Advancing Space Weather Forecasting through Artificial Intelligence: The AIMFAHR Project

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Abstract

Artificial **I**ntelligence **M**odeling Framework **F**or **A**dvancing **H**eliophysics **R**esearch (**AIMFAHR**) is an initiative aimed at integrating community-wide AI efforts into a unified AI modeling framework, advancing system-of-systems science in Sun-Earth interactions and enhancing the predictability of space weather hazards.

The AIMFAHR project selected AI-based models of magnetopause reconnection, cusp dynamics, auroral precipitation, field-aligned currents (FACs), ionospheric electrodynamics, thermospheric density, and ground magnetic fields as the initial modeling suite to simulate geomagnetic storms.

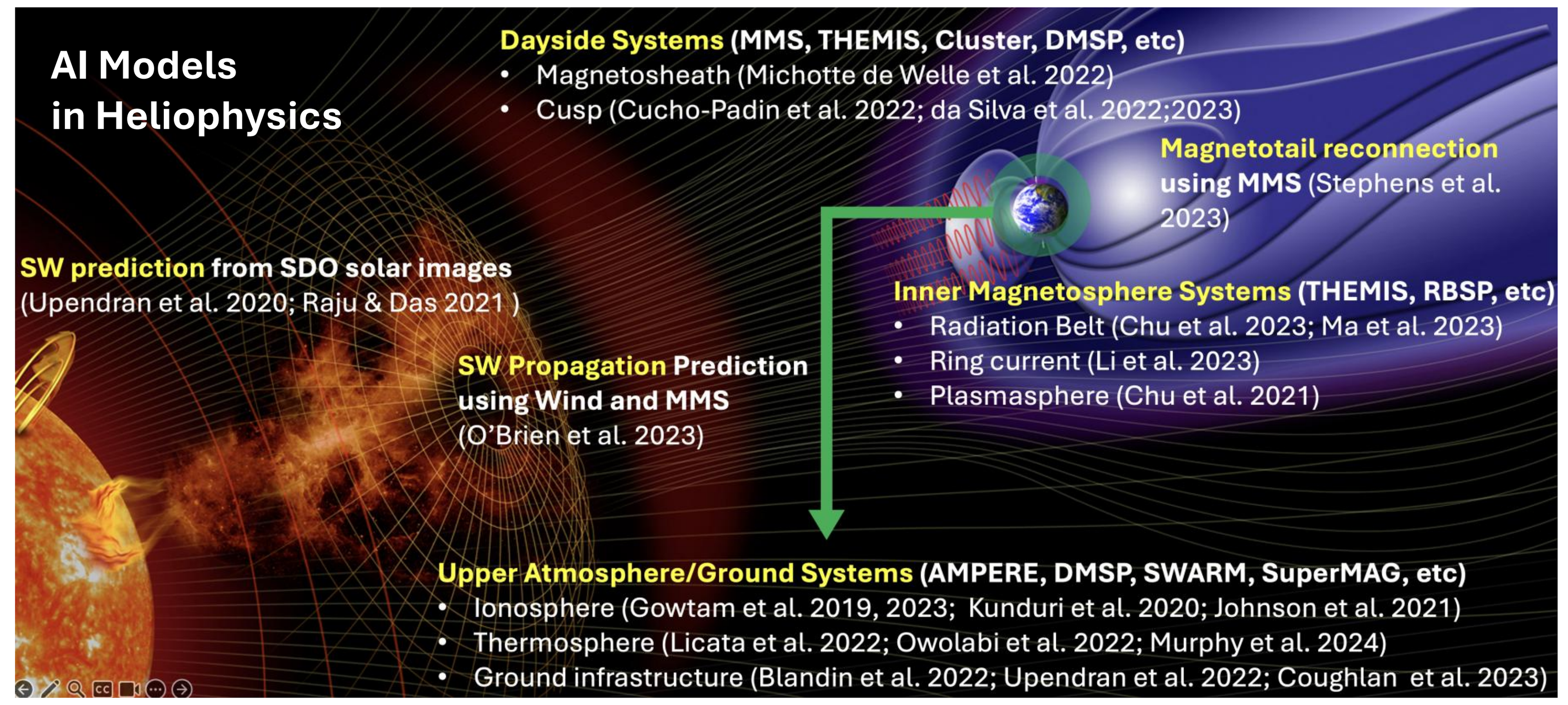
The AIMFAHR models reveal storm responses across geospace systems from a data-driven perspective, including :

