Current Continuity in Auroral System Science: A 3D Modelling Approach to Current Closure in Non-Sheetlike Auroral Arcs

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1 Science/Technical/Management

1.1 Introduction and Motivation

Auroral arc scale coupling of the magnetosphere and ionosphere (MI) involves complex system level science and is an open area of study (Wolf, 1975; Seyler, 1990; Cowley, 2000; Lotko, 2004; Fujii et al., 2012; Khazanov et al., 2018; Yoshikawa and Fujii, 2018; Clayton et al., 2021; Lynch et al., 2022). The auroral ionosphere plays a non-passive role in this coupling. It does so by keeping the closure of field-aligned currents (FAC), carried by accelerated and background populations, self-consistent with both magnetospheric convection patterns and the resulting conductivity volume. The most recent relevant simulation study of auroral arc current closure is two-dimensional and a quarter century old (Karlsson and Marklund, 1998) which motivates this proposal to **study three-dimensional simulations of FAC closure in quasistatic auroral arc systems.**

For high-latitudes, the 2D (latitude-longitude) topside relation between quasi-static ($\partial_t \mathbf{B} = 0$) ionospheric $\mathbf{E} \times \mathbf{b}/B$ flow, FAC, and conductances is (Kelley, 2009, Eq. 8.15):

$$j_\parallel(x,y) = \Sigma_P(\nabla_\perp \cdot \mathbf{E}) + \mathbf{E} \cdot \nabla_\perp \Sigma_P + (\mathbf{E} \times \mathbf{b}) \cdot \nabla_\perp \Sigma_H \tag{1}$$

where $j_\parallel$ is the topside FAC map orthogonal to $\mathbf{b}$, Σ_P and Σ_H are the height-integrated Pedersen and Hall conductivities, i.e. conductances, $\mathbf{E}$ is the ionospheric electric field, and $\mathbf{b} = \mathbf{B}/B$ is the magnetic field direction. This describes how, for quasistatic situations, the magnetospheric currents and convection patterns couple to the ionosphere for given conductance maps in 2D. However, this ignores the neutral wind, finite parallel resistivity in the lower E region, and, in fact, it integrates out all altitudinal dependencies. Furthermore, these maps are highly sensitive to auroral precipitation. For ideal, sheetlike arcs (latitudinally narrow, longitudinally aligned, with no along arc gradients) finding self-consistent solutions is well-posed, but it is not well understood what degree of deviation from sheetlike arcs significantly breaks the along-arc symmetry of a discrete auroral system.

For non-idealized auroral arc systems, finding a geophysically coherent set of topside maps of plasma flow, FAC, and conductances requires a better understanding of the path current closure takes through a non-height-integrated, three-dimensional conductivity volume. Auroral system science has been studied largely in 2D (altitude-latitude) (Goertz and Boswell, 1979; Mallinckrodt,

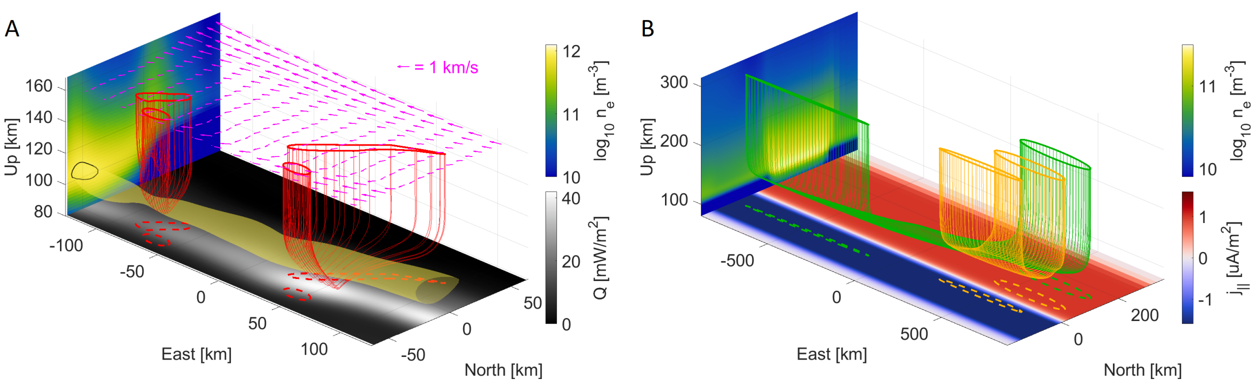

Figure 1: 3D simulations, one driven by flow data from Clayton et al. (2021) (A) and one being a theoretical 3 keV, 3 mW/m^2 basic sheetlike auroral arc system (B). (West planes) electron density latitude-altitude cuts. (Isosurface, A) electron density at 8×10^{11} m^{-3}. (Bottom planes) topside total precipitating electron energy flux (A) and FAC (B). (Magenta arrows, A) topside ion flow. Calculated current flux tubes are shown with their respective projections onto the bottom panel (dashed).

1985), but in more recent years focus has shifted to 2.5 to 3D systems partly for this reason (Amm et al., 2008; Fujii et al., 2011, 2012; Marghitu, 2012; Yoshikawa and Fujii, 2018; Clayton et al., 2019, 2021; Yano and Ebihara, 2021). One reason we care about altitude is because the electric-field-aligned closure currents (Pedersen currents) have conductivities that peak at higher altitudes than those closing across the electric field (Hall currents). Given that auroral precipitation can directly impact both how much and at what altitude impact ionization occurs, this directly affects the current closure morphology. From an energetics standpoint, this is important as Hall currents do not dissipate electromagnetic energy ($\mathbf{j}_H \cdot \mathbf{E} = 0$), while Pedersen currents produce Joule heating.

Fig. 1A depicts an example 3D simulation driven by ion flow and auroral precipitation data from Clayton et al. (2021). This plot visualizes current closure with flux tubes created by sourcing streamlines at a closed curve and assuming divergence-free current. The precipitation-driven conductivity has along-arc gradients which significantly change the current closure morphology $\sim$100 km apart. This illustrates that even seemingly sheetlike arc systems incorporate altitude- and along-arc-dependent, sensitive interactions between plasma flow, current, and conductivity. In fact, a simulation with absolutely no along-arc structure by design, Fig. 1B, shows that even a fully sheetlike arc system can display 3D current closure morphology.

