

Thesis Proposal:
Current Continuity in Auroral System Science

Jules van Irsel

April 28, 2022

Thesis Advisor: Kristina A. Lynch
Committee Members: Yi-Hsin Liu, James W. LaBelle

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).

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

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 Alfvénic 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” Magnetosphere-Ionosphere 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 outer magnetosphere as an intermediary. This context is what’s often referred to as magnetosphere-ionosphere (MI) coupling (Wolf, 1975; Cowley, 2000; Lotko, 2004). The global, quasi-steady picture 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 Birke-land currents, which come in up-down pairs. Out in the magnetosphere, any deviation from a dipolar magnetic field will require currents to sustain, simply from Ampere’s law. These FAC pairs arise because such magnetospheric current need to close and the collisional ionosphere is the easiest path to do so. However, 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. This precipitation is longitudinally aligned, dynamic, and highly structured, such that this closure path is non-trivial.

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 overall affects between the two limiting cases where a generator 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 (1s - 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 having a parallel potential drop on field

lines that much prefer to be equipotential). 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 these altitudes, on these field lines (TEMERIN, KNIGHT CITE).

A method of sustaining such a parallel electric field is through *double layers* at the bottom end of the acceleration region. Double layers are *Debye sheaths* which consist of two parallel layers of opposite charge sustained by the order of magnitude difference in electron and ion temperatures.

A 3D model of the acceleration region including electron dispersion by (SEYLER CITE) shows that a steady-state superposed oblique Alfvén waves can also 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 typical 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 affects the ionosphere's ability to carry current, i.e. the ionospheric conductivity.

These U-shaped potentials are like latitudinal aligned ridges on the two-cell polar cap potential. The precipitation they produce has strong gradients, it can appear and stretch out west or eastward, it can strengthen and reach deeper into the ionosphere, it can wiggle and bend. The ionospheric conductivity is very sensitive to this precipitation, so this local morphology directly controls the current continuity.

1.3 Ionospheric Ohm's Law and Current Continuity

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

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

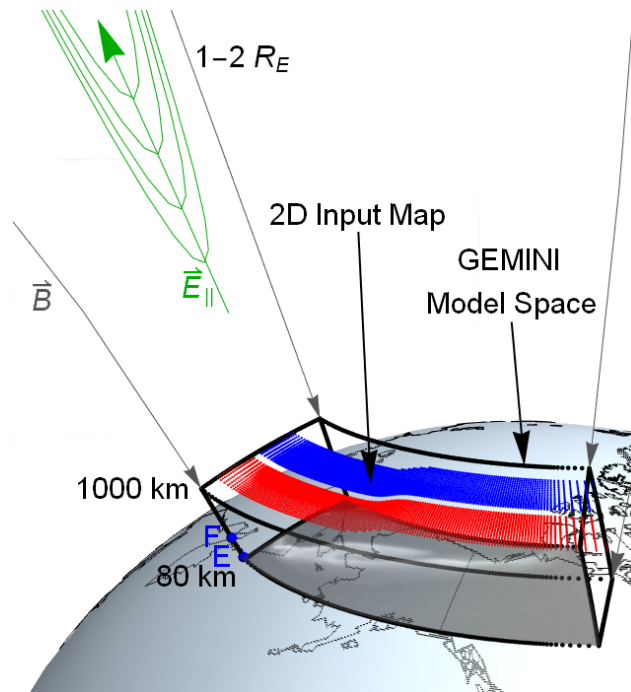


Figure 1: The general framework and context of this work. The dotted black box depicts the GEMINI model space over Alaska from 80 km to ~ 1000 km in altitude. The approximate E and F region peaks are shown on the side in blue. The U-shaped potential/parallel electric field is shown in green at around $1-2 R_E$ (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.

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

1.4 3D Modelling: Why now?

