in agreement with Brace and Theis [1978]), which implies that (since higher densities are associated with increased upflow) we might expect to see increased outflow with colder temperatures. While this isolated effect may be correct, the more important effect is that of sunlight on the flux tubes, which can increase ionospheric densities by as much as an order of magnitude seasonally. New EISCAT data from the International Polar Year (IPY) underscores this effect, clearly showing the seasonal effect of solar UV ionization on ionospheric density. Further simulation results investigated the direct role of photoionization on upflow, showing that O⁺ fluxes can more than double as sunlight affects densities along the flux tube throughout the day.
Investigating how the ionosphere responds to the injection of plasma from the magnetosphere is crucial to our understanding of the near-Earth environment. A long-standing question in magnetosphere-ionosphere coupling has been whether the ionosphere is an active driver of magnetospheric processes or plays a more passive role in responding to magnetospheric inputs. We know, for instance, that the outflow of ionospheric plasma has a significant effect on magnetic reconnection rates in the magnetotail, which affects the timescales for most magnetospheric processes. To determine the answer to this question, in situ ionospheric observations are needed to inform, validate, and improve ionospheric and magnetospheric models and further our understanding of these global processes. Although relatively short-lived and limited in spatial extent compared to satellites, sounding rockets present unique access to the ionospheric altitudes in question.

This thesis outlines the operation and development of two instruments that are used on rocket payloads to measure the precipitating electrons themselves and the response of the ionospheric thermal electrons. The first is the Electron Retarding Potential Analyzer (ERPA), which measures ionospheric electron temperature. Operating on Langmuir theory, this combination Faraday cup and retarding potential analyzer achieves measurements of electron temperature at altitudes that pose challenges for ground-based radar and traditional electrostatic analyzers. The second instrument is the Electron PLASma instrument, a top hat electrostatic analyzer that measures the energy and pitch angle distribution of precipitating electrons. For the 2015 Rocket Experiment for
Neutral Upwelling 2 (RENU2) mission, the EPLAS was designed to measure electrons from 6 eV to 18 keV.

This thesis also explores the response of the ionosphere to the influx of precipitating electrons; in particular, two studies are presented that incorporate both in situ rocket observations and results from simulations. The first focuses on the ionospheric feedback instability (IFI), which generates small-scale electromagnetic signatures and produces low-altitude density cavities in the vicinity of auroral arcs. The 2009 Auroral Current and Electrodynamic Structure (ACES) mission observed the first in situ observations indicative of both of these key observational characteristics of the IFI. Current models predicted that the small-scale electromagnetic signatures, often associated with ULF waves, would persist throughout the downward current region (DRC). However, the ACES-High rocket only saw these signatures near the boundaries of the DRC. This led to the formulation of a new model that decoupled the upward and downward field-aligned current (FAC) regions and yielded results in better agreement with the observations. It remains unclear why the FAC regions would be decoupled in regards to IFI. Unfortunately, the trajectory of the ACES-High rocket took it to altitudes above where the density cavity was theorized to exist, barring absolute confirmation of the cavity’s existence; however, it did see a localized density enhancement in the DRC indicative of the upwards evaluation of plasma from lower altitudes predicted by the models. It would be highly beneficial if future missions or analysis of further rocket, satellite, and/or radar data could obtain direct observation of both characteristics of the IFI.

The second study investigates the effect of ionospheric density on ion upflow. Variations in rocket observations of ionospheric parameters, such as electron temperature and density, at various altitudes on the dayside and nightside motivated questions regarding the impact these parameters might have on Type-2 ion upflow. Results from a one-dimensional single flux tube model show that increased ionospheric density lengthens the time it takes the ionosphere to heat in response to precipitation. Questions still remain as to which processes contribute to the evolution of this
heating at very high altitudes. The simulations also showed that enhanced density increases net O$^+$
upflow fluxes despite inhibiting the strength of the ambipolar electric field and decreasing the upflow
speed. These results explain observed seasonal enhancements in ion upflows as increased solar UV
photoionization during the summer can enhance ionospheric density by as much as an order of
magnitude. Finally, further simulations directly demonstrated enhanced ion upflows resulting from
increased ionospheric densities caused by solar photoionization.

While many questions remain regarding the nature of the role of the ionosphere in the coupling
between the magnetosphere and ionosphere, it is certain that we must study the system as a whole
if we wish to truly understand the nature of the geospace environment and the resulting space
weather events that can affect mankind.


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