- spatiotemporal variation of magnetopause reconnection;
- cusp motion and the evolution of cusp ion energy dispersions;
- auroral intensification and boundary motion;
- increases in FACs, ionospheric conductance, and potentials;
- enhanced upper-atmosphere Joule heating;
- thermospheric density enhancement; and
- intensified geomagnetic field disturbances.

Future AIMFAHR activities will focus on coupling ML models, quantifying uncertainties, and transitioning the ML models toward operational applications.

Artificial Intelligence Modeling Framework For Advancing Heliophysics Research (AIMFAHR)

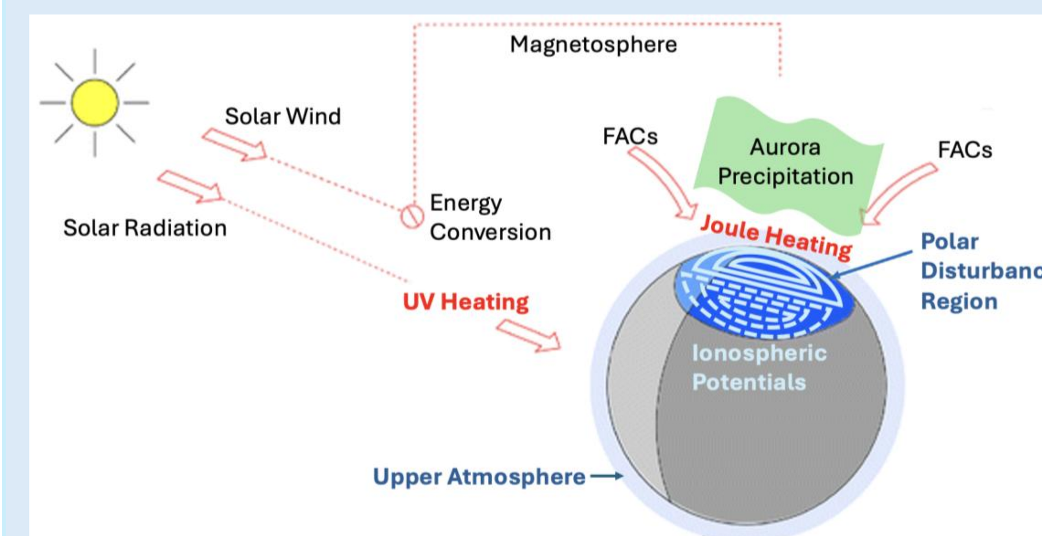
1. Integrate community-wide heliophysics ML models into a unified modeling framework.
2. Advancing heliophysics systems science.
3. Improve space weather modeling.
4. Real-Time Space Weather prediction