2 Thesis Statement

3 Approach and Methodology

4 Science Studies

5 Tasks and Goals

References

- Amm, O., Aruliah, A., Buchert, S. C., Fujii, R., Gjerloev, J. W., Ieda, A., Matsuo, T., Stolle, C., Vanhamäki, H., and Yoshikawa, A. (2008). Towards understanding the electrodynamics of the 3-dimensional high-latitude ionosphere: present and future. *Annales Geophysicae*, 26(12):3913–3932.
- Archer, W. E., Knudsen, D. J., Burchill, J. K., Jackel, B., Donovan, E., Connors, M., and Juusola, L. (2017). Birkeland current boundary flows. *Journal of Geophysical Research: Space Physics*, 122(4):4617–4627.
- Brekke, A. (1989). Auroral ionospheric conductances during disturbed conditions. *Ann. Geophys.*, 7:269–280.
- Clayton, R., Burleigh, M., Lynch, K. A., Zettergren, M., Evans, T., Grubbs, G., Hampton, D. L., Hysell, D., Kaeppler, S., Lessard, M., Michell, R., Reimer, A., Roberts, T. M., Samara, M., and Varney, R. (2021). Examining the auroral ionosphere in three dimensions using reconstructed 2d maps of auroral data to drive the 3d gemini model. *Journal of Geophysical Research: Space Physics*, 126(11):e2021JA029749. e2021JA029749 2021JA029749.
- Cowley, S. (2000). Magnetosphere-ionosphere interactions: A tutorial review. *Magnetospheric Current Systems, Geophys. Monogr. Ser.*, 118:91–106.
- Dungey, J. W. (1961). Interplanetary magnetic field and the auroral zones. *Phys. Rev. Lett.*, 6:47–48.
- Evans, D. S. (1974). Precipitating electron fluxes formed by a magnetic field aligned potential difference. *Journal of Geophysical Research (1896-1977)*, 79(19):2853–2858.
- Fang, X., Randall, C. E., Lummerzheim, D., Wang, W., Lu, G., Solomon, S. C., and Frahm, R. A. (2010). Parameterization of monoenergetic electron impact ionization. *Geophysical Research Letters*, 37(22).
- Grubbs, G., Michell, R., Samara, M., Hampton, D., Hecht, J., Solomon, S., and Jahn, J.-M. (2018). A comparative study of spectral auroral intensity predictions from multiple electron transport models. *Journal of Geophysical Research: Space Physics*, 123(1):993–1005.

- Kelley, M. C. (2009). *The earth's ionosphere : plasma physics and electrodynamics*. International geophysics series, v. 96. Academic Press, Amsterdam ;, 2nd ed. edition.
- Lotko, W. (2004). Inductive magnetosphere-ionosphere coupling. *Journal of Atmospheric and Solar-Terrestrial Physics*, 66(15):1443–1456. Towards an Integrated Model of the Space Weather System.
- Lühr, H., Park, J., Gjerloev, J. W., Rauberg, J., Michaelis, I., Merayo, J. M. G., and Brauer, P. (2015). Field-aligned currents' scale analysis performed with the swarm constellation. *Geophysical Research Letters*, 42(1):1–8.
- Lysak, R. L. (1985). Auroral electrodynamics with current and voltage generators. *Journal of Geophysical Research: Space Physics*, 90(A5):4178–4190.
- Paschmann, G., Haaland, S., and Treumann, R. (2003). *Theoretical Building Blocks*, pages 41–92. Springer Netherlands, Dordrecht.
- Richmond, A. D. (2010). On the ionospheric application of poynting's theorem. *Journal of Geophysical Research: Space Physics*, 115(A10).
- Rother, M., Schlegel, K., and Lühr, H. (2007). Champ observation of intense kilometer-scale field-aligned currents, evidence for an ionospheric alfvén resonator. *Annales Geophysicae*, 25(7):1603–1615.
- Solomon, S. C. (2017). Global modeling of thermospheric airglow in the far ultraviolet. *Journal of Geophysical Research: Space Physics*, 122(7):7834–7848.
- Sugiura, M., Maynard, N. C., Farthing, W. H., Heppner, J. P., Ledley, B. G., and Jr., L. J. C. (1982). Initial results on the correlation between the magnetic and electric fields observed from the de-2 satellite in the field-aligned current regions. *Geophysical Research Letters*, 9(9):985–988.
- Wolf, R. A. (1975). Ionosphere-magnetosphere coupling. *Space Science Reviews*, 17(2):537–562.
- Wygant, J. R., Keiling, A., Cattell, C. A., Johnson, M., Lysak, R. L., Temerin, M., Mozer, F. S., Kletzing, C. A., Scudder, J. D., Peterson, W., Russell, C. T., Parks, G., Brittnacher, M., Germany, G., and Spann, J. (2000). Polar spacecraft based comparisons of intense electric fields and

poynting flux near and within the plasma sheet-tail lobe boundary to uvi images: An energy source for the aurora. *Journal of Geophysical Research: Space Physics*, 105(A8):18675–18692.

Zettergren, M. and Semeter, J. (2012). Ionospheric plasma transport and loss in auroral downward current regions. *Journal of Geophysical Research: Space Physics*, 117(A6).

Zettergren, M. D., Semeter, J. L., and Dahlgren, H. (2015). Dynamics of density cavities generated by frictional heating: Formation, distortion, and instability. *Geophysical Research Letters*, 42(23):10,120–10,125.