CENTER FOR

GEOSPACE STORMS

Transforming the understanding and predictability of space weather

INNOVATE

EMPOWER

DISCOVER

Understanding stormtime geospace as a complex system: Recent progress from the Center for Geospace Storms

Slava Merkin & CGS team

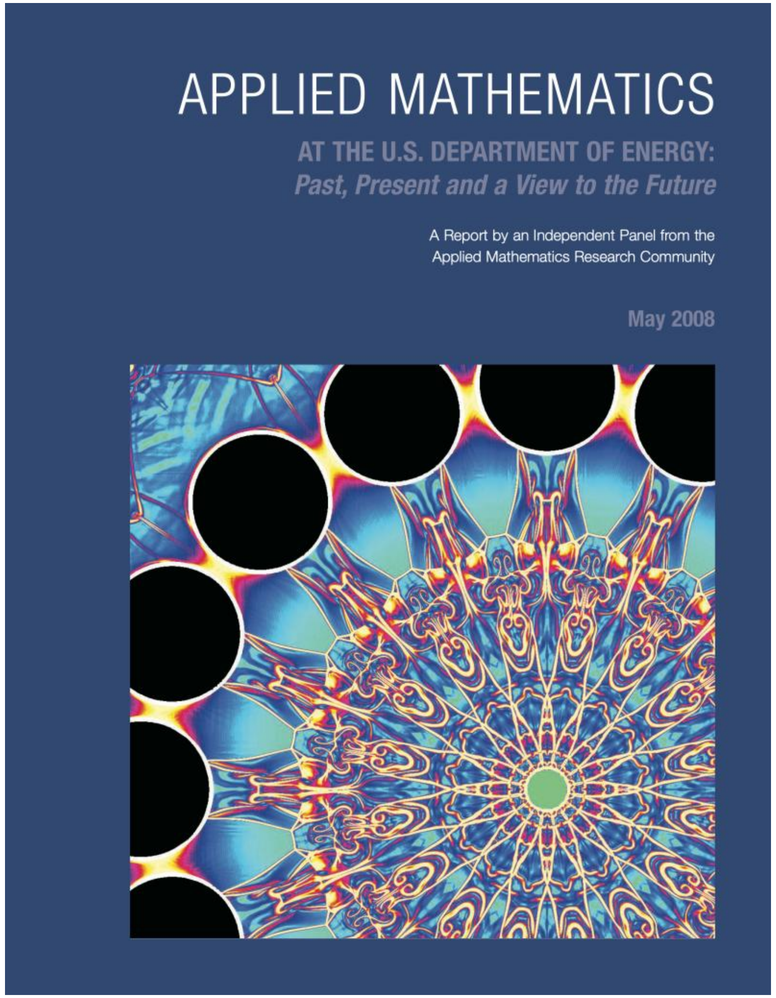
JOHNS HOPKINS APPLIED PHYSICS LABORATORY / NATIONAL CENTER FOR ATMOSPHERIC RESEARCH / RICE UNIVERSITY
UNIVERSITY OF CALIFORNIA, LOS ANGELES / SYNTEK TECHNOLOGIES / UNIVERSITY OF NEW HAMPSHIRE / VIRGINIA TECH

CGS

What is a complex system?

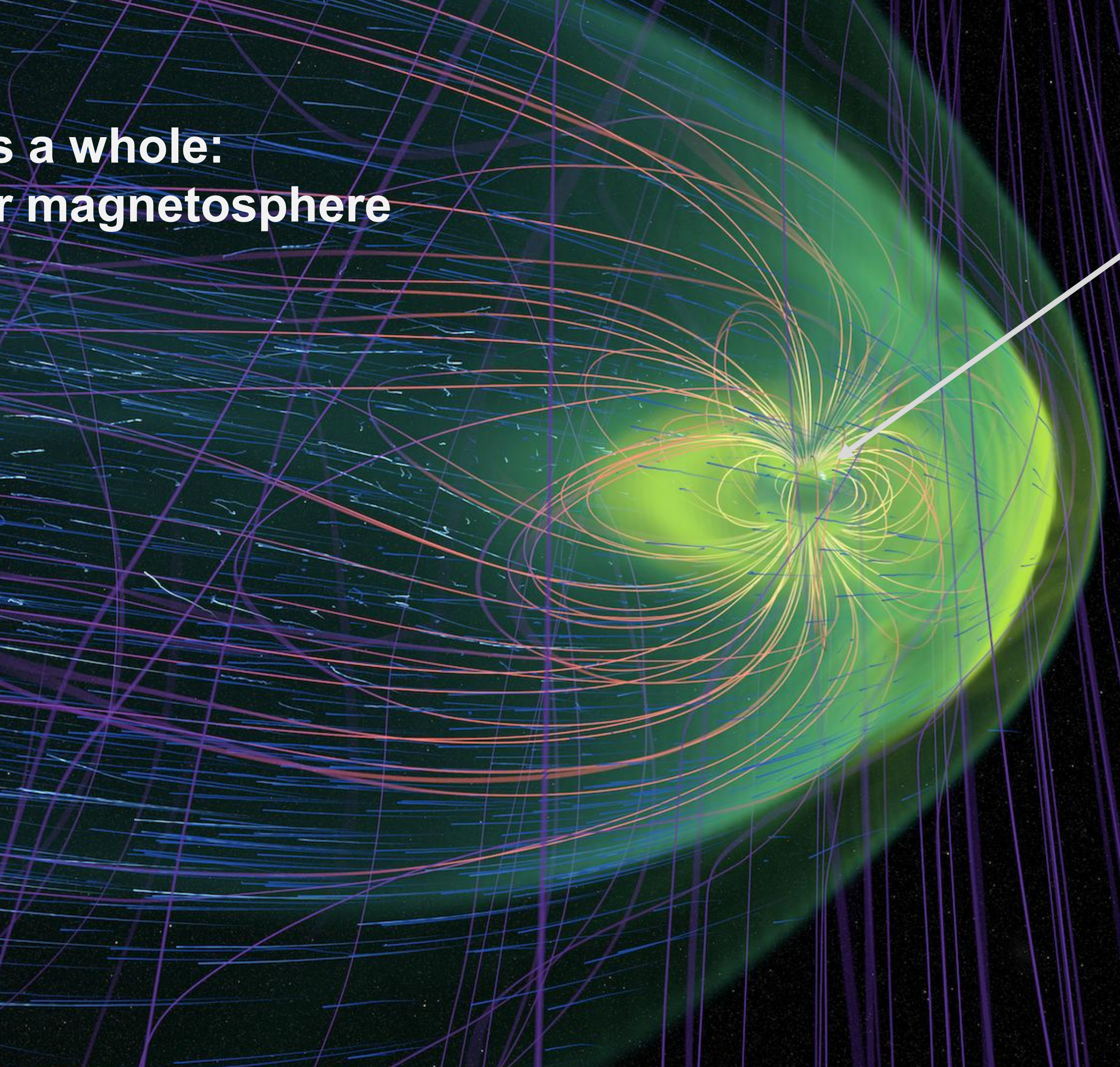
“A ***complex system*** is a collection of multiple processes, entities or nested subsystems where the overall system is difficult to understand and analyze because of the following properties:

- The system components do not necessarily have mathematically similar structures and may involve different scales in time or space.
- The number of components may be large, sometimes enormous;
- Components can be connected in a variety of different ways, most often nonlinearly and/or via a network. Furthermore, local and system-wide phenomena may depend on each other in complicated ways;
- The behavior of the overall system can be difficult to predict from the behavior of individual components.
- Moreover, the overall system behavior may evolve along qualitatively different pathways that may display great sensitivity to small perturbations at any stage.”



Geospace is a *complex* system

It is strongly coupled across domains and scales



Treat geospace as a whole:
- Inner and outer magnetosphere
- Ionosphere
- Thermoshere
- Atmosphere

"The tyranny of scales"

Incomplete physics

Missing parameterizations

Poorly constrained initial & boundary conditions

Characterizing and predicting this system entirely from first principles is not possible

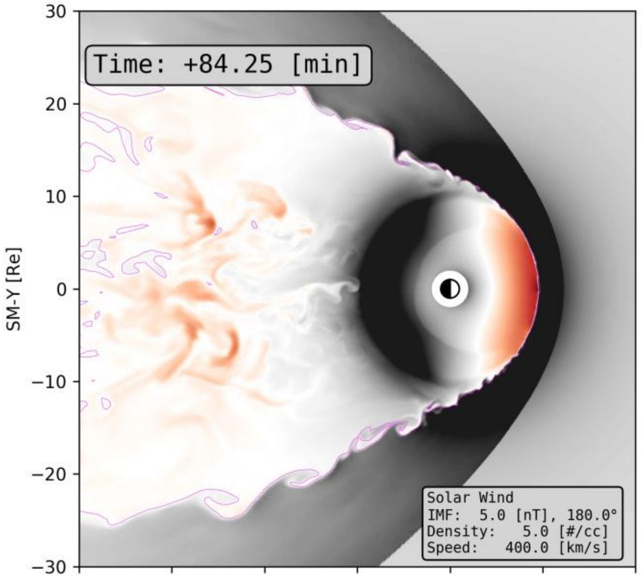
Credit: MAGE model simulation by CGS, animation by NASA/SVS

Geospace is a complex system (multi-scale and multi-physics)

The complexity of the underlying physics defines the challenge of space weather prediction

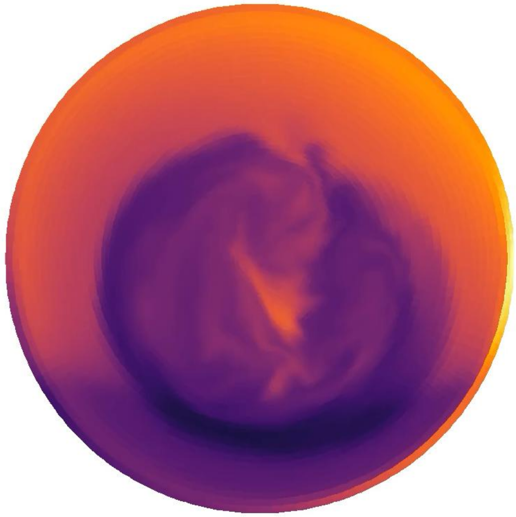
- Because of collective cross-scale interactions in stormtime geospace, understanding and predicting space weather requires models that **treat geospace as a whole**.
- **Mesoscale processes are important** because they lead to "emergent" global behavior.
- A “whole geospace model” must include **two-way coupling to the lower atmosphere**.