To further illustrate how visualizing 3D current morphology can help our understanding of auroral physics, Fig. 2 depicts a simulation based on case 1 of a study done by Mallinckrodt (1985). This study demonstrates that by introducing an eastward background electric field (analogous to a steady southward neutral wind, $\mathbf{U} \times \mathbf{B}$), the Cowling effect (Cowling, 1932; Chapman, 1956) can produce currents at higher altitudes that oppose the nominal Pedersen currents. This creates a spiral effect in 2D (Mallinckrodt, 1985, Fig. 9), yet, in 3D it is revealed that this is an isolated, helical current flux tube as shown in black in Fig. 2.

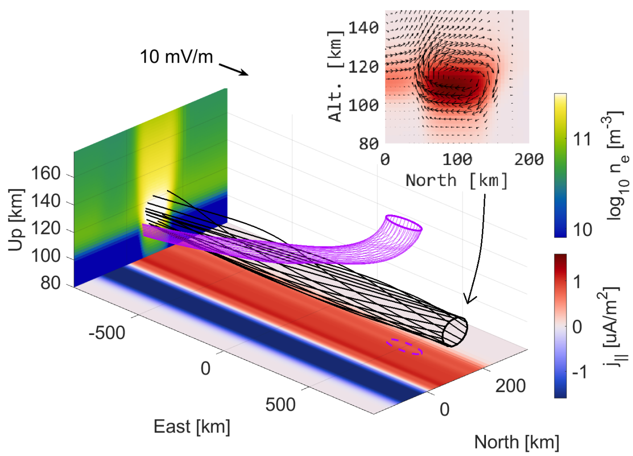

Figure 2: Simulation modelled after case 1 from Mallinckrodt (1985). The configuration is the same as Fig. 1B, but with one flux tube sourced vertically on the east side, centered around the helical current signature.

Current continuity and Ohm's law tells us how current, plasma flow, and conductivity behave: $\nabla \cdot (\bar{\bar{\sigma}} \cdot \mathbf{E}) = 0$, and by integrating out the 3rd dimension, Eq. (1) provides a powerful tool for describing MI coupling. However, this hides significant intuition and physics about 3D ionospheric current closure, especially for less idealized auroral arcs systems. This gained intuition can help to determine consistency between topside maps of $j_{||}(x, y)$, $\mathbf{E}(x, y)$, and precipitation, that are geophysically coherent for non-idealized auroral arc systems.

1.2 Science Questions and Objectives

In this work, the following science questions and objectives will be investigated:

- SQ 1: What self-consistency constraints exist in creating a geophysically coherent set of F-region quasistatic auroral system drivers?
- SQ 2: What understanding of auroral system science can be gained by investigating the 3D morphology of ionospheric current closure?

SQ 3: What degree of along-arc structure significantly breaks the sheetlike discrete auroral model and what auroral features are most sensitive to this structure?

SO 1: Develop a public catalog of theoretical 3D auroral arc system simulations that illustrate non-idealized, non-sheetlike morphologies.

SO 2: Develop infrastructure to systematically drive and query the GEMINI ionospheric model such that the catalog can be easily expanded upon.

1.3 Approach and Methodology

To address these science questions and objectives, a catalog of auroral arc system cases will be simulated using state-of-the-art 3D ionospheric modelling provided the Geospace Environment Model of Ion-Neutral Interactions (GEMINI) (Zettergren and Semeter, 2012; Zettergren and Snively, 2019). This is a multi-fluid (6 ions + electrons), quasi-electrostatic model with its particle continuity including chemical production/loss and photo/impact ionization. Calculations of local densities, flows, and temperatures are treated self-consistently and the model includes thermal conduction heat flux, collisional heating, thermoelectric electron heat flux, and inelastic cooling/heating from photoelectrons. This is supplemented with Maxwell's equations and, at the time of writing, includes no displacement current or magnetic induction effects. With this the system is solved through having divergence-less currents, curl-free electric fields, and invoking Ohm's law.

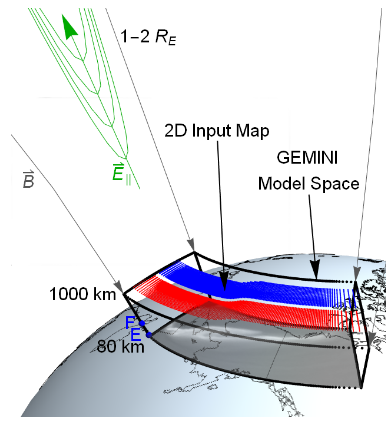

Figure 3: The general context of this work. The black box depicts the GEMINI model space over Alaska from 80 km to ∼1000 km in altitude. The auroral acceleration region is shown in green. The magnetic field lines connecting to the magnetosphere are shown in gray. The top of the model space shows an example of a 2D input map of FAC and the bottom shows roughly where auroral emission lies.

Fig. 3 illustrates the context in which this work will use GEMINI. For our use, the model spans ∼3000 km east-west, ∼1000 km north-south, and has an altitude span from the lower E region to the topside F region. Presently, the grid resolutions reach down to 20, 2, and 2 km in longitude, latitude, and altitude respectively. The magnetic field inside the model space is aligned with the radial coordinate and is constant. The model is driven at its topside F-region boundary with 2D, time-dependent maps of total precipitation energy flux, Q, and characteristic energy, E_0, to generate the impact ionization via calculations described in Fang et al. (2008, 2010). These drivers exists at the top of the model space, i.e. the topside F-region. In addition, the model can be driven with either a topside map of FAC (as shown in Fig. 3) or perpendicular plasma flow in the form of an electric potential map, ϕ_E.

GEMINI can use Maxwellian precipitation calculations by Fang et al. (2008), but is also set up to implement a composite spectrum based off of multiple mono-energetic calculations by Fang et al. (2010), or it can use the GLobal airglOW (GLOW) model (Solomon, 2017). These methods will be used to compare against stereotypical electron energy spectrum data (FAST, sounding rockets, etc.) and a calculation choice will be made using these comparisons.

