Thesis Application Abstract: *Current Continuity in Auroral System Science*

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Background and Motivation: 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):

$$j_{\|}(x, y) = \Sigma_P \nabla_\perp \cdot \mathbf{E}_\perp + \mathbf{E}_\perp \cdot \nabla_\perp \Sigma_P - \left(\mathbf{E}_\perp \times \hat{\mathbf{b}}\right) \cdot \nabla_\perp \Sigma_H, \tag{1}$$

where $j_{\|}$ 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 we 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.

Thesis statement: 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).

Approach and Methodology: 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).

Thesis Aim: 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.

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.

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.

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.

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).

Solomon, S. C. (2017). Global modeling of thermospheric airglow in the far ultraviolet. *Journal of Geophysical Research: Space Physics*, 122(7):7834–7848.

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.