Magnetosphere



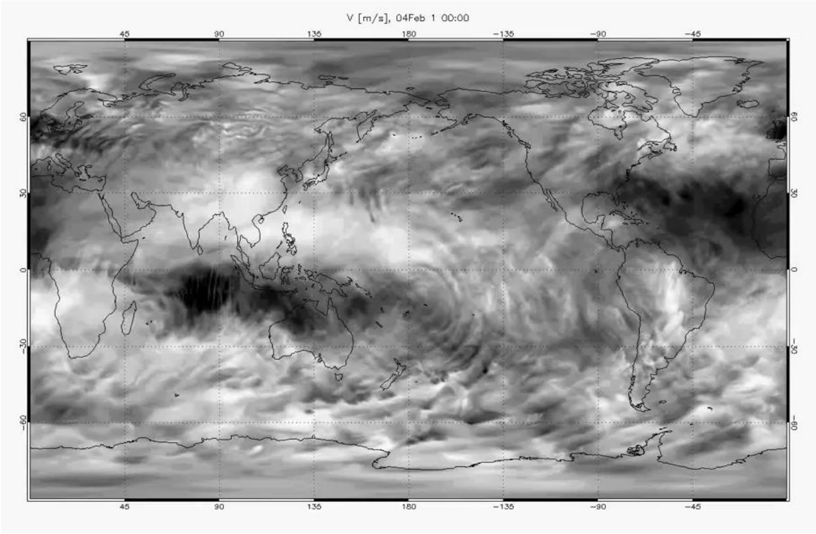
~0.1–300 Re

Ionosphere-Thermosphere



70–1,000 km

Lower & Middle atmosphere

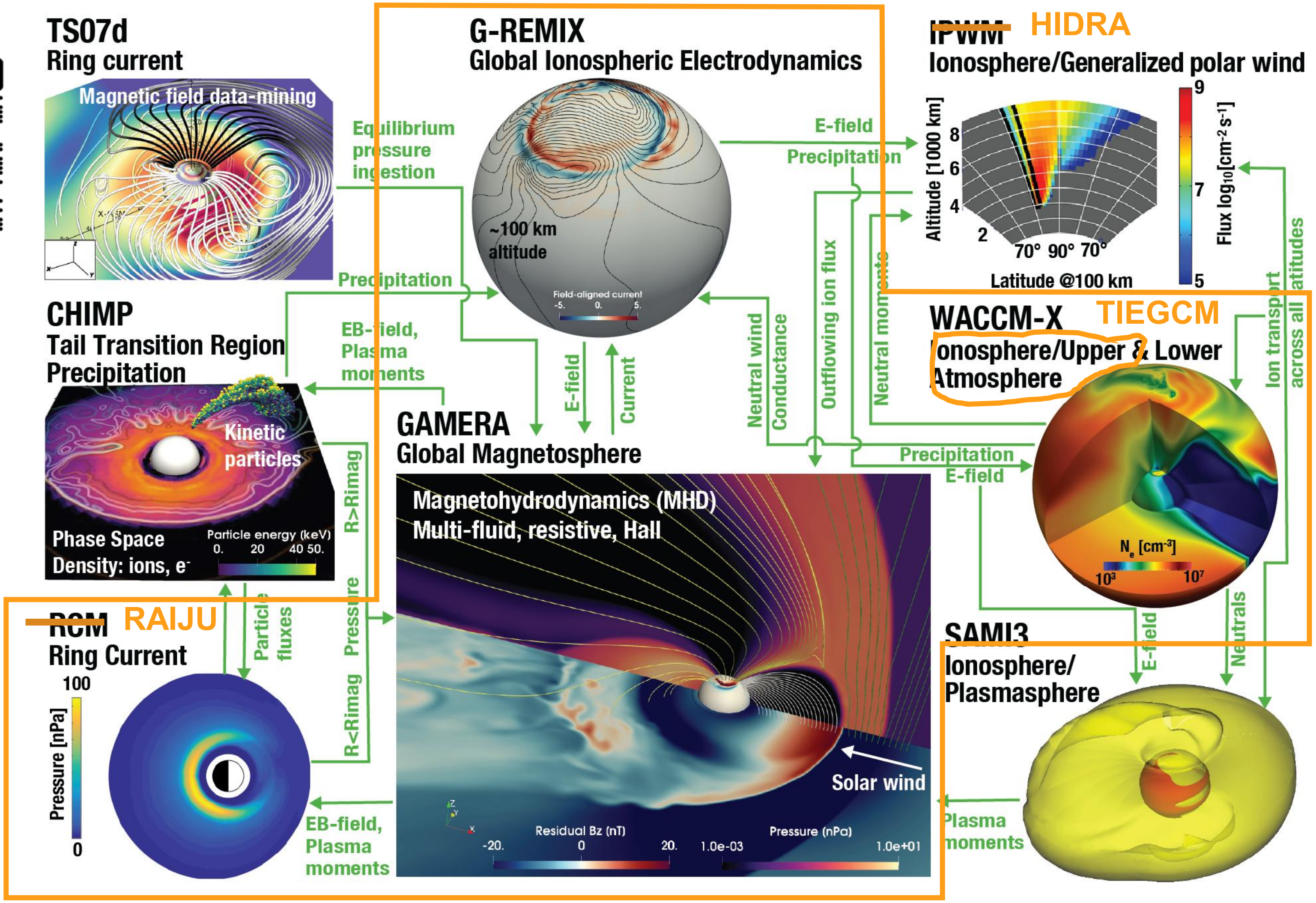


0-70 km

Multiscale Atmosphere-Geospace Environment (MAGE)

Current status and longer-term vision

- MAGE 0.75 (GAMERA+REMIX+RCM)
  - Available for runs on request at the NASA CCMC
- MAGE 1.0 (GAMERA+REMIX+RCM*+ TIEGCM)
  - Science production since 2020
  - Delivered to CCMC
  - Expect runs on request and OSS release **this month**
- Open-source post-processing and analysis suite
  - `pip install kaipy`

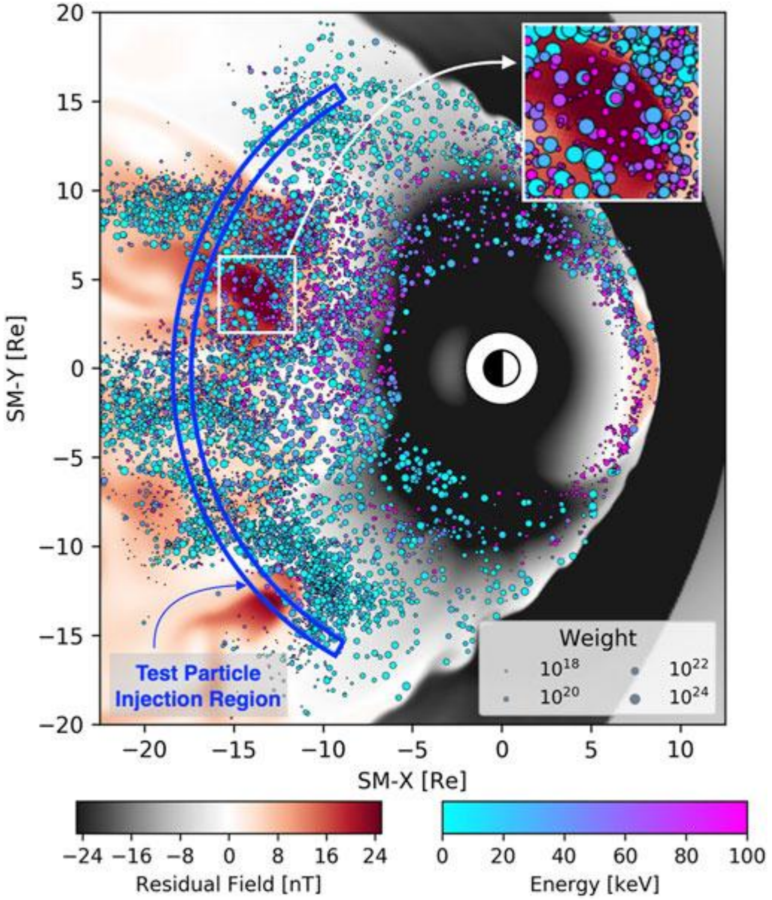


cgs.jhuapl.edu/Models

CGS Science Themes

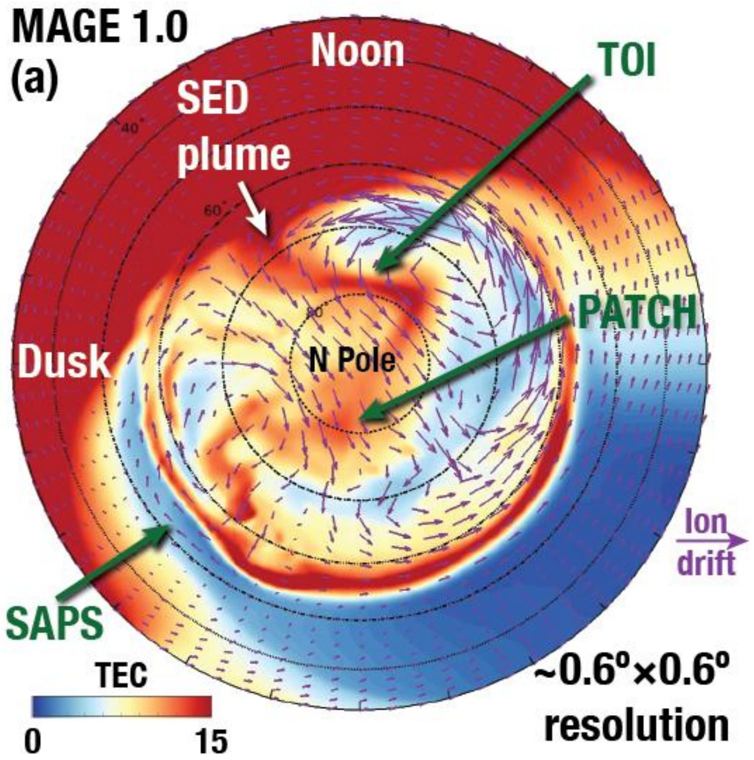
Mesoscale processes with global-scale consequences

Multiscale ring current build-up



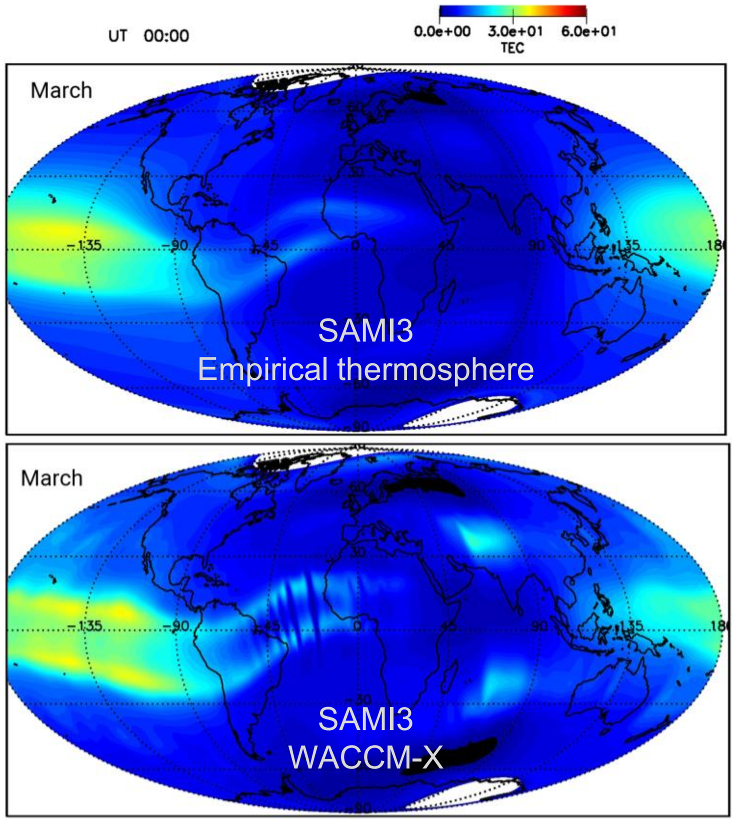
Sorathia et al. (2021)
Sciola et al. (2023)