1D across-arc cuts of total energy flux, characteristic energy, and FAC (or electric potential) are produced through a mix of literature values (Wu, 2020) and lower order physics (outlined in the next paragraph). These cuts are then replicated along a chosen 2D arc profile much like what is done by Clayton et al. (2021). Fig. 4 shows an example of three input maps, $Q(x, y)$, $E_0(x, y)$, and

$j_\parallel(x,y)$, with a slight along-arc bend in its profile. These maps have a constant band of precipitation embedded in an upward current sheet that is poleward of an accompanying return current sheet. This example illustrates a basic level of along-arc structure that will be introduced as a means to stray from idealized, sheetlike arcs.

Preliminary physics constraints are applied to a set of 1D across-arc cuts used in producing the driving maps. Choices of FAC and electric potential cuts are related by using the sheetlike version of Eq. (1), with x being north:

$$j_\parallel(x) = \frac{\mathrm{d}}{\mathrm{d}x}(\Sigma_P E_x(x)) \implies E_x(x) = \frac{1}{\Sigma_P}\int_{x_0}^{x} j_\parallel(x')\mathrm{d}x', \tag{2}$$

where x_0 is arbitrarily chosen such that $E_x(x_0) = 0$ (Mule, personal communication, November 2022). Additionally, for Maxwellian precipitation, along with a derivation by Rönnmark (2002) built on the Knight relation (Knight, 1973), Q is related to E_0 through the accelerated portion of the FAC:

$$j_{\parallel,a} = q_e \int_0^\infty \phi_M(E)\mathrm{d}E = \frac{q_e Q}{2E_0} = q_e n_a \sqrt{\frac{E_0}{2m_e}} \implies Q = \sqrt{\frac{2}{m_e}} n_a E_0^{3/2}, \tag{3}$$

where q_e, m_e, E, and ϕ_M are the electron charge, mass, energy and energy spectrum, and n_a is the acceleration region density. Lastly, it is ensured that, naturally, $j_\parallel > j_{\parallel,a}$.

With the tools outlined above, a catalog will be constructed of theoretical, parameterized inputs of stereotypical flow, FAC, and precipitation maps, each with progressively more complex along-arc structure. These inputs and their parameters will be systematically adjusted and built upon in order to compare the GEMINI outputs (plasma flow, 3D current closure, densities) and investigate their impacts on breaking system symmetry. Fig. 5 shows four example simulations of such a catalog. These are all built off of Fig. 1B and demonstrate how: (A) a bend in the arc profile reshapes the flux tube, (B) increasingly lower FAC density stretches out the current flux tube westward as it aims to conserve flux, (C) flux tubes will merge with the electrojet current system if unable to close at all, and (D) how a northward electric field (steady eastward neutral wind) can squeeze the system longitudinally by providing more Pedersen closure opportunities.

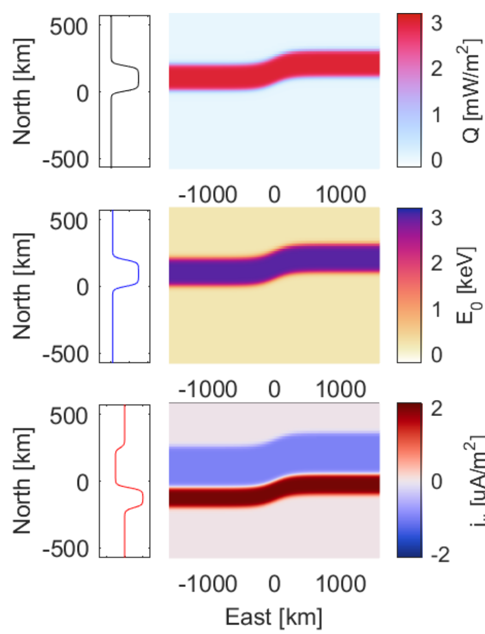

Figure 4: Set of GEMINI driver maps along with their 1D across-arc cuts. Top: total electron energy flux. Middle: characteristic energy. Bottom: Field-aligned current.

The catalog will be divided into ~10 categories including effects by precipitation, FAC, potential vs. FAC model driving, arc profile, arc motion, background electric fields, and a mix & match category. Per category, ~10 parameters will be varied over ~10 values, for an estimated 1000 simulations. Simulation analyses will largely be done using automated methods. Parameters will include, for instance, magnitudes of Q (0.1–100 mW/m^2), E_0 (0.2–20 keV), FAC (0.1–100 μA/m^2), gradient scale lengths across (5–50 km) and along the arc (>1000–60 km), widths (6–300 km), background electric fields (-40–40 mV/m), distance between FAC sheets (0–100 km), west- and equatorward drifts (-10–10 km/s), FAC precipitation and return sheet width ratios (0.1–1), as well as the degree of bend, number of arcs, and more.