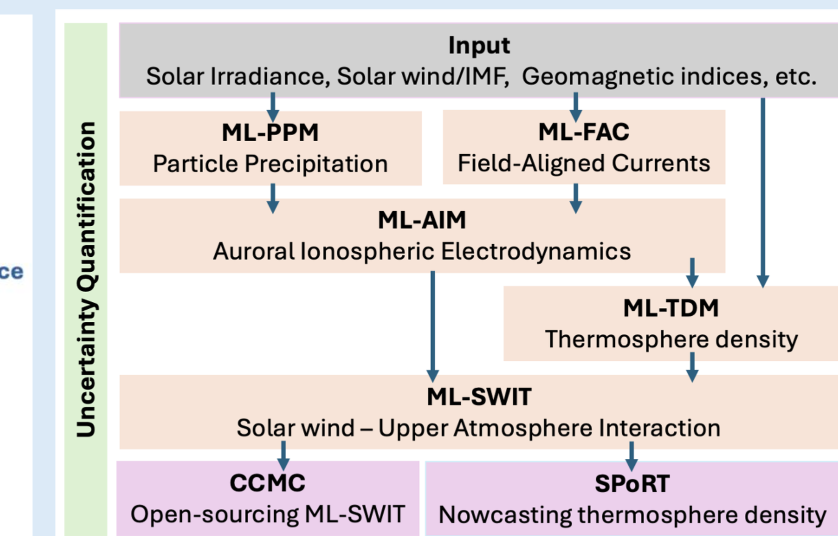
NASA Heliophysics ISFM Project (Oct. 2024 – present)

1. Enhance our understanding of solar wind - upper atmosphere interactions.
2. Advance space weather predictions by utilizing state-of-the-art AI approaches.
3. Promote the AIMFAHR initiative within the heliosphere community (e.g., GEM workshop MLGEM resource group; AGU AI sessions; bi-weekly virtual AIMFAHR meetings).

Principal modes of Energy Transfer from Sun to Earth



ISFM Activity Summary



Please join the bi-weekly AIMFAHR online meeting!
Contact saigowtam.valluri@nasa.gov
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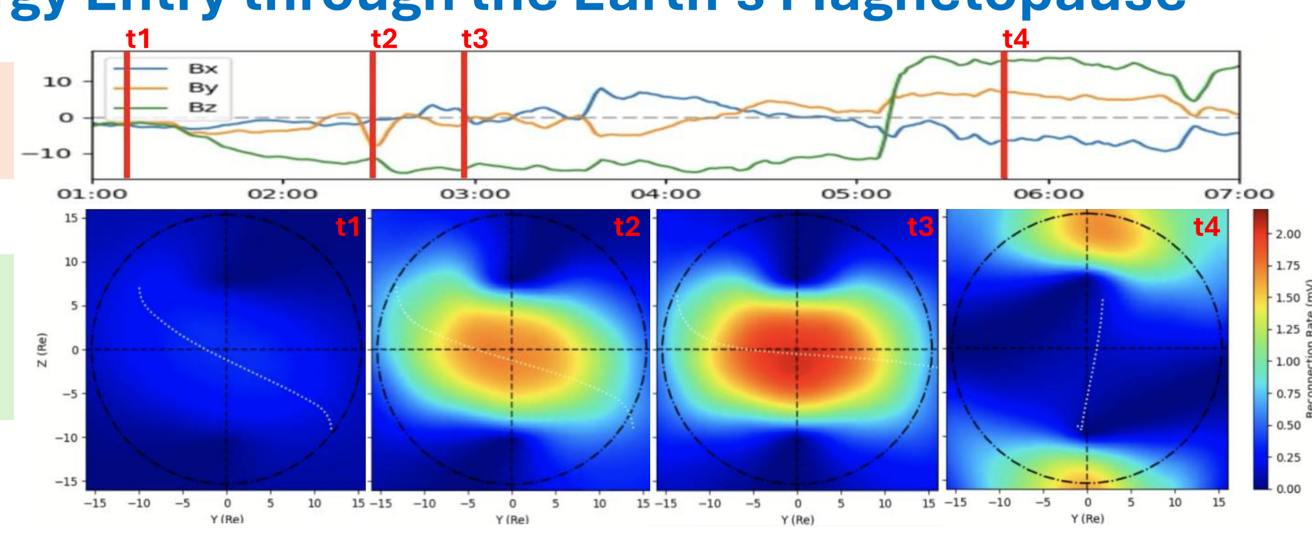
Solar Wind Energy Entry through the Earth's Magnetopause

Interplanetary Magnetic Fields (IMF)