Mesoscale ionospheric structure



Lin et al. (2021, 2022)
Bao et al. (2023)
Albarran et al. (2024)

Lower atmosphere-ionosphere coupling

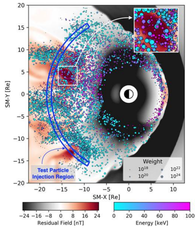


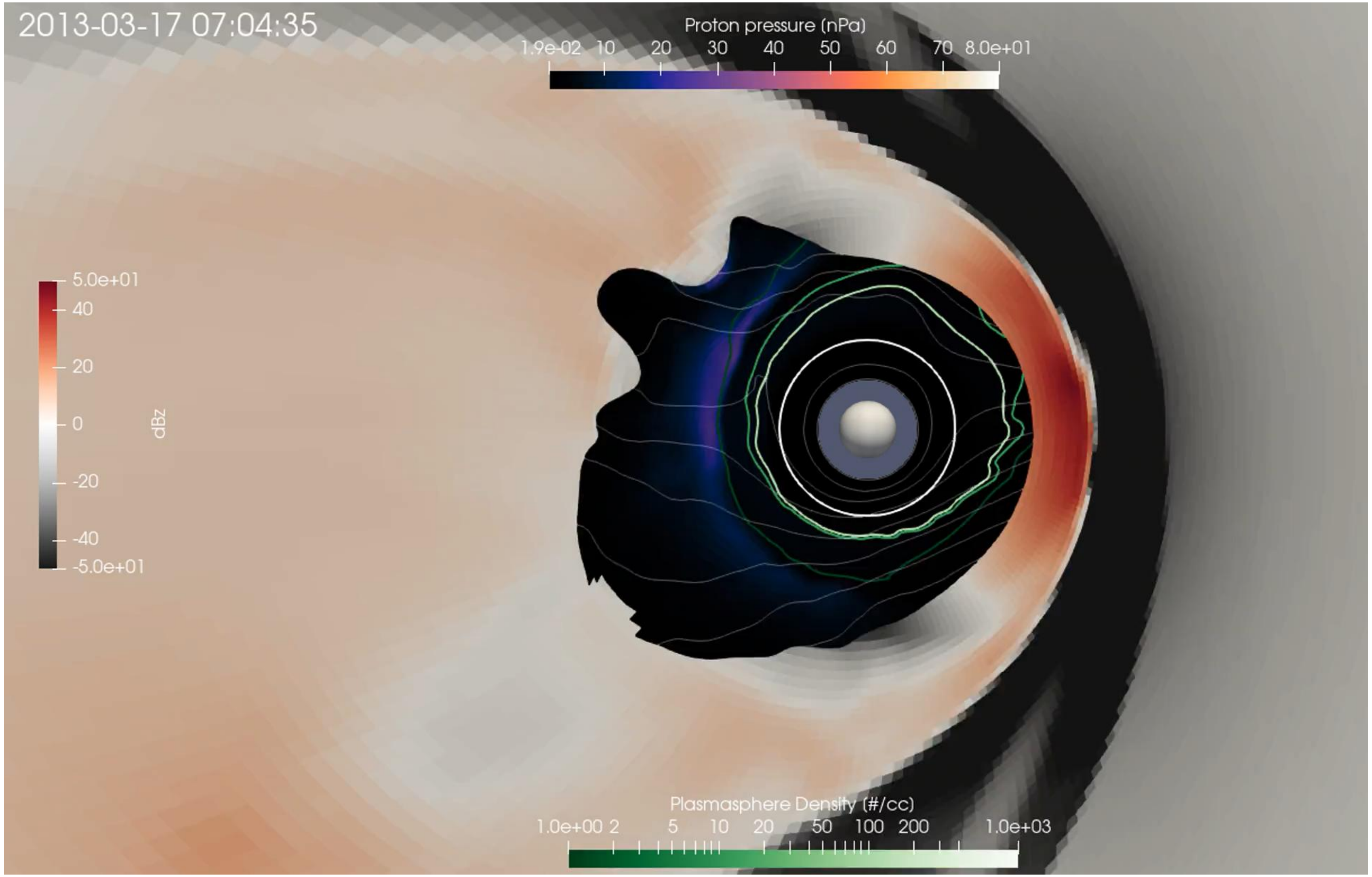
Huba & Liu (2020, 2023)
Huba & Lu (2024)