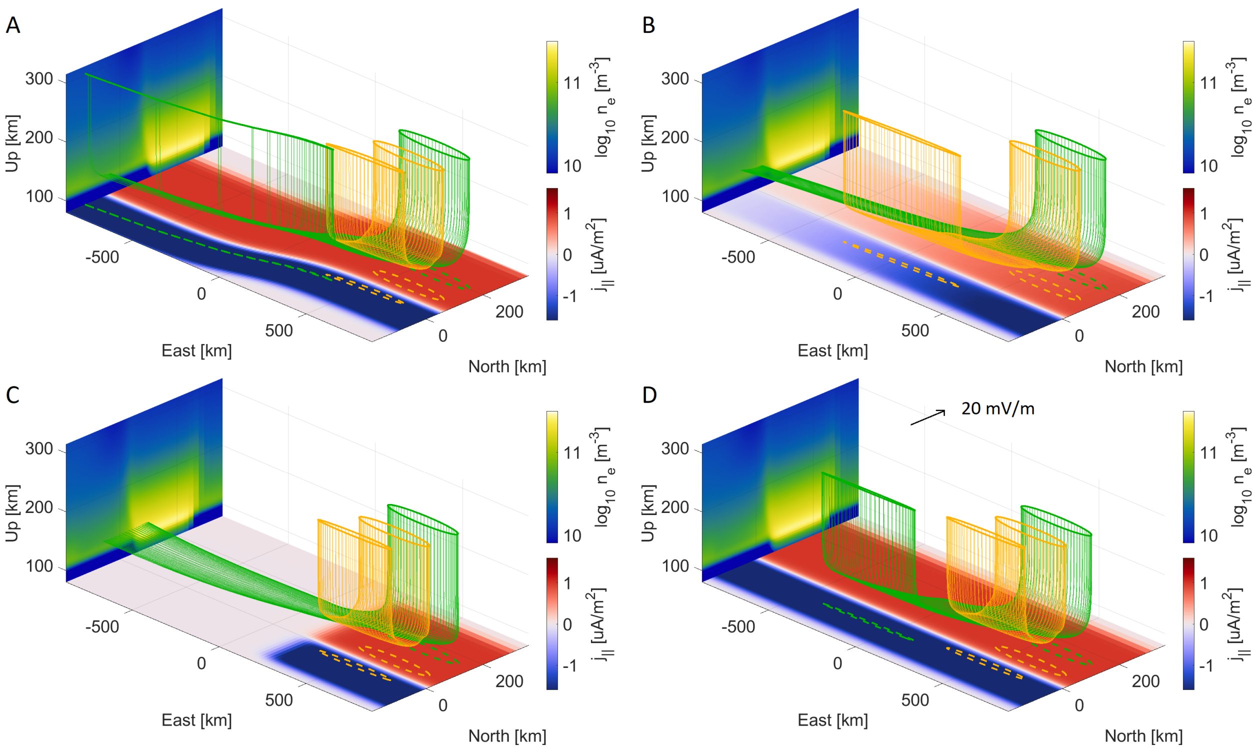

Figure 5: Example catalog simulations stemming from Fig. 1B: (A) A slight bend is added to the arc profile. (B) The FAC intensity gradually fades westward. (C) The FAC abruptly stops. (D) A 20 mV/m northward electric field is imposed. Figure configurations follow Fig. 1B.

1.4 Science Closure

To address SQs 1-2, >10 data-driven GEMINI simulations, as opposed to catalog simulations, will be created, like Fig. 1A, where at least some of the information about the model drivers is known via existing experiments. These will be treated as "ground truth" and analyzed using new knowledge obtained from the catalog about 3D morphologies and the physics governing them. The modelled behavior of these data-driven simulations will be dissected into various categories/building block simulations provided by the catalog. Possible data to be used include multi-spectral all-sky imagery (DASC, 2023), to provide maps of characteristic energy and total precipitation energy flux (Grubbs II et al., 2018a,b), in conjunction with 1D across-arc cuts of ion flow and FAC data replicated along imagery defined arc contours as is done by Clayton et al. (2021). Such 1D cuts will be provided by either existing sounding rocket (Grubbs II et al., 2018b; Clayton et al., 2021) or spacecraft data such as the European Space Agency's SWARM Mission (Swarm, 2023). Data conjunctions will be found using AuroraX (2023).

To address SQ 3, quantitative morphological parameters (those describing the 3D shapes of output data) will be compared against various simulations in the catalog. Fig. 6 shows an example set of three comparisons of such parameters. The left panel shows the amount of east-west vs. north-south deflection of the centroids of both terminating ends of current flux tubes like those shown in Figs. 1, 2, and 5. The middle panel shows the distance from the FAC inflection line to the northern of those centroids vs. the average altitude of current closure for a given flux tube. This reveals that FAC can close well above 120 km, as long as the closure cross-section of the flux tube is enlarged. This is seen in the right panel which shows that same inflection distance against the altitude range over which current closure happens. These comparisons are made for a series of 6 simulations with increasing precipitation intensity (green shades), as well as for a low

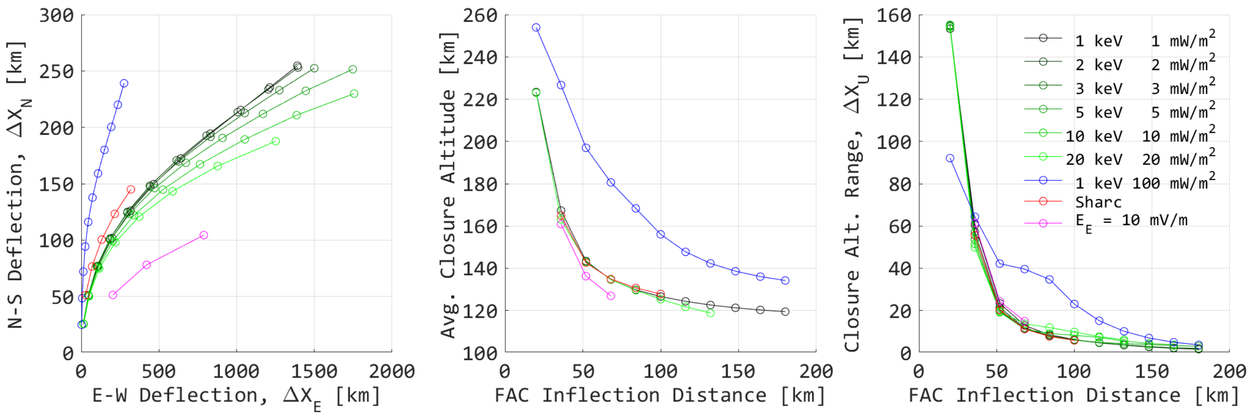

Figure 6: A set of example comparisons of morphological parameters for a series of simulations. Left: North-south vs. east-west deflection of the centroids of the terminal ends of different current flux tubes. Middle: The average closure altitude of different current flux tubes vs. the northern centroid distance to the FAC inflection line. Right: The range in altitude of the closure part of different current flux tubes vs. the same distance from the FAC inflection line.

energy, high flux simulation (blue), and the simulations from Fig. 5C (red), and Fig. 2 (magenta). This allows for systematic and quantitative analysis of the sensitivity of 3D morphology to various input parameters. Our goal with SQ 3 is to discover what most drives deviations from sheetlike auroral arc systems through similar comparisons.