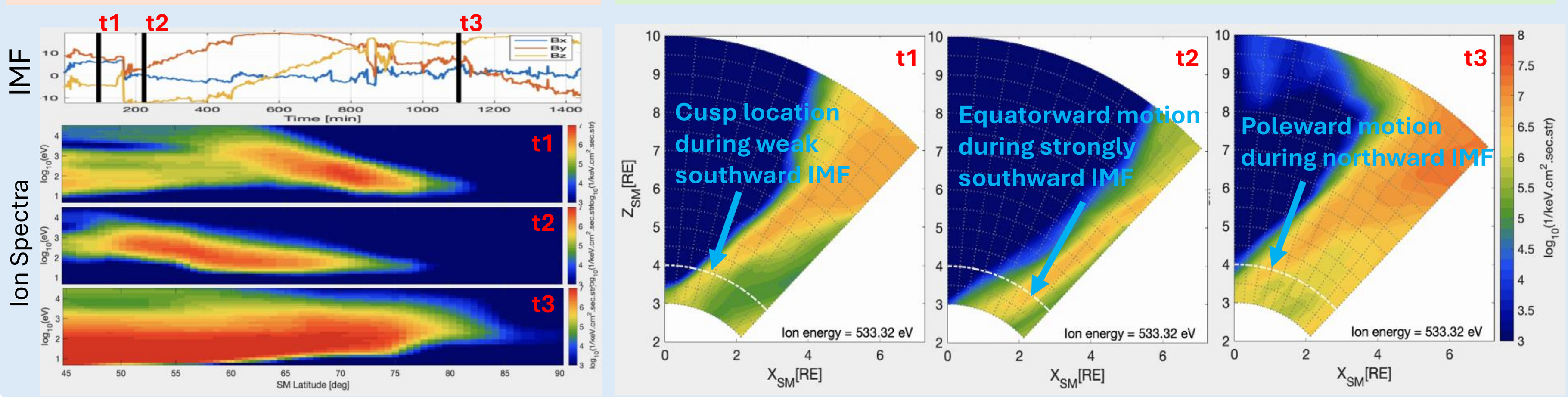
Reconnection rate on magnetopause, seen from the Sun.



- The data-driven reconnection model predicts when, where, and how much solar wind energy enters Earth's magnetosphere through magnetopause reconnection.
- Reconnection rates increase near the equator during southward IMF.
- Reconnection sites shift to higher latitudes during northward IMF.

Initial Impact of Solar Wind Energy on the Cusp

Cusp Ion Energy Dispersion | **Cusp Motion seen on the Noon-Midnight Meridional Plane**



- The ML-Cusp model predicts cusp ion energy dispersion and cusp motion resulting from magnetopause reconnection under weekly southward (t1), strongly southward (t2), and northward (t3) IMF conditions.
- This model supports the NASA TRACERS mission launched in Jul 2025 for studying the relation between the cusp and the magnetopause reconnection.

