Thesis Proposal: *Current Continuity in Auroral System Science*

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Abstract

The local coupling of the Earth's ionosphere and the magnetosphere (IM) is an open area of study. A common context is to view the magnetosphere to have certain demands of field aligned currents (FAC) or perpendicular flow patterns to which the ionosphere responds. In the electrostatic case, this response can be simplified to satisfying current closure the path of which is dictated by the ionospheric conductivity (Paschmann et al., 2003; Wolf, 1975; Brekke, 1989; Kelley, 2009).

$$j_\parallel(x,y) = \Sigma_P \nabla_\perp \cdot \mathbf{E}_\perp + \mathbf{E}_\perp \cdot \nabla_\perp \Sigma_P - \left(\mathbf{E}_\perp \times \hat{\mathbf{b}}\right) \cdot \nabla_\perp \Sigma_H,$$

where $j_\parallel$ is a 2D horizontal map of FAC at the topside ionosphere, $\mathbf{E}_\perp$ is the ionospheric electric field with $\mathbf{V}_\perp = \mathbf{E}_\perp \times \mathbf{B}_0/B_0^2$, and Σ_P and Σ_H are the Pedersen and Hall conductances. This tells us that, given a 2D horizontal map of FAC (or perpendicular flow) and with knowledge of the ionosphere's conductances one can find a solution for the electric field (or FAC). The conductivity, however, depends strongly on the precipitation spectrum via impact ionization (Evans, 1974; Fang et al., 2010; Grubbs et al., 2018; Solomon, 2017). Additionally, straggling recombination can induce a hysteresis of precipitation dynamics. Because of these factors, it is not well understood how the ionosphere "chooses" its response and, especially for non-idealized arc structures, finding the physical solution is non-trivial.

The aim of this thesis is to find physical, self-consistent solutions to the ionospheric current continuity equation using state-of-the-art ionospheric 3D modelling to provide insight into the role the ionosphere plays in IM coupling for less idealized auroral events. In particular, knowing the portions of FAC closed by Pedersen currents, which produce collisional Joule heating, versus Hall currents, which are non-dissipative (Amm et al., 2008; Clayton et al., 2021), gives insight into the extent to which the ionosphere acts as a load to a magnetospheric generator (Wygant et al., 2000).

For idealized sheet-like auroral arcs, those with minimal longitudinal variation, this is a relatively well-posed problem. The interest of this thesis lies in determining the limitations of this idealized morphology by introducing along-arc structure and using 3D simulations of the auroral ionosphere produced by the Geospace Environment Model of Ion-Neutral Interactions (GEMINI) (Zettergren and Semeter, 2012; Zettergren et al., 2015). Placing the model input boundary conditions at the topside ionosphere, a 2D map of either FAC or electric potential along with a 2D map of electron

precipitation drives the model space. A rich set of illustrative cases based on statistics (Mule, A., Kawamura, M.) of both satellite (FAST, SWARM, etc.) and ground-based (THEMIS-GBO, REGO, etc.) data will be used to develop these maps. A substantial part of this project will include creating tools to properly visualize the inherent 3-dimensionality of the ionospheric current system. The *317 Lynch Rocket Lab* team will aid in this development.

Overall, this description of electrostatic IM coupling is only valid up to time scales of ∼100 s (Lotko, 2004; Richmond, 2010). Lotko (2004) describes a model that allows for limited dynamics (time scales of 10 s) by including inductive IM coupling while retaining quasistatics. An additional component of this thesis will be to modularly apply this physics to GEMINI in order to implement relevant Alfénic effects. A second module to be possibly added to GEMINI would include a bookkeeping of energy flow and implementing Poynting theorem constraints (Richmond, 2010).

This work will strive to be able to better use the abundance of all-sky imagery data available, supplemented by in-situ data and modelling, by means of systematically exploring the third dimension in auroral system science; the ultimate aim is to be able to "read the aurora" by simply looking at them.

1 Background and Motivation

1.1 "Local" MI Coupling

The aurora are likely the earliest evidence of a connection to the Sun and our atmosphere through the Earth's magnetic field (see Anders Celsius and Olav Hiorter's work from 1747 (Paschmann et al., 2003)). Yet, they are displayed at the terminal end of a very complex system governed by highly non-linear plasma physics, which is referred to as auroral system science. But, beautiful as they are, the aurora themselves are only the visible portion of this system. The morphology, color, and dynamics of the aurora are all the result of an interplay of electromagnetic fields, currents, collisional interactions, etc. all within the partly ionized layer of our atmosphere, i.e. the ionosphere.

This connection, or coupling, ultimately is driven by the Sun, but let's consider the region where the Solar wind touches the magnetosphere, the magnetopause, to be the driver instead. This context is what's often referred to as magnetosphere-ionosphere (MI) coupling (Wolf, 1975; Cowley, 2000; Lotko, 2004). The global, quasi-steady picture (i.e. ignoring storms and more dynamical events) for electric field coupling is the two cell convection pattern, first outlined by Dungey (1961) and further explained by Paschmann et al. (2003), Section 8.3. This $\mathbf{E} \times \mathbf{B}$ drift cycle of dayside geomagnetic field lines disconnecting to the IMF, draping anti-Sunward, reconnecting to the IMF, and dipolarizing while drifting back to the dayside, has electric fields that map down to the polar cap via the equipotential field lines. But, the ionosphere is not a passive component in this mapping. In addition to convection, there is a coupling through field-aligned currents (FAC), a.k.a Birkeland currents which come in up-down pairs. Such currents need to close perpendicular to the magnetic field which they can only do inside the collisional ionosphere. The path of closure depends strongly on the ionospheric response to, not just the electric fields, but also precipitation of hot plasma from the magnetosphere.