1.5 Science Mission Directorate Relevance

By investigating the role the auroral ionosphere plays in MI coupling, this work directly addresses the second high level science goal of the Heliophysics Decadal survey: "Determine the dynamics and coupling of Earth's magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs" (NRC, 2013). More specifically, this work addresses the Heliophysics Theory, Modelling, and Simulations (H-TMS) program by using "numerical simulations and modeling synergistically with data analyses and rigorous theory development" (ROSES, 2022, appx B.1).

1.6 Schedule and Milestones

Prior to the prospective start date of this project, the following work will be completed: 1) reproducible, expandable methods for GEMINI setup, driving, and 3D output visualization will be in place (van Irsel et al., 2021b,a), 2) comparisons of different precipitation calculation methods (Fang et al., 2008, 2010; Solomon, 2017) will be made to best represent our needs, 3) a paper will be submitted on preliminary findings regarding the 3D nature of auroral system science based on work presented by van Irsel et al. (2022), and 4) all required courses will be completed. After that, the project schedule and milestones are as follows:

> Year 1: Develop the simulation catalog; develop tools for analyzing morphological parameters; submit a paper on scientific findings addressing SQ 3
>
> Year 2: Find in-situ and ground-based imagery conjunctions; generate data-driven simulations; submit a paper on scientific findings addressing SQs 1-2; the FI's thesis will be defended.

In addition to this, the FI will disseminate research at the 2023/24 AGU Fall Meetings and the 2024/25 Cedar Workshops.

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J. van Irsel (FI) was the primary developer for the proposed science. This work stems from the FI's Ph.D. thesis proposal which was accepted May, 2022 and will be defended August, 2025.

4 Research Readiness Statement

In addition to the graduate level core physics courses (classical, statistical, and quantum mechanics, as well as electricity and magnetism), the FI has completed courses entitled: *introductory plasma physics*, *magnetohydrodynamics*, *plasma kinetic theory*, and *computational plasma dynamics*. This has provided the FI a fundamental, proficient understanding of the physics used in this project and the GEMINI model including (but not limited to): Maxwell's equations, the Fokker-Planck equation, the transport equations for a multi-species plasma, and ionization and recombination rate physics.

The FI has conducted and will continue to conduct self-directed studying of auroral arc systems by means of literature research, attending conferences/science meetings, and weekly science discussions with members of the auroral science community covering multiple disciplines and institutions. In addition to this, the FI has significantly contributed to multiple science proposals involving auroral system science including the 2019 NASA MIDEX Concept Study Report entitled *Auroral Reconstruction CubeSwarm* (ARCS).

The FI has also taken several computer science courses covering both Python and FORTRAN and is proficient in Mathematica and MATLAB as well. The FI is also familiar with running physics-based models using high-performance computing. The FI has developed scripts to setup, run, and query GEMINI simulations, either one at a time or an automated series of them, and has extended knowledge about the model itself including the physics it contains. Weekly meetings with the model's co-developer, M. Zettergren, ensure continued support in this regard.

The FI aims to graduate with a Ph.D. in Physics, focusing on auroral plasma physics, by August, 2025, covering a total degree period of 6 years. The FI will have finished all course requirements of this degree by the prospective start date of this proposal.

Additionally, the FI completed the NSF's 2020 ISR Summer School gaining fundamental knowledge about the workings and use of incoherent scatter radars. The FI has also done field-work at the Poker Flat Research Range in Alaska as well as at the Svalbard Rocket Range in Ny-Ålesund providing integration support of instrumentation onto sounding rockets.

5 Curriculum Vitae of PI

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I. EDUCATION

A.B.	Physics	Washington University, St Louis, MO	1984
	Physics	Northeastern University, Boston, MA [part-time graduate course work]	1985-87
M.S.	Physics	University of New Hampshire, Durham, NH	1990
Ph.D.	Physics	University of New Hampshire, Durham, NH	1992

II. EXPERIENCE

Dartmouth College since 2002; Professor 2012-present; Dept Chair 2019-2022 University of New Hampshire 1992-2002

- Auroral sounding rocket program: PI, Enstrophy sounding rocket mission, 1999. CoI, Sersio, 2004. PI, Cascades, 2005. CoI, ROPA, 2007. CoI, Scifer2, 2008. PI, Cascades2, 2009. CoI, RENU, 2010. CoI, MICA, 2012. CoI, SmallRockets, 2012. CoI, RENU2, 2015. PI, Isinglass, 2017. CoI, Kinet-X, 2021. CoI, C-Rex-2, 2021. CoI, LAMP, 2022. CoI, Apophis, 2023.
- Mesospheric sounding rocket program: mesospheric charged dust particles. PI, Dust Orions sounding rocket mission, 2002 and 2005. Co-I, Sporadic Atom Layers rocket, 1998. Guest instrumenter, Norwegian HotPay2, 2008. Guest instrumenter, German ECOMA mission, 2008.
- Low-resource spacecraft development: instrument and spacecraft bus development for cubesat-class sounding rocket and balloon payloads. New Hampshire EPSCoR funding (RocketCube) and JPL-SURP student funding (GreenCube). ARCS NASA Midex Concept Study Report, 2021-2022.
- NSF Career award, 2006: thermal plasma laboratory facility and Cluster satellite studies.
- FAST satellite program: Guest Investigator, 1999-2005.
- Cluster Satellite Program, Electron Drift Instrument: scientific development, EDI instrument.
- Teaching: Magnetospheric Physics, Ionospheric Physics, Statistical Mechanics, Plasma Physics, Classical Mechanics, Electricity & Magnetism. Student mentorship, graduate & undergraduate.
- Editing: Core group editing “Auroral Plasma Physics”, ISSI space sciences series book, 2002.
- *University of New Hampshire Graduate Student 1988-1992*
- *Air Force Geophysics Laboratory USAF Lieutenant/Research Physicist 1984-1988*
- *Washington University Undergraduate Research Assistant 1981-1984*