Aurora Precipitation driven by Solar Wind – Geospace Interaction

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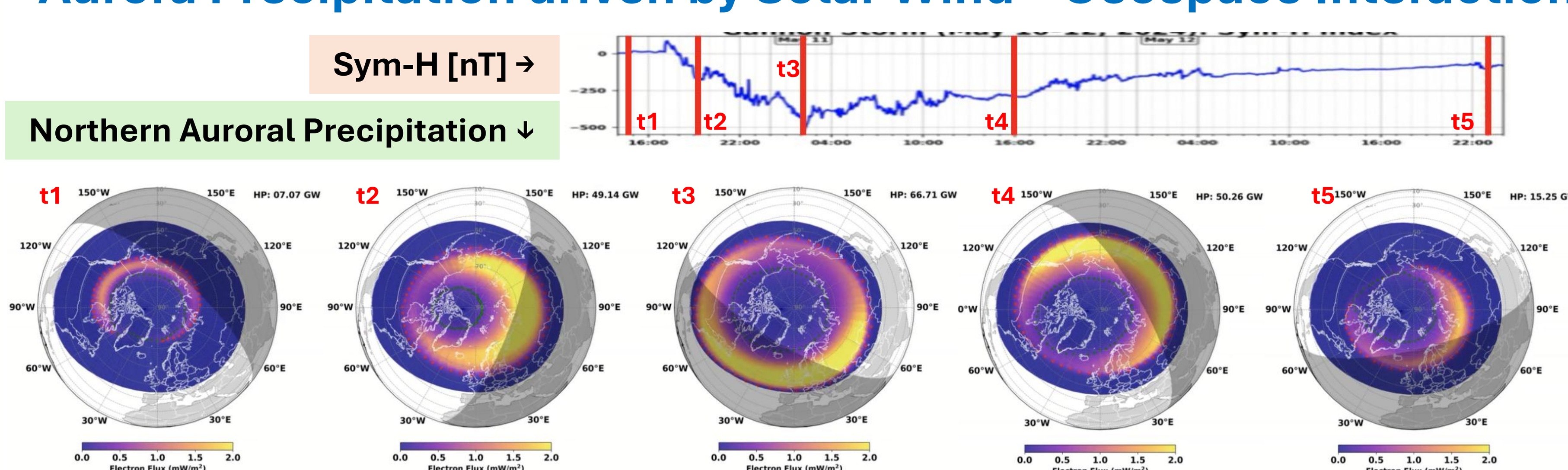
Northern Auroral Precipitation ↓



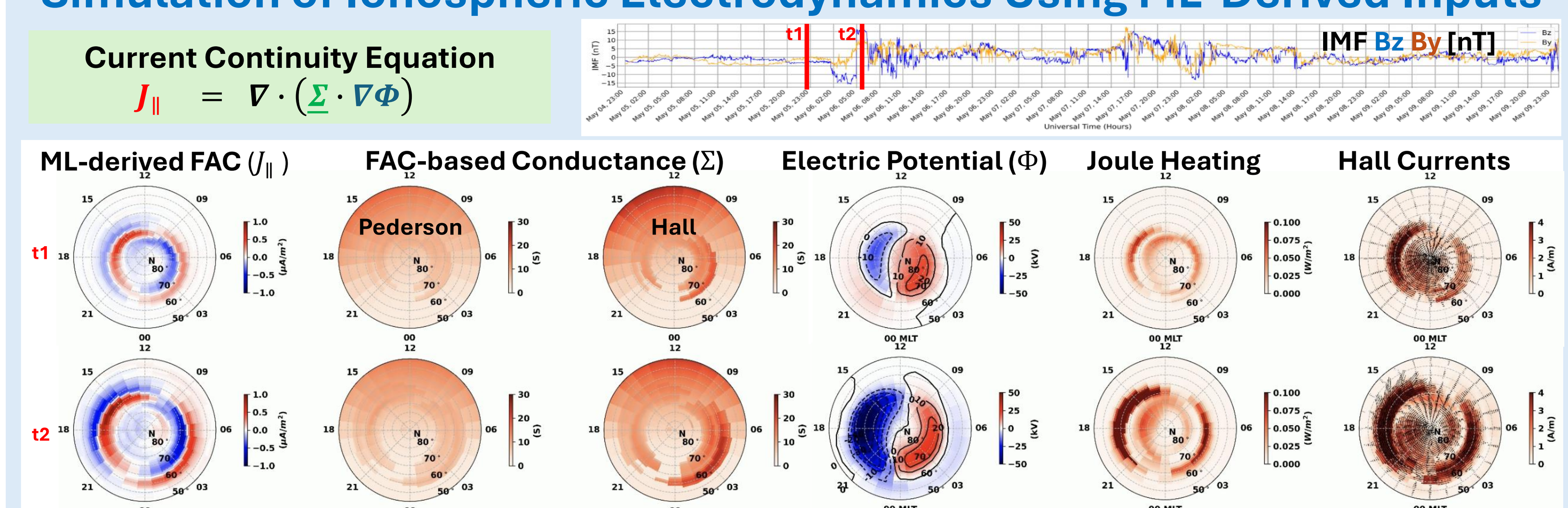
- The ML-Aurora model predicts auroral intensification and expansion during a geomagnetic storm.
- It provides crucial input for physics-based global upper atmosphere models and enhances space weather forecasting capabilities.