Modeling of the inner magnetosphere

Drift-kinetic inner magnetosphere coupled with global MHD outer magnetosphere

Science Theme 1

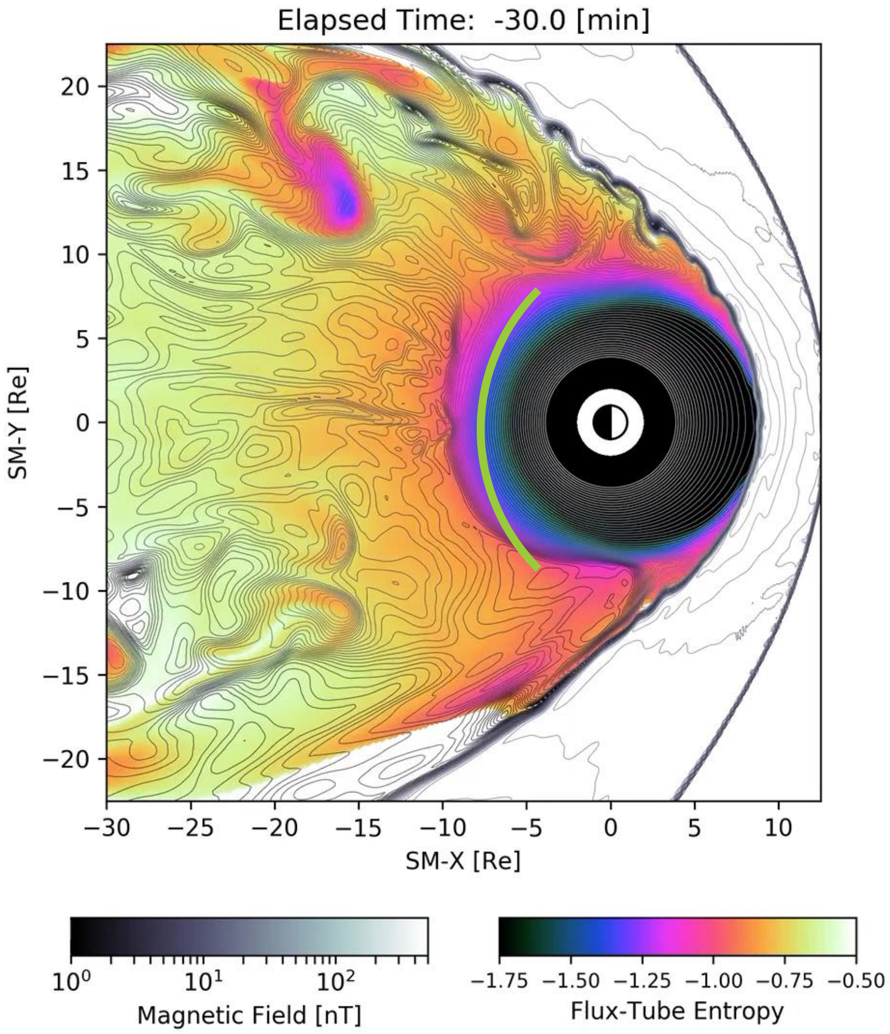


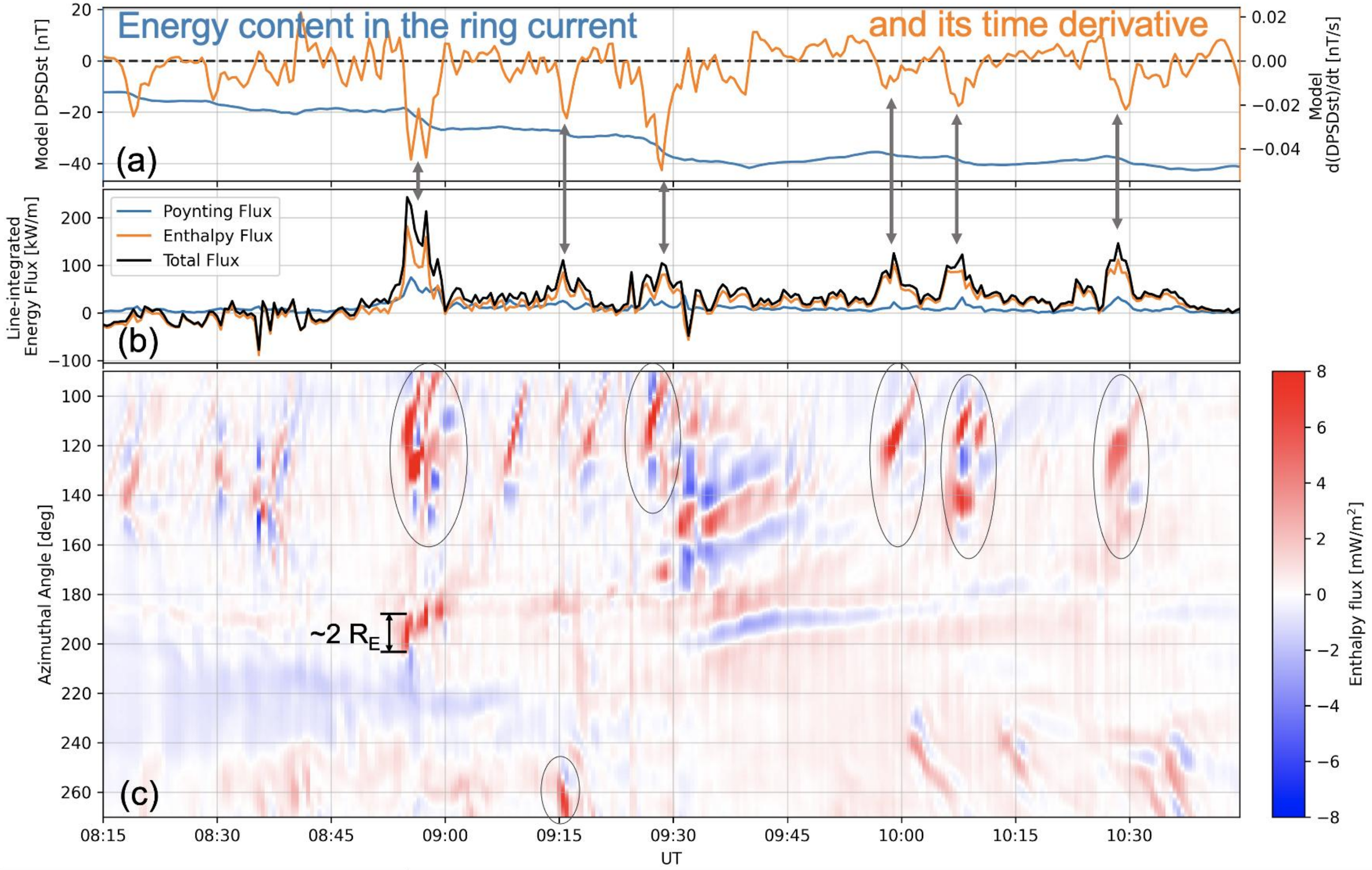


Sciola et al., 2025, in prep

Storm-time Ring Current Build-Up via Mesoscale Transport

~50% ring current buildup comes from mesoscale plasma sheet flows



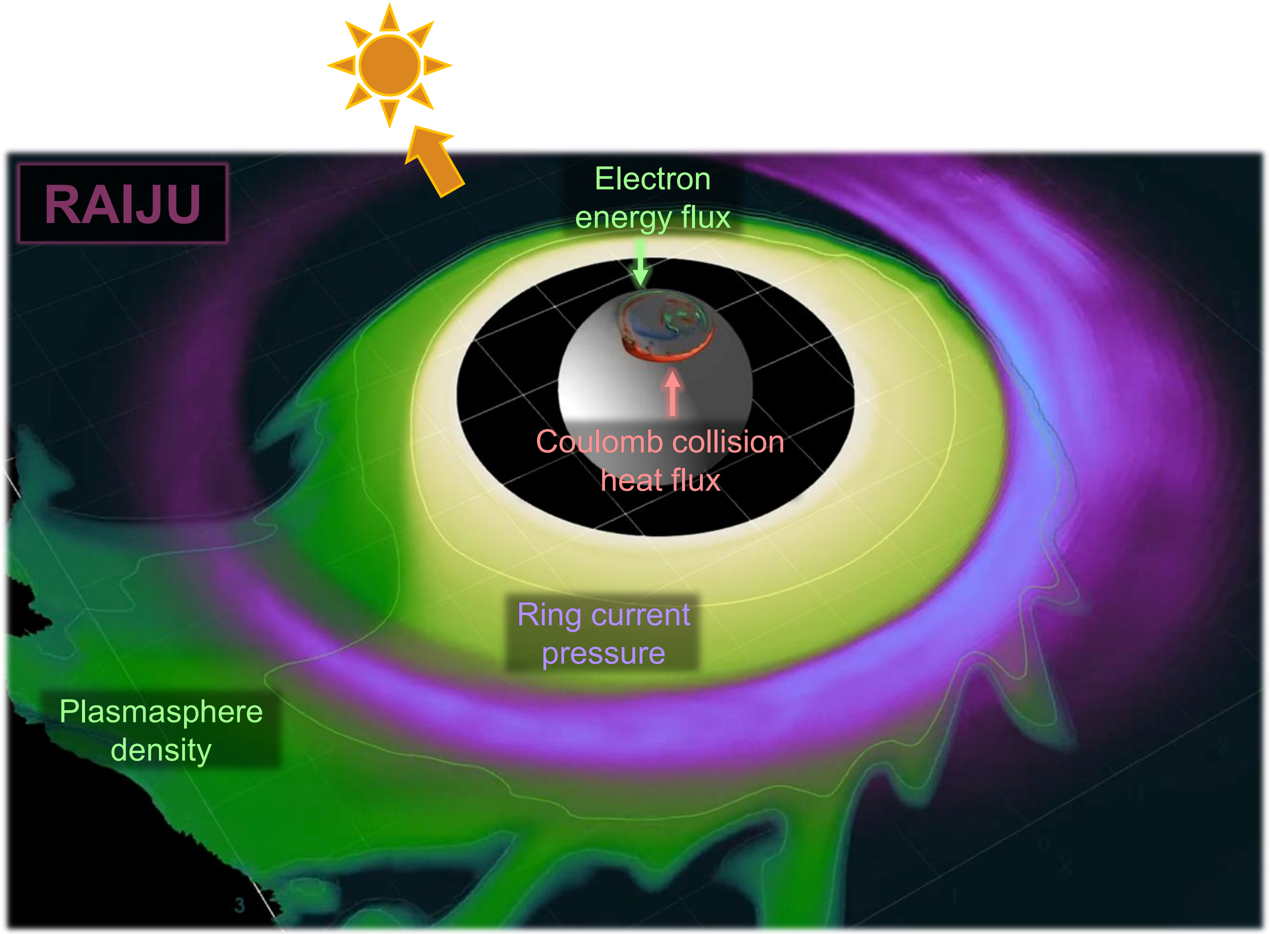


Sciola et al. (2023; JGR, doi: 10.1029/2023JA031693)

Ring current Advection Integrated over J and μ (RAIJU)

Drift-kinetic inner magnetosphere model

- Inherits physical and mathematical formulation from the Rice Convection Model (RCM)
- Completely rewritten model infrastructure and core solver
- Very high ionospheric grid resolution (17 km in latitude and 0.5 deg in longitude), enables resolution of the magnetospheric drivers of structured auroral phenomena (e.g., omega bands, giant auroral undulations, etc.)
- Flexible mapping between GAMERA and RAIJU fluids enables better handling of plasmasphere and solar wind H+, inclusion of O+
- Energy-resolved precipitation allows for more accurate calculation of conductance and aurora spectra

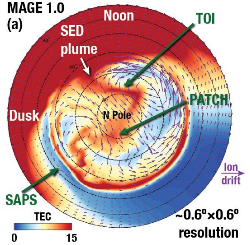


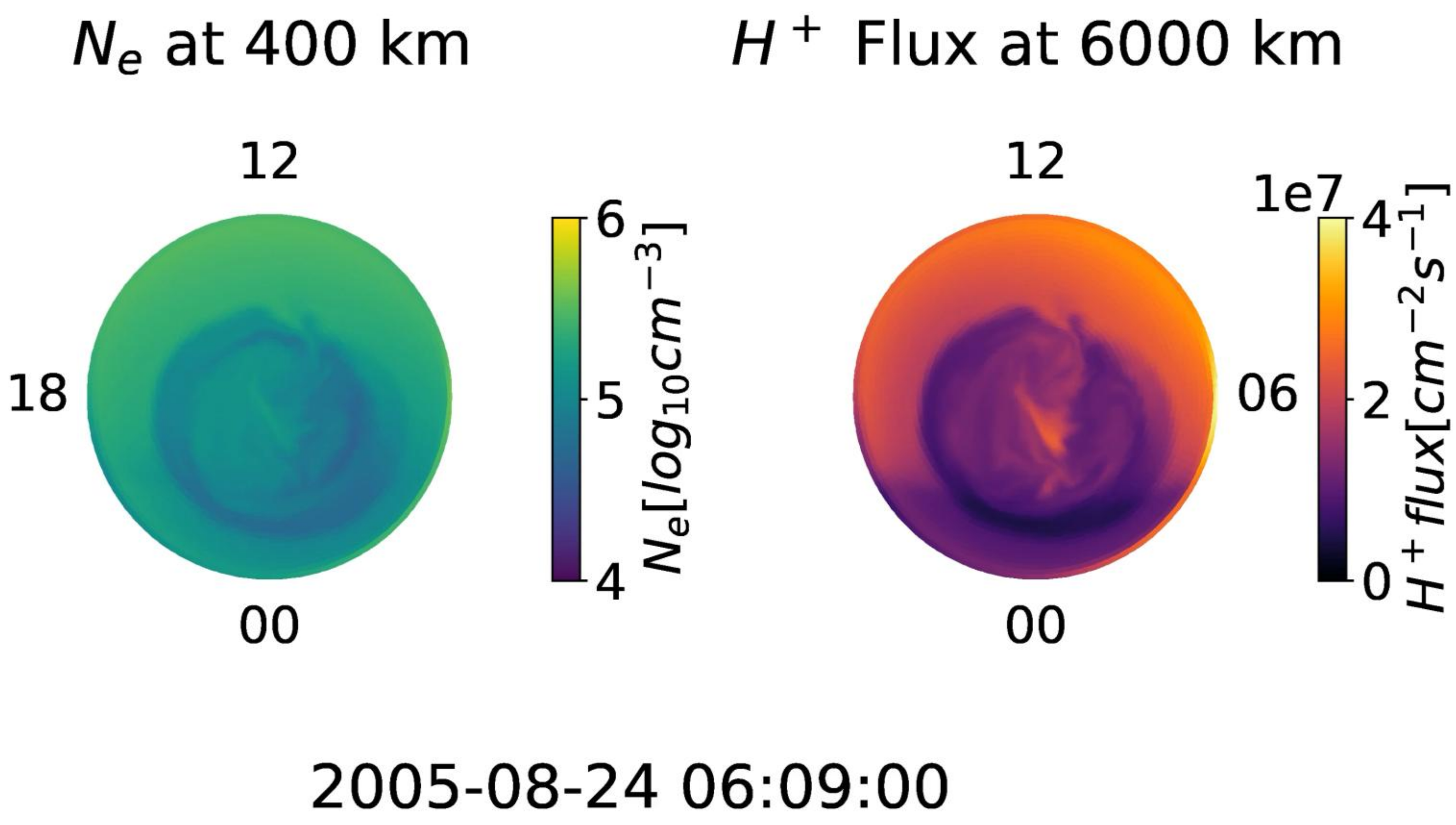
Sciola et al., 2025, in prep

High-resolution simulations of polar ionosphere

High-Latitude Ionosphere Dynamics for Research Applications (HIDRA)