III. SELECTED PUBLICATIONS

- K Lynch, E McManus, J Gutow, M Burleigh, M Zettergren, An ionospheric conductance gradient driver for subauroral picket fence visible signatures near STEVE events, JGR, 2022. DOI: 10.1029/2022JA030863
- R Clayton, M Burleigh, K Lynch, M Zettergren et al., Examining the Auroral Ionosphere in Three Dimensions Using Reconstructed 2D Maps of Auroral Data to Drive the 3D GEMINI Model, JGR, 2021. DOI: 10.1029/2021JA029749
- M Fraunberger, K Lynch, et al., Auroral Ionospheric Plasma Flow Extraction using Subsonic Retarding Potential Analyzers, Rev. Sci. Instr., 2020, DOI: 10.1063/1.5144498.
- T Karlsson et al., SSR 2020, DOI: 10.1007/s11214-020-0641-7
- R Clayton, K Lynch, et al., Two-dimensional maps of in situ ionospheric plasma flow data near auroral arcs using auroral imagery. JGR, 2017. DOI: 10.1029/2018JA026440
- T M Roberts, K Lynch, et al., A Small Spacecraft for Multipoint Measurement of Ionospheric Plasma, Rev. Sci. Inst., vol 88, 2017. DOI: 10.1063/1.4992022

- T M Roberts, K Lynch, et al., Magnetometer-Based Attitude Determination for Deployed Spin-Stabilized Spacecraft, J. Guidance, Control, and Dynamics, 2017. DOI: 10.2514/1.G002591
- L Fisher, K Lynch, et al., Including sheath effects in the interpretation of planar retarding potential analyzer's low-energy ion data, Rev. Sci. Inst., vol 87, 2016. DOI: 10.1063/1.4944416
- P Fernandes, K Lynch, et al., Measuring the seeds of ion outflow: auroral sounding rocket observations of low-altitude ion hating and circulation, JGR, 2016. DOI: 10.1002/2015JA021536
- K Lynch, D Hampton, M Zettergren, et al., MICA sounding rocket observations of conductivity-gradient generated auroral ionospheric responses, JGR, 2015. DOI: 10.1002/2014JA020860
- M Zettergren, K Lynch, D Hampton, et al., Auroral ionospheric F-region density cavity formation and evolution: MICA campaign results, J. Geophysical Research, 2014, DOI: 10.1002/2013JA019583.
- K Lynch, M Mella, D Hampton, et al., Structure and dynamics of the nightside poleward boundary: sounding rocket & groundbased observations of auroral electron precipitation in a rayed curtain, JGR, 2012.
- L Gayetsky and K Lynch, Flowing Ion Population from a Resonance Cavity Source, Review of Scientific Instruments, 2011.
- M U Siddiqui, L Gayetsky, M Mella, K Lynch, and M R Lessard, Design and Use of a Collimated Electron and Ion Source for Plasma Sheath Studies, Physics of Plasmas, 2011.
- M Mella, K Lynch, D Hampton, et al., Sounding rocket study of an auroral poleward boundary intensification sequence, Journal of Geophysical Research, 2011.
- P Bracikowski, K Lynch, and L Gayetsky, Low-resource cubesat-scale sensorcraft for auroral and ionospheric plasma studies, in 24th Annual AIAA/USU Conference on Small Satellites (2010).
- NRC Committee on Solar and Space Physics (CSSP) Heliophysics Assessment ad-hoc committee, A performance assessment of NASA's Heliophysics program, NRC report, 2009.
- K Frederick-Frost, and K Lynch, Experimental studies of low density and temperature ion and electron sheaths, Physics of Plasmas, 2007.
- K Lynch, J Semeter, M Zettergren, P Kintner et al., Auroral ion outflow: low altitude energization, Ann. Geophys., 2007.
- K Frederick-Frost, and K Lynch et al., SERSIO: Svalbard EISCAT rocket study of ion outflows, J. Geophys. Res., 2007.
- G Paschmann, S Haaland, R Treumann, eds., "Auroral Plasma Physics", Space Sci. Rev. 103, no. 1-4, 2002.
- K Lynch, J Bonnell, C Carlson, W Peria, Return-current-region aurora: E-parallel, j-z, particle energization, and BBELF wave activity, J. Geophys. Res., 2002.

IV. SERVICE

Member, National Academies Heliophysics Decadal "ITM" Panel, 2023.
Member, NASA Sounding Rocket Working Group (SRWG), 1999-2003; 2010-2013; 2022-2023.
Member, NRC Basic Plasma Science Committee, 2016-2018.
Member, DOE Fusion Energy Sciences Advisory Committee (FESAC), 2016-2018.
Chair, National Academies Heliophysics Decadal "Platforms" Working Group, 2010-2011.
Member, National Academies "Comm. NASA Heliophysics Performance Assessment", 2008-2009.
Member, National Academies "Comm. on Solar and Space Physics (CSSP)", 2006-2010.
Member, NRC Decadal survey "Plasma 2010: An assessment of and outlook for plasma science", 2005-2007.
Member, NASA Geospace MOWG, 2005-2009.
Member, NASA Magnetospheric Constellation Science and Technology Development Team (STDT), 1999-2001.
Member, NASA Geospace Multiprobes Science Definition Team, 1997.

6 Curriculum Vitae of FI

Jules van Irsel

Graduate Student

C: (603) 266 8084 | E: jules.van.irsel.gr@dartmouth.edu

Education

Dartmouth College Hanover, NH
Doctor of Philosophy in Physics *Sep. 2019 – Present*

University of Calgary Calgary, AB
Bachelor of Science, Astrophysics (Honours), 4.00 *Sep. 2014 – June 2018*

Southern Alberta Institute of Technology Calgary, AB
Mech. Eng. Tech., Design and Development (Honours), 3.96 *Sep. 2012 – June 2014*

Experience

Graduate Student Hanover, NH
Dartmouth College – K. A. Lynch *Sep. 2019 – Present*

- Approved thesis proposal: *Current Continuity in Auroral System Science: A 3D Modelling Approach to Current Closure in Non-Sheetlike Auroral Arcs*: Expected Defence: Aug., 2025.
- Aided in developing NASA's ROSES-2022 proposal: *Geophysical Non-Equilibrium Ionospheric System Science* (GNEISS, PI: K. Lynch)
- Aided in developing NASA's MIDEX-2019 proposal and through its Phase A Concept Study Report: *Auroral Reconstruction CubeSwarm* (ARCS, PI: K. Lynch)
- Ran multiple 3D multifluid ionospheric plasma simulations and developed several tools for driving and visualizing resulting rich data volumes
- Vacuum/plasma tested and rewrote the GSE software for Petite Ion Probes (PIP) and oversaw their integration onto NASA's *Loss through Auroral Microburst Pulsations* (LAMP, PI: A. Halford) sounding rocket mission