Real-Time Auroral Boundary Predictions ➡

Simulation of Ionospheric Electrodynamics Using ML-Derived Inputs

Current Continuity Equation

$$J_{\parallel} = \nabla \cdot (\underline{\Sigma} \cdot \nabla \Phi)$$



- The MLAIM model predicts high-latitude ionospheric electrodynamics by solving the current continuity equation using ML-derived Field-Aligned Currents (FAC).
- It predicts enhancements in FACs, conductance, electric potentials, Joule heating, and Hall currents during southward IMF turnings.

Real-Time Auroral Electrodynamics ➡

Thermospheric Density and Satellite Drag

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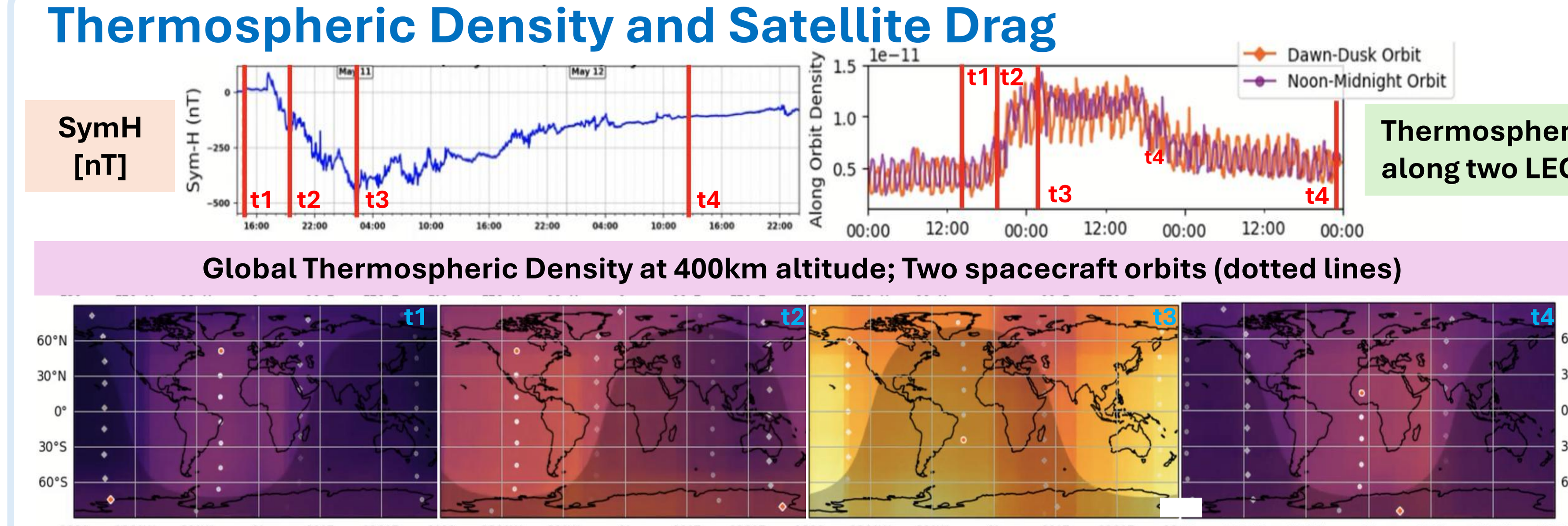
Thermospheric density along two LEO orbits

Global Thermospheric Density at 400km altitude; Two spacecraft orbits (dotted lines)