Science Theme 2





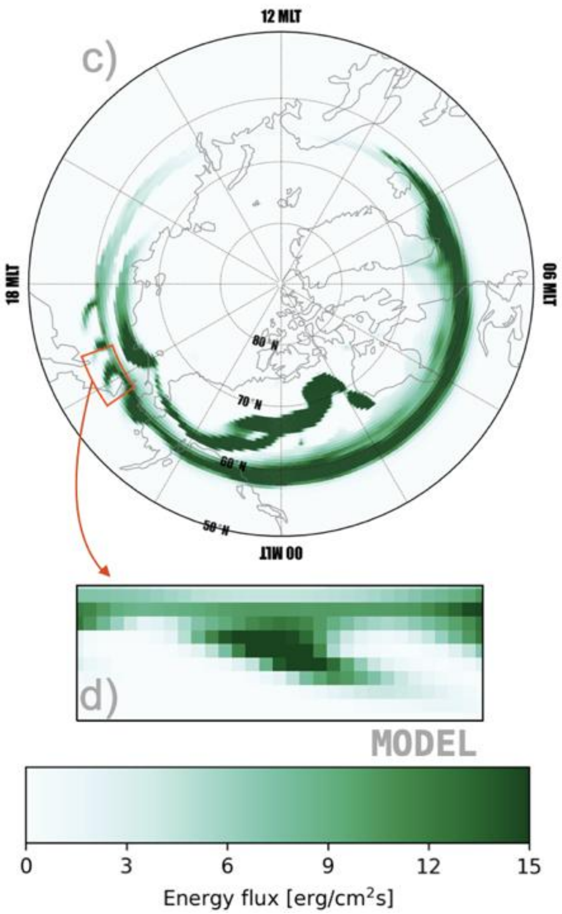
Video courtesy R. Varney (UCLA)

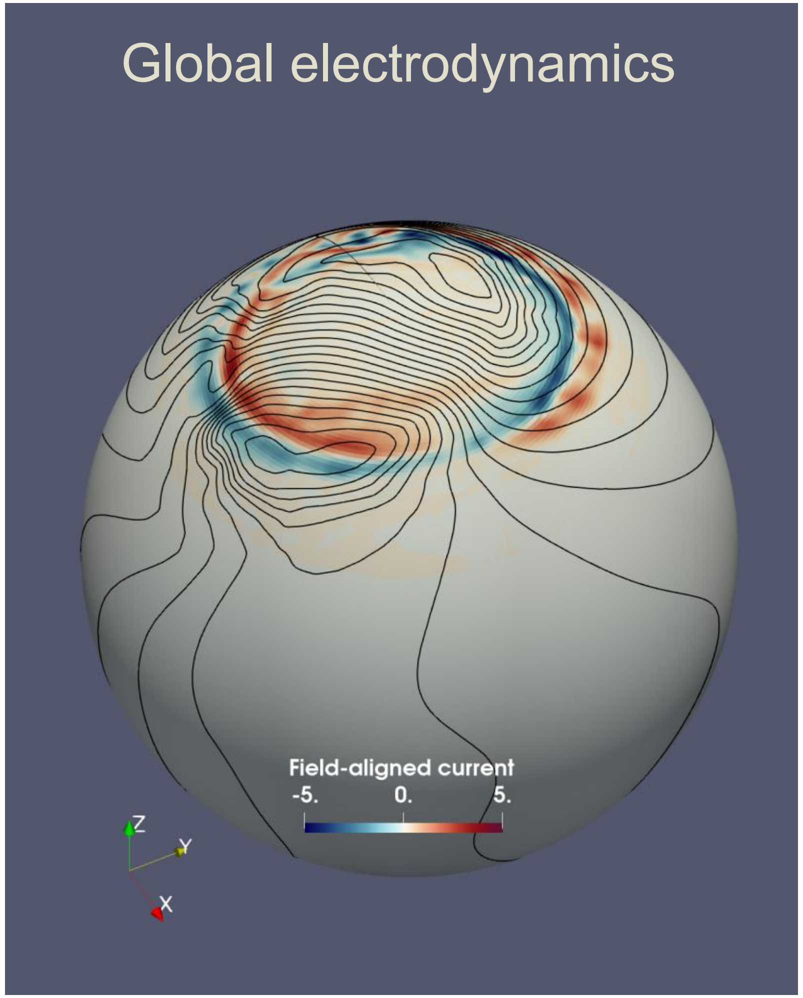
- Convection and precipitation from a high-resolution MAGE simulation of 2005-08-24 CME-Storm (Pham et al. 2021)
- Tongues of ionization & Polar Cap Patches: Mesoscale F-region density structures (Crowley, 1996; Foster et al., 2000)
- Propagating Polar Wind Jets: Mesoscale polar wind outflow structures (Schunk et al., 2005).

Some nascent challenges we are addressing

Focus on magnetosphere-ionosphere-thermosphere coupling

Energetic particle precipitation





Global Geospace Modeling of Aurora

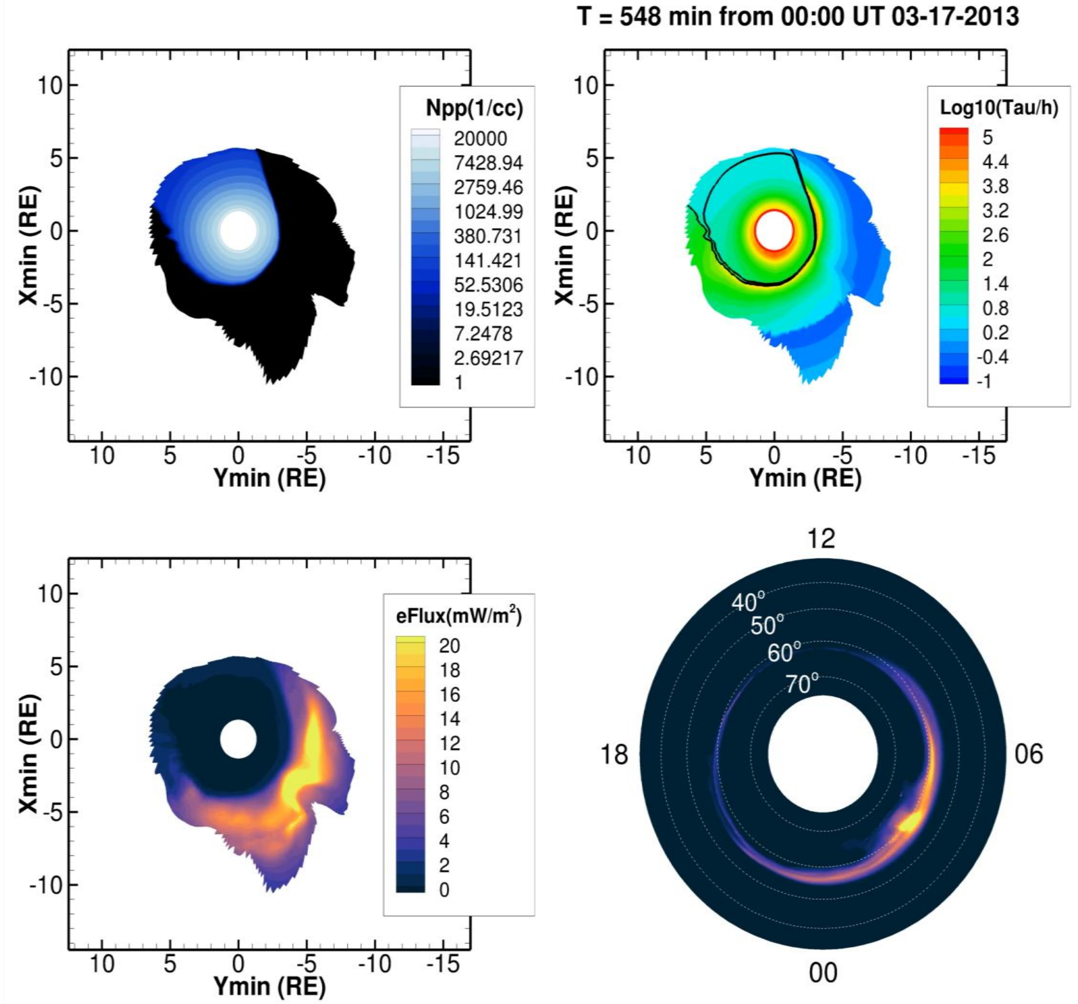
A quintessential multi-scale geospace process

Plasmasphere

- Plasmasphere "cold" channel using Gallagher initial condition in RCM
- Refilling using empirical model (Denton+ 12)
- Dynamically evolves with self-consistent electrostatic potential

Three critical elements

- Plasmasphere
- Wave/Electron lifetime model
- Electron transport model



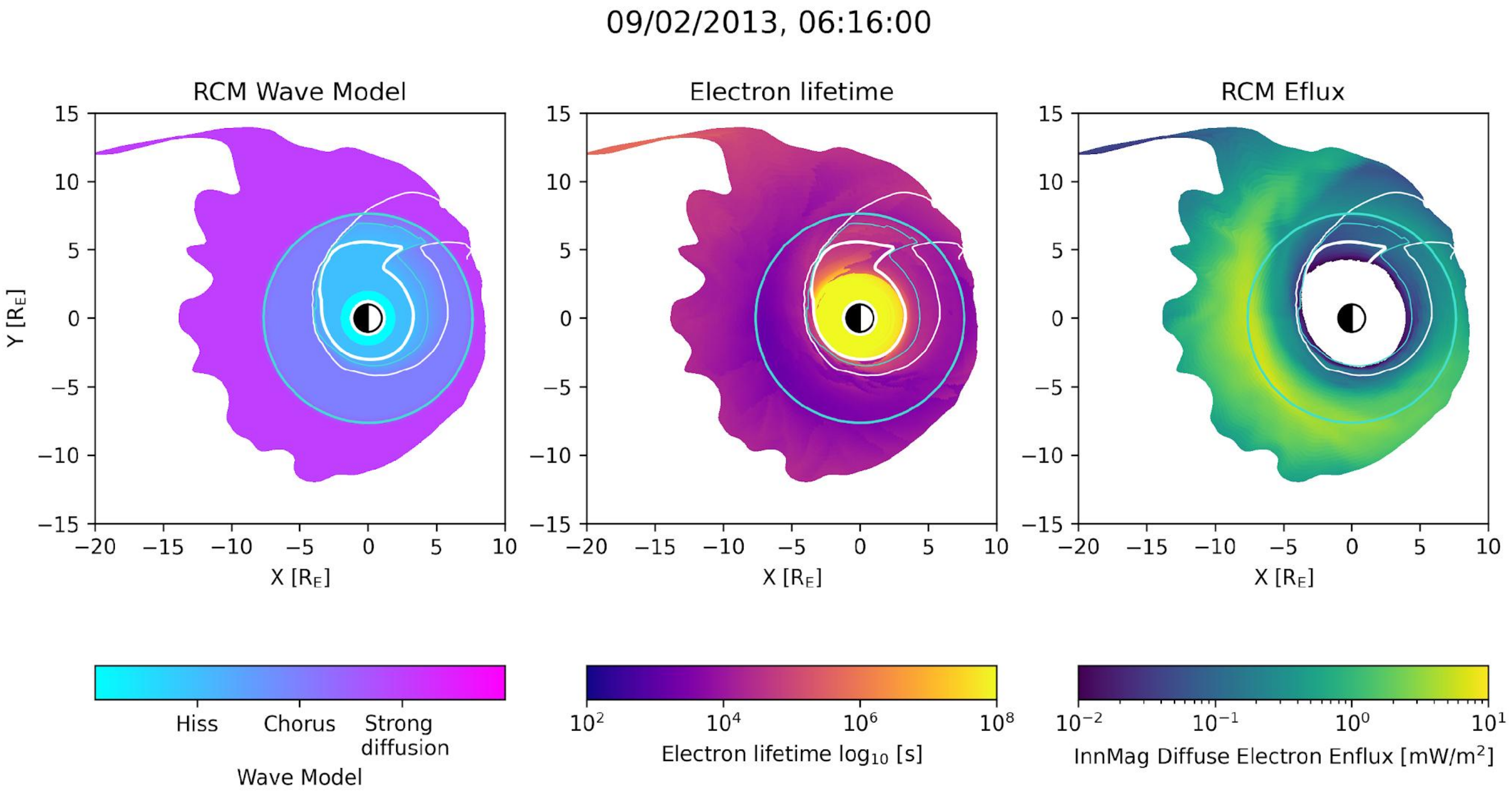
Lin, Bao, et al., 2025, in prep

Global Geospace Modeling of Aurora

A quintessential multi-scale geospace process

MAGE precipitation (Dragon King)