Instrument Design and Assembly Assistant Calgary, AB
University of Calgary – J. K. Burchill *May 2018 – Aug. 2019*

- Mechanically and electrically redesigned a Miniature Plasma Imager (MPI) lowering its power consumption and introducing optical baffling
- Assisted in MPI environment testing (vacuum, vibration, plasma, etc.) and oversaw its integration onto NASA's *Cusp-Region EXplorer 2* (C-REX 2, PI: M. Conde) sounding rocket mission
- Oversaw integration of an MPI onto NASA's *Visualizing Ion Outflow via Neutral Atom Sensing 2* (VISIONS 2, PI: D. Rowland) sounding rocket mission

Research Internship Calgary, AB
University of Calgary – J. K. Burchill *May 2017 – Oct. 2017*

- Summer research into ionospheric upflow in the topside F-Region
- Used ESA's SWARM data to perform a superposed epoch analysis using electron temperature enhancements (as a probe for electron precipitation) and ion vertical flow

Mechanical Design Engineer & MWD Technician Calgary, AB
QCD Group of Companies – T. Russell *May 2014 – Oct. 2014*

- Helped maintain and service vertical shock absorbers used in measurements while drilling (MWD) technology
- Designed a first prototype of a bearing removal tool used in servicing the shock absorber

Conferences & Meetings

2022 AGU Fall Meeting Chicago, IL
Poster: "Auroral System Science: Determining Geophysical Boundary Conditions for Multifluid Volumetric Simulations of Auroral Arcs"
2022 CEDAR Workshop Austin, TX
Oral: "Two Threads for 3D Auroral Modelling: How to Drive and How to See"
Poster: "Auroral System Science: Multifluid 3D GEMINI Simulations of Auroral Arc Ionospheric Current Closure"
2021 AGU Fall Meeting Virtual
Oral: "The Effect of Hall Conductance Gradients on Field-Aligned Currents in Non-Sheetlike Auroral Arcs"
2021 CEDAR Workshop Virtual
Poster: "FAC Contributions from Hall Conductance Gradients in Non-Sheetlike Auroral Arcs"
2020 CEDAR Workshop Virtual
Poster: "Auroral Ionosphere: Combining Swarm Ion Flows and THEMIS Imagery with Machine Learning"
2017 AGU Fall Meeting New Orleans, LA
Poster: "Multi-scale investigation of low-altitude ion upflow and electron temperature correlations in the cusp/cleft ionoshphere"
4th Swarm Science Meeting Banff, AB
Volunteering opportunity

Awards & Scholarships

NSERC USRA: Undergraduate Student Research Award 2018
PURE Award: Program for Undergraduate Research Experience Award 2017
Skills Alberta: 4th place in Mechanical Computer Aided Design and Drafting 2012

Technical Skills

Software: Autodesk Inventor, Solidworks, Solidworks Visualize, Paraview, Dipstrace
Programming Languages: Python, MATLAB, Mathematica, Fortran, HTML/CSS, C
Developer Tools: Git, VS Code, Windows Subsystem for Linux, HPC, multi-threading
Other: CAD, surface-mount soldering, prototyping, GD&T

7 Current and Pending Support Statement for PI

Investigator: Kristina A. Lynch
Other agencies (including NASA) to which this proposal has been/will be submitted: N/A

Support: Current
Project/Proposal Title: In-Situ Measurements of Neutral and Plasma Dynamics Associated with Earth's Cusp-Region Thermospheric Mass Density Anomaly C-REX 2
Role: Co-I (Dartmouth PI), Lead PI: Mark Conde
Source of Support: University of Alaska, Fairbanks (NASA HTIDS)
POC: Debbie Davis-Ice djdavisice@alaska.edu 907-474-7646

Total Award Period Covered: 07/01/2017 - 09/12/2023 (NCE-2)

Person-Months Per Year Committed to the Project: .5 month per year (obligation met)

Support: Current
Project/Proposal Title: Loss through Auroral Microburst Pulsations (LAMP)
Role: Dartmouth PI (Updated 2022 replacing mission PI at GSFC as Alexa Halford instead of Sarah Jones)
Source of Support: NASA HTIDS
POC: Alexa Halford alexa.j.halford@nasa.gov 301-286-7794

Total Award Period Covered: 05/21/2018 - 5/20/2023 (NCE-2)

Person-Months Per Year Committed to the Project: .5 month per year

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Support: Current
Project/Proposal Title: KiNET-X: Kinetic-scale Energy and Momentum Transport Experiment
Role: Co-I (Dartmouth PI), Lead PI: Peter Delamere
Source of Support: University of Alaska, Fairbanks (NASA HTIDS)
POC: Debbie Davis-Ice djdavisice@alaska.edu 907-474-7646

Total Award Period Covered: 05/01/2018 - 04/30/2023 (NCE-2)

Person-Months Per Year Committed to the Project: 1 month per year

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Support: Pending
Project/Proposal Title: Apophis Eclipse Campaign Augmentation to SEED campaign
Role: Co-I (Dartmouth PI), Lead PI: Aroh Barjatya
Source of Support: Embry-Riddle Aeronautical University (NASA Prime)
POC:

Total Award Period Covered: 10/01/2022 - 12/31/2024

Person-Months Per Year Committed to the Project: .5 month years 2 & 3

Support: Pending
Project/Proposal Title: GNEISS Rocket: Geophysical Non-Equilibrium Ionospheric Systems Science Rocket
Role: PI
Source of Support: NASA H-LCAS
POC: Dan Moses dan.moses@nasa.gov

Total Award Period Covered: 09/01/2023 - 08/31/2026

Person-Months Per Year Committed to the Project: 1 month per year

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Support: Pending
Project/Proposal Title: ANTICS: Auroral network for ionosphere imaging with CubeSats
Role: Co-I (Dartmouth PI), Lead PI: Romina Nikoukar
Source of Support: Johns Hopkins University Applied Physics Laboratory (NASA H-FORT)
POC: Misty Crawford misty.crawford@jhuapl.edu 240-228-4466

Total Award Period Covered: 03/01/2023 - 02/28/2028

Person-Months Per Year Committed to the Project: .25 month year 1, .5 month year 5

Support: Pending
Project/Proposal Title: LAMP-2 (Loss through Auroral Microburst Pulsations - 2) sounding rocket
Role: Co-I (Dartmouth PI), Lead PI: Allison Jaynes
Source of Support: University of Iowa (NASA H-LCAS)
POC: Dan Moses dan.moses@nasa.gov

Total Award Period Covered: 07/12/2023 - 07/11/2027

Person-Months Per Year Committed to the Project: .33 month years 1-3, .5 month year 4

8 Current and Pending Support Statement for FI

The FI has no current and pending to report.