Given the dictation of electric fields and FACs by the magnetospheric driver, it's not uncommon to adapt an electric circuit description. With this, the driver is considered an electric generator with $\mathbf{j} \cdot \mathbf{E} < 0$ which is balanced by dissipation in either the acceleration region, or inside the ionosphere itself via Pedersen currents, but more on this later. Lysak (1985) considers such a description and investigates the difference between a generator that holds a steady current, or one that holds a steady voltage. While the generator mechanism itself is outside of our scope, he concludes that the resulting auroral currents change their natural scale lengths based on pure voltage or current drivers. Furthermore, in-situ spacecraft measurements have shown directly that both flow and FAC can be highly structured embedded within the larger scale current system (Archer et al., 2017; Lühr et al., 2015; Rother et al., 2007; Sugiura et al., 1982). The auroral system science governing/driving these mesoscale (10s - 100s of km) structures is what is meant by local MI coupling. In terms of time scales, this work will primarily focus on dc coupling.

1.2 Discrete Auroral Precipitation

Apart from electric field and current coupling, a third mechanism relevant to this context is the "acceleration region", placed at 1-2 R_E above the ionosphere and below the magnetospheric driver. Quiet, discrete auroral arcs are the result of precipitating electrons which have been accelerated through a U-shaped potential (the U-shape resulting from the high degree of constancy in the perpendicular electric field). It's theorized that this potential forms in low density regions (night-side) in order to accelerate charge carriers into the loss cone to accommodate current demands at

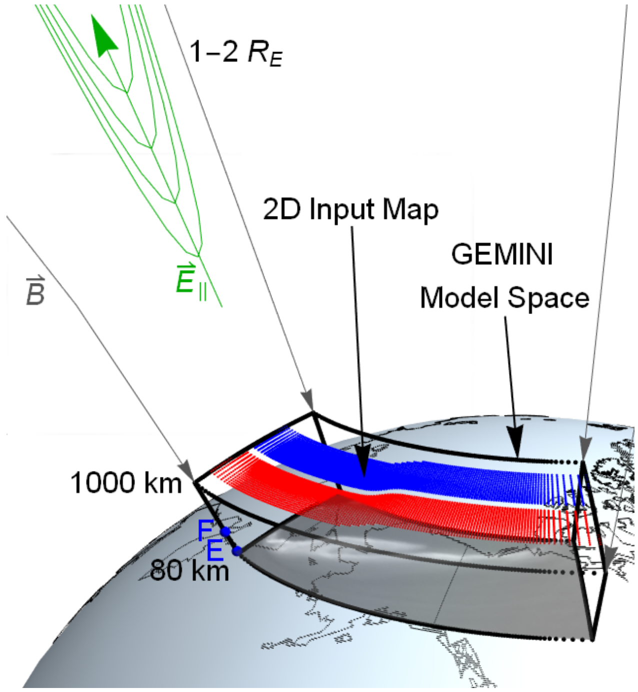

Figure 1: The general framework and context of this work. The dotted black box depicts the GEMINI model space over Alaska from 80 km to ∼1000 km in altitude. The approximate E and F region peaks are shown on the side in blue. The U-shaped potential/parallel electric field is shown in green at around 1-2 R_E (almost to scale). The magnetic field lines connecting to the magnetospheric generator region are shown in gray. The top of the model space shows an example of a 2D input map of FAC and the bottom shows roughly where auroral emission lies.

these altitudes (TEMERIN CITE).

A 3D model of the acceleration region including electron dispersion by (SEYLER CITE) shows that a steady-state superposed oblique Alfvén waves can develop a parallel electric field, along with thin, structured current sheets. This again adds to the local MI coupling scene with respect to the scale sizes involved in this precipitation mechanism. This work does not, however, focus on the mechanism of sustaining the parallel electric field.

Ultimately, this parallel potential drop creates a signature electron differential number flux, including thermal, beaming, and secondary components Fang et al. (2010); Evans (1974). This electron spectrum is known as inverted-V precipitation based on the pointed shape of the electron energy in spectrograms. This energy provides density enhancements in the lower ionosphere via impact ionization which directly impacts the ionosphere's ability to carry current, i.e. the ionospheric conductivity.

1.3 Ionospheric Ohm's Law

Up until this point we've isolated the local MI coupling problem to quasi-electrostatic, mesoscale convection, FAC, and ionospheric conductivity. To determine the manner in which the ionosphere can respond to these variables, the ionospheric Ohm's law is applied. Following the derivation in chapter 8 by Kelley (2009), we start with

$$\mathbf{j} = \sigma \cdot (\mathbf{E} + \mathbf{U} \times \mathbf{B}), \tag{1}$$

with $\mathbf{j}$ being the current density, σ the conductivity tensor, $\mathbf{U}$ the neutral wind velocity, and $\mathbf{B}$ the magnetic field.

1.4 3D Modelling: Why now?

2 Thesis Statement

3 Approach and Methodology

4 Science Studies

5 Tasks and Goals

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