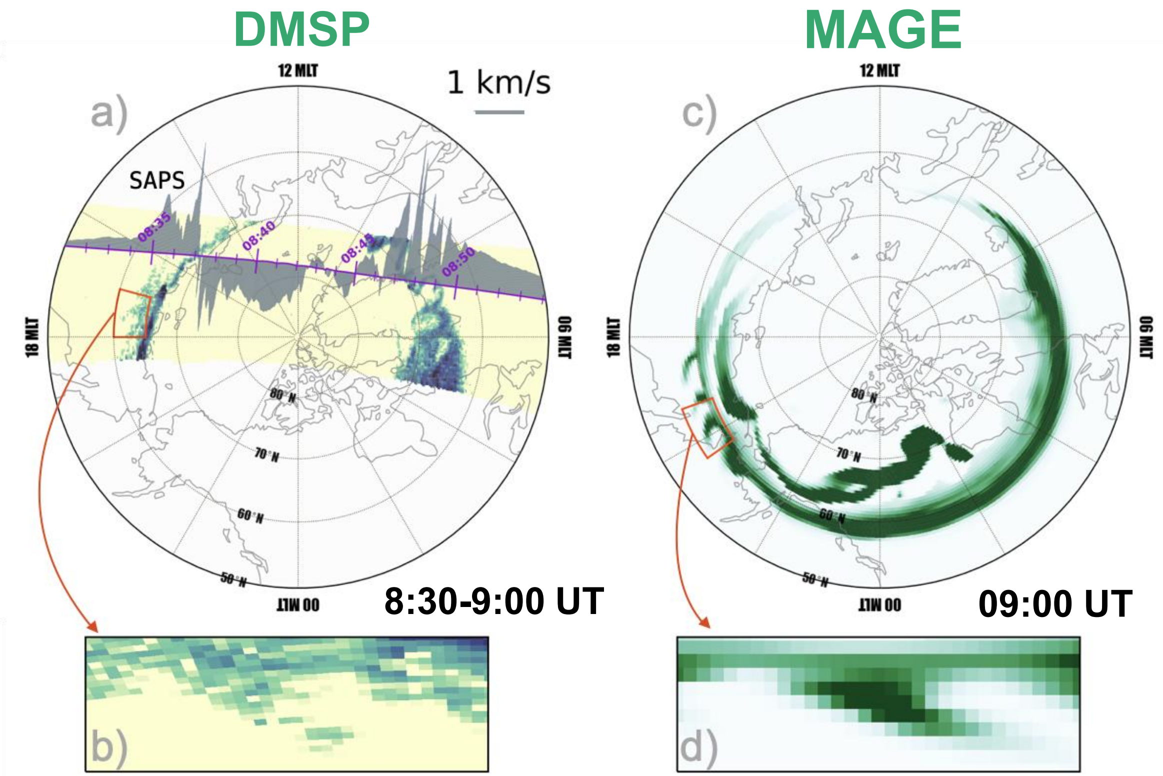
- Use empirical lifetime models (due to pitch-angle diffusion) to inform electron losses in RCM
- Chorus (Wang+ ’24) and hiss (Orlova+ ’14)
- Dynamic plasmapause location sets boundary between wave populations (Chen+ ’19)
- Integrate mono-energetic from GAMERA (Zhang+ ‘15) and diffuse electron precipitation from RCM (Lin+ ’21)
- Direct cusp entry, broad-band in the works

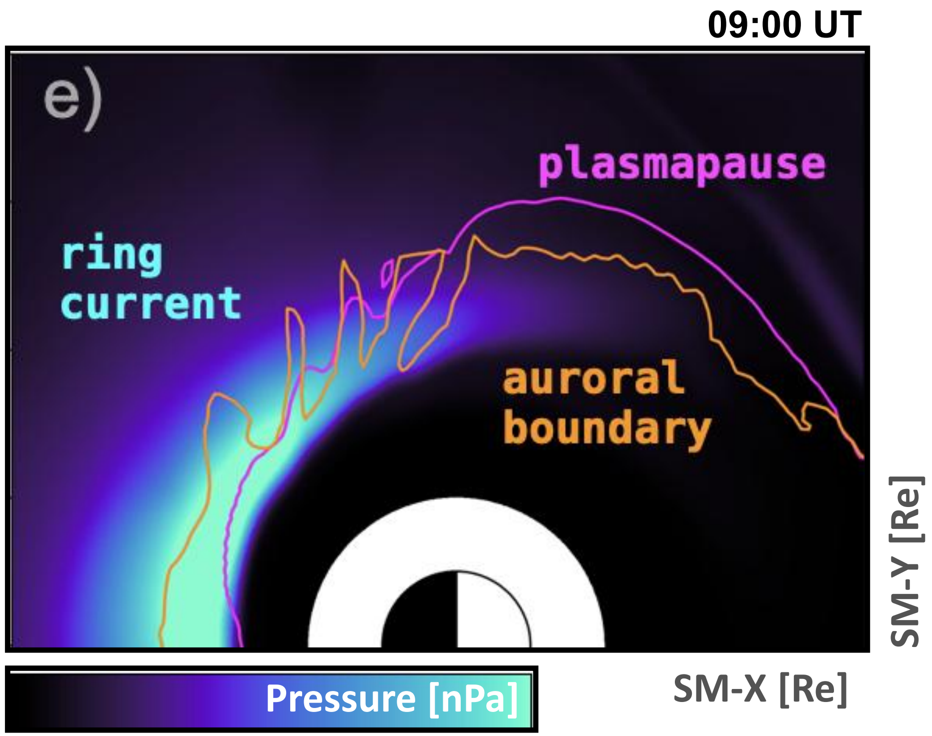


Lin, Bao, et al., 2025, in prep

Global Geospace Modeling of Aurora

Auroral Giant Undulations

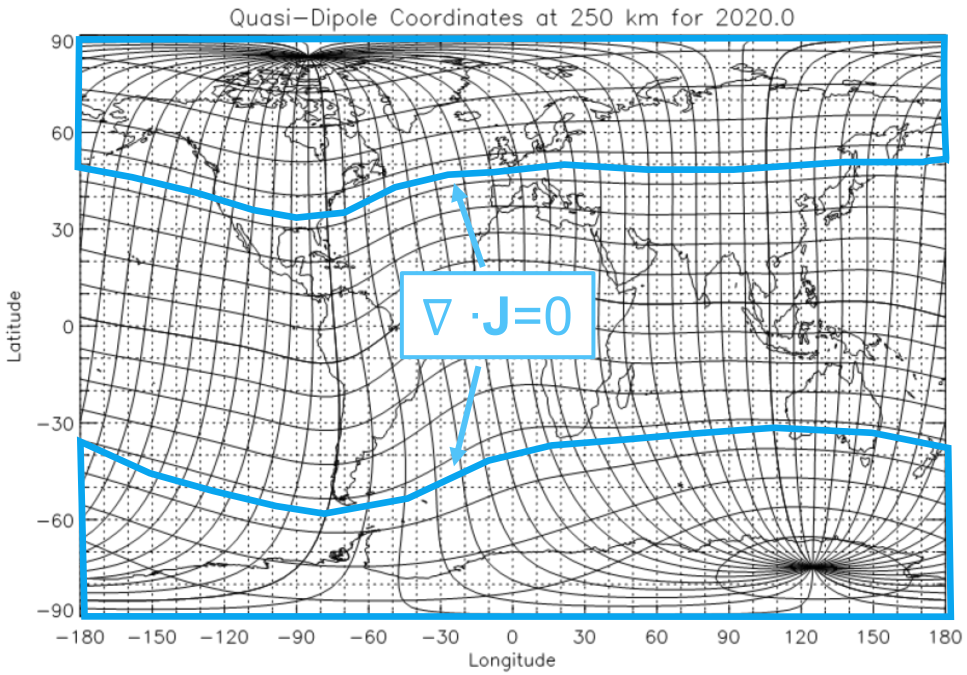




- Very similar morphology between data/model
- Different time/location (but similar)
- Different quantity, LBHS vs. electron energy flux

- Matching auroral and plasmapause undulations
- Interchange unstable configuration
- Ring current inward of equatorward auroral boundary
- SubAuroral Polarization Stream (SAPS)

Global (pole-to-pole) electrodynamics



High latitude region

Low latitude region

High latitude region

Low latitude region:
- **E**·**B**=0 (in 3D)
- **E**=-∇Φ (in 3D)
- J|| calculated
- B0 conjugacy

lumped

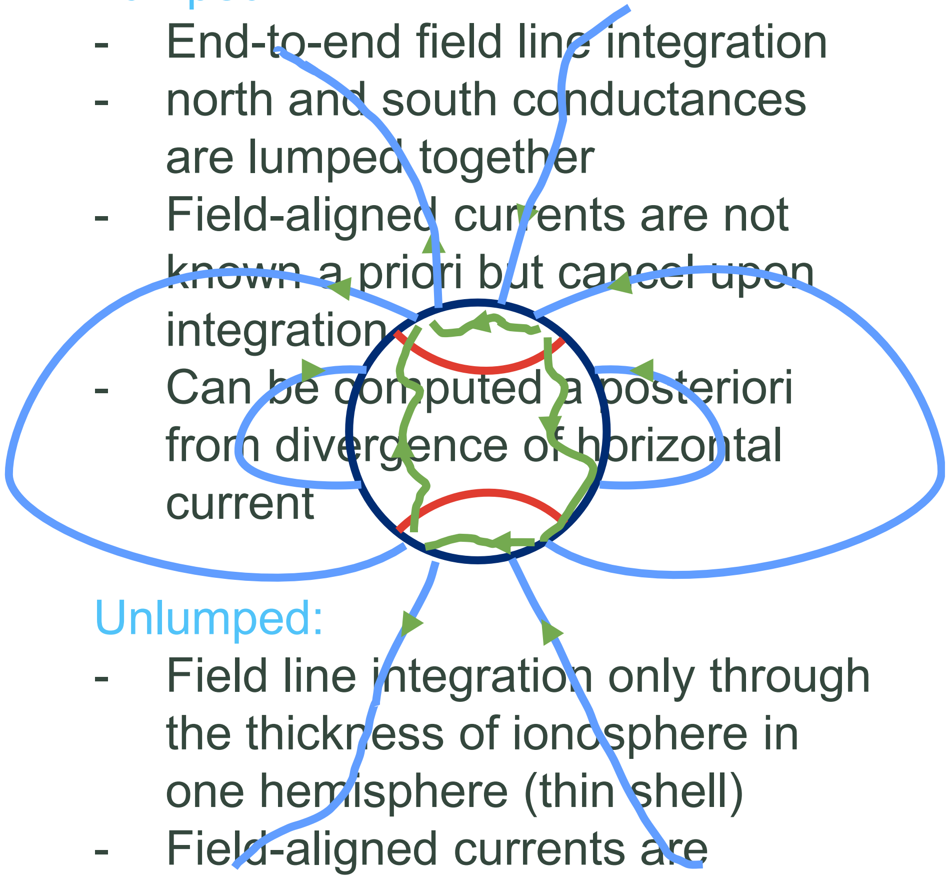
High latitude region:
- **E**·**B**=0 (in 3D)
- **E**=-∇Φ (only inside ionosphere)
- J|| prescribed
- No conjugacy

unlumped

∇·[Σ·(-∇Φ+uxB)]=J||

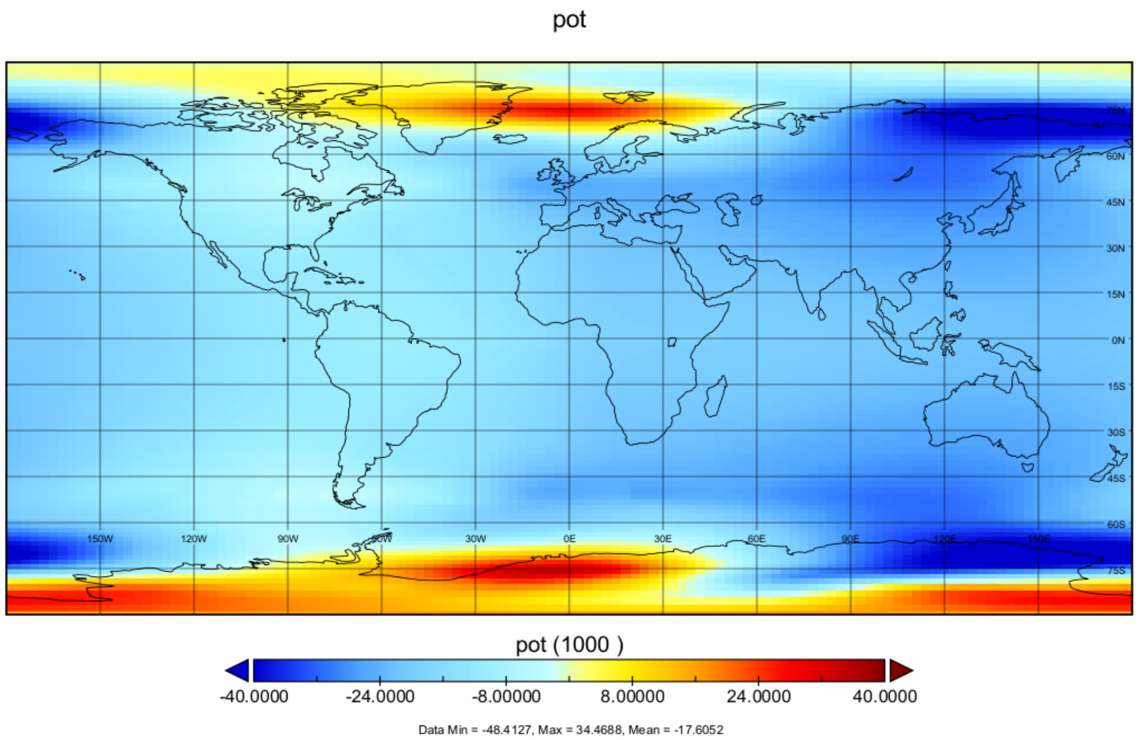
Lumped:
- End-to-end field line integration
- north and south conductances are lumped together
- Field-aligned currents are not known a priori but cancel upon integration
- Can be computed a posteriori from divergence of horizontal current

Unlumped:
- Field line integration only through the thickness of ionosphere in one hemisphere (thin shell)
- Field-aligned currents are assumed to be known

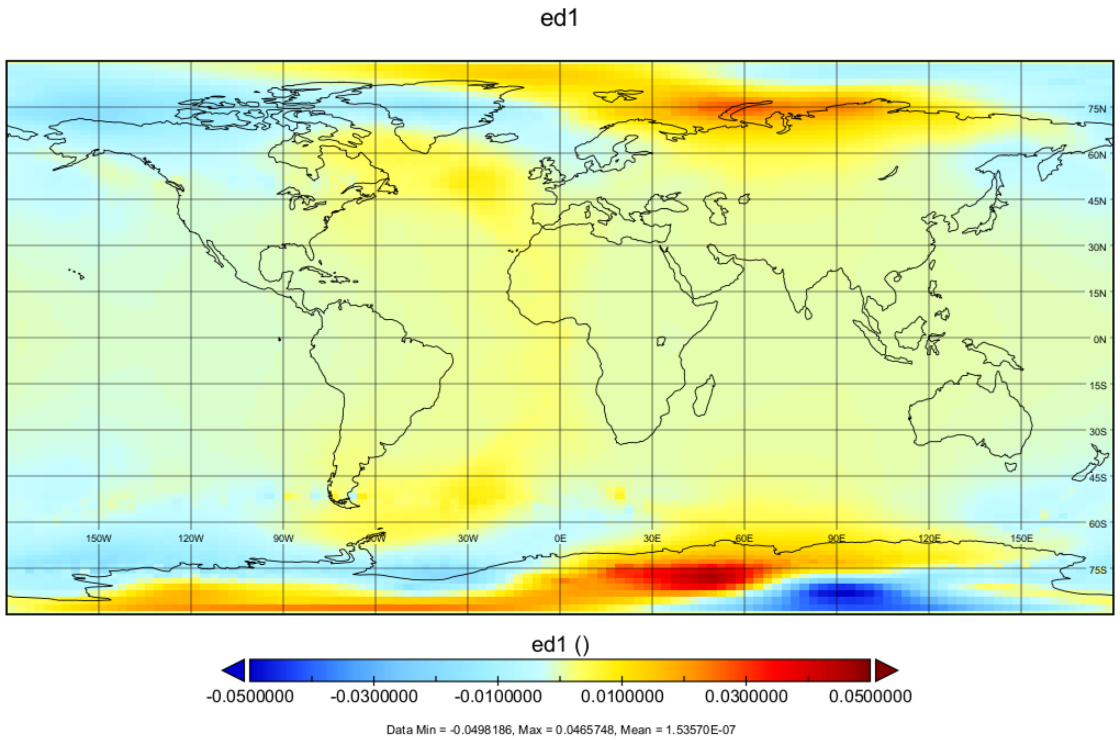


Global (pole-to-pole) electrodynamics

Potential



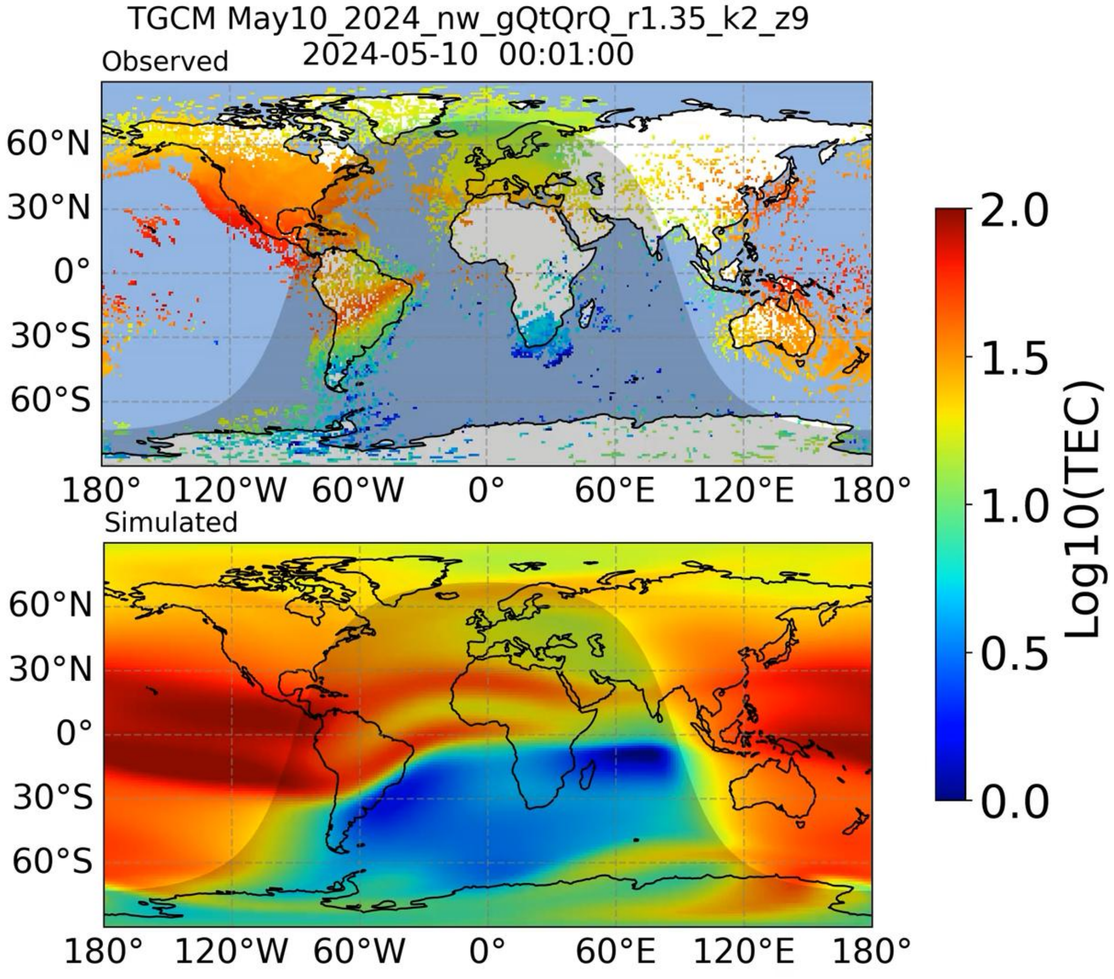
Zonal electric field



Work by Haonan Wu, A. Maute, A. Richmond (NCAR/HAO)

Summary

- CGS is discovering the fundamental physics of solar storm impacts on geospace
- CGS is building the Multiscale Atmosphere-Geospace Environment (MAGE) model
  - MAGE 0.75 available at CCMC
  - MAGE 1.0 is a fully coupled magnetosphere-ionosphere-thermosphere model
  - Slated for OSS release this month
- Some MAGE highlights
  - Ring current build-up requires capturing mesoscale transport in the magnetotail
  - Realistic global geospace modeling of aurora (e.g., giant auroral undulations)
  - Innovative inner magnetosphere model (extremely high spatial and energy resolution)
  - New, high-resolution model of the polar ionosphere (Polar cap patches, tongues of ionization, polar wind jets, etc)
  - Global, pole-to-pole ionospheric electrodynamics (SAPS, penetration electric fields, etc)



Pham et al., 2025, in prep


CGS
CENTER FOR
GEOSPACE STORMS

EZIE OSSE

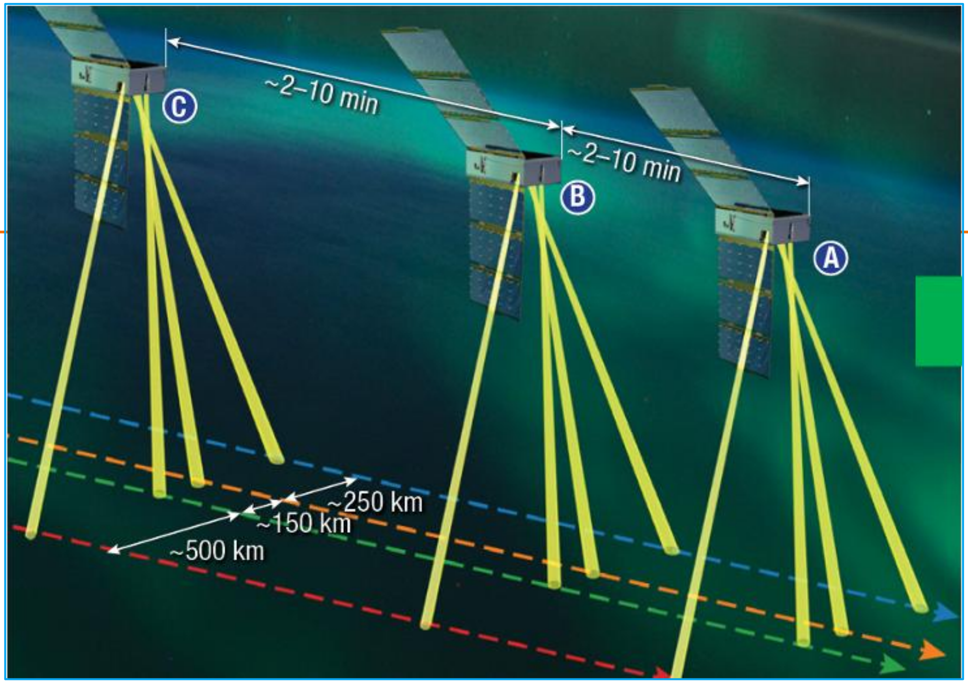
OSSE Step 1: Global MHD Simulations

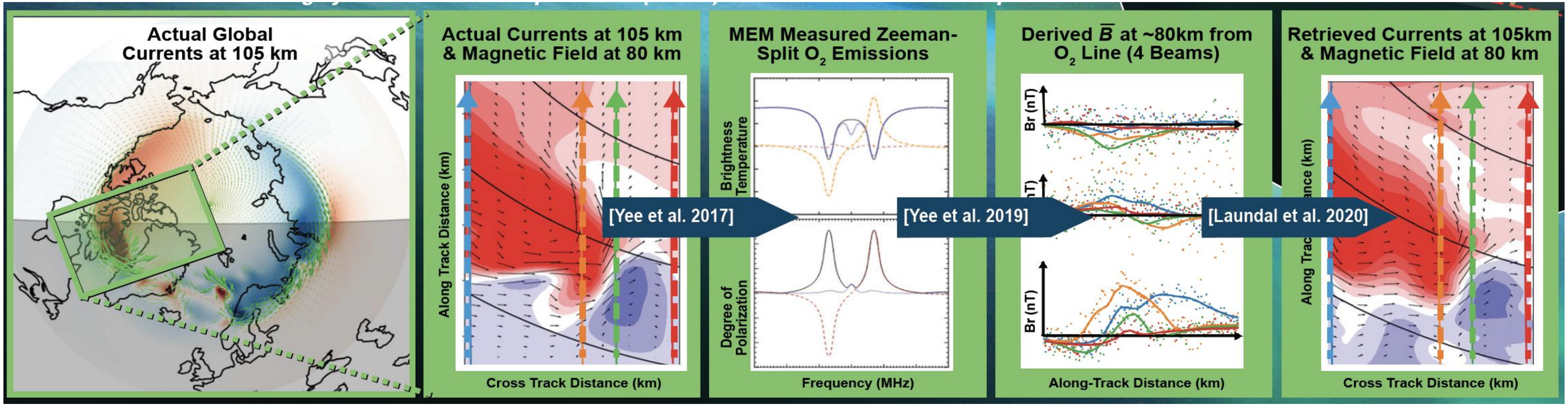
OSSE Step 2: Observation Event Simulations

OSSE Step 3: Observed Radiances Simulations

OSSE Step 4: Vector B-Fields Retrievals

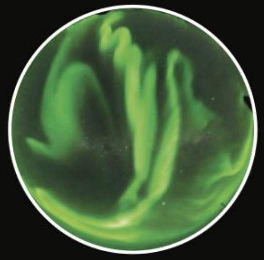
OSSE Step 5: Current Retrievals



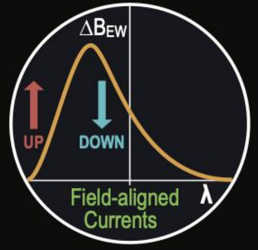


CINEMA’s nine CubeSat constellation and powerful instrument suite add a ground-breaking capability to NASA’s fleet, solving a longstanding mystery about Earth’s magnetosphere.

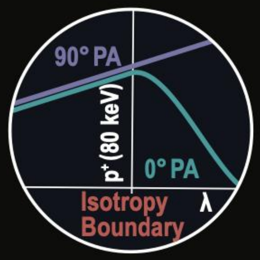
What determines when and how the magnetosphere explosively releases its stored energy?



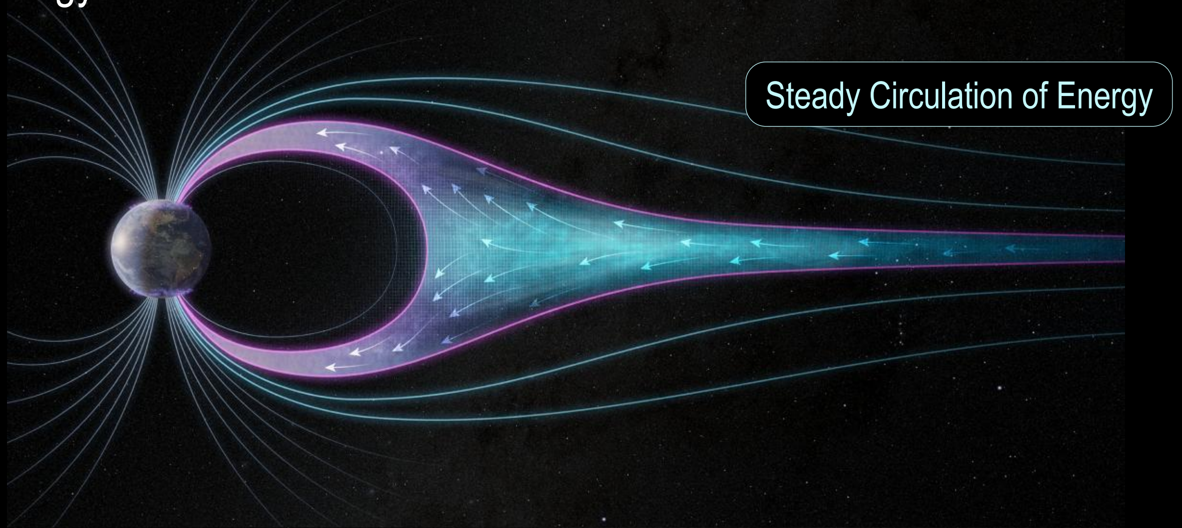
AIM:
Auroral Imaging

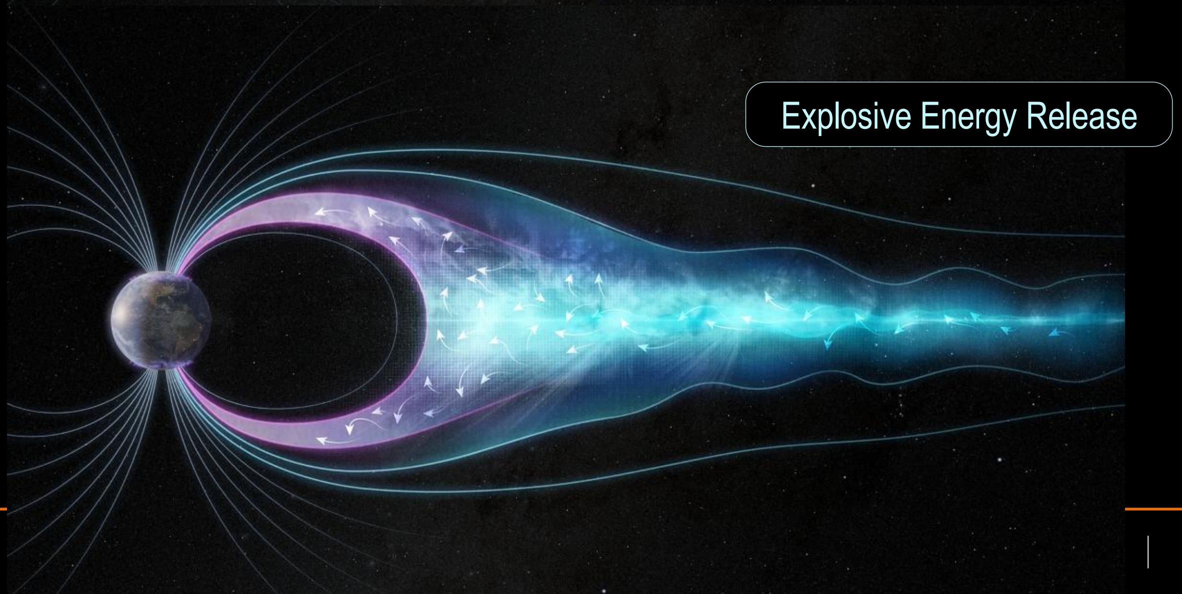


MAGNET:
Magnetometers



PARSEL:
Energetic Particles





CINEMA OSSE

Adam Michael (JHUAPL)