9 Mentoring Plan or Agreement

Adapted from K. Cantwell's (Dartmouth) and the University of Washington's Mentoring Plan.

9.1 Identifying Information

Mentee (FI): Jules van Irsel
Mentor (PI): Kristina A. Lynch

9.2 Proposed Project

The Mentee will address limitation of 2D approaches when analyzing the ionospheric role in MI coupling for quasistatic auroral arc systems, especially those that are non-idealized and non-sheetlike. This will be done by using state-of-the-art, 3D multi-fluid, quasi-electrostatic modelling of the auroral ionosphere to produce a catalog of stereotypical simulations of increasingly more complex auroral drivers. These simulations will then be contrasted against data-driven runs to determine the following: 1) what constraints exist in creating a geophysically coherent set of auroral drivers, 2) what new physical understanding can be gained by investigating 3D morphology of ionospheric current closure, and 3) what auroral features significantly break sheetlike symmetry and to what degree.

9.3 Presentation and Publication Plan

9.3.1 Anticipated Presentations

The Mentee will present project results at the American Geophysical Union (AGU) Fall Meetings in December of 2023-24 and/or the Cedar Workshops in June of 2024-25. These meetings will aid in the Mentee's career development and expand both professional and scientific networking. We acknowledge and thank the NSF's generous graduate student support in making the Cedar Workshops possible.

9.3.2 Anticipated Publications

The Mentee will submit at least two first-author publications to the Journal of Geophysics Research: Space Physics. The Mentor will aid in co-authoring and editing.

9.4 Career Development

The Mentor will continue to provide the Mentee with ample opportunities of networking and career development through meetings and collaboration across the scientific community. Furthermore, the Mentee will continue to be given the opportunity to mentor and guide undergraduate research assistants.

9.5 Professional Development Resources

Professional development resources are available through Dartmouth College's Guarini School of Graduate and Advanced Studies including support in general training, health and wellness, academics, teaching, career development, and research grants and funding.

9.6 Plans for Ongoing Mentoring Meetings

Ongoing weekly meetings involving the Mentee and Mentor include but are not limited to: a one-on-one meeting, a general *Lynch Lab* meeting, a GEMINI *Lynch Lab* subgroup meeting, and a GEMINI science meeting with external collaborators. Yearly meeting with the Mentee's Ph.D. committee will be held each spring term.

9.7 Formal Evaluation

The Mentor, as the Mentee's research advisor, will provide a research course grade once per academic term. The Mentee will attend yearly formal update meetings with his thesis committee and ultimately will defend his thesis.

9.8 Signatures

Signature of Mentee: Date:

Feb. 2, 2023

Signature of Mentor: Date:

2 Feb 2023

10 Budget and Narrative

10.1 Salaries

Jules van Irsel, FI, requests support at $40,200 for year one plus health insurance in the amount of $5,000 and health access fee costs in the amount of $424. Graduate support and health access fees include a 3% annual increase, health insurance includes a 6% annual increase.

10.2 Travel

FI will attend domestic AGU and/or Cedar conferences to disseminate research results. Funds for travel are spread out over the two-year period. Rates are based on travel to San Francisco, CA (AGU). One person, 6 days. Meals and Lodging rates based on government per diem for San Francisco, CA. Flight estimate based on Orbitz for December. Registration and abstract fee based on AGU site for current graduate student rates, Dartmouth Coach and local transportation based on current coach rates and similar travel expenses.

Flights:	$359
Lodging: 5 nights $288/night	$1,440
Meals: 2 days $59.25/day + 4 days $79/day	$435
Registration:	$300
Abstract submission:	$40
Dartmouth Coach: RT to Logan Airport	$66
Local transportation in San Francisco:	$40
Total per trip:	**$2,680**

Travel for approximately two trips for a total cost of $5,233 supported from the FINESST project.

10.3 Publications

FI will submit two (standard 25-page unit) publications to JGR. One paper per year estimated at $1,000 per paper for a total of $2,000.

10.4 F&A

N/A no indirects applied to participant costs for FINESST funding.

10.5 Budget Summary

Agency:	NASA
Solicitation:	FINESST
Title:	Current Continuity in Auroral System Science: A 3D Modelling Approach to Current Closure in Non-Sheetlike Auroral Arcs
Principle Investigator	K. A. Lynch
Participant costs:	J. van Irsel
Start date:	9/1/2023
End date:	8/31/2025

Personnel		**Year 1 9/1/2023 8/31/2024**	**Year 2 9/1/2024 8/31/2025**	**Total**
FI van Irsel C/Y	*12 mos/yr*			
Stipend		$40,200*	$41,406	$81,606
Health		$5,000	$5,300	$10,300
Health access fee		$424	$437	$861
3% increase/yr stipend & fee				
6% increase health				
Total salaries		**$45,624**	**$47,143**	**$92,767**
Travel		**$3,376**	**$1,857**	**$5,233**
Publications		**$1,000**	**$1,000**	**$2,000**
Total direct cost		**$50,000**	**$50,000**	**$100,000**
Overhead				
MTDC (unallowed)	0%	$0	$0	$0
Total cost Dartmouth		**$50,000**	**$50,000**	**$100,000**

***Year 1 stipend calculation**	
FY24 DC stipend	$40,000
9/1/23 - 6/30/24	$33,333
7/1/24 - 8/31/24	$6,867
Stipend year 1	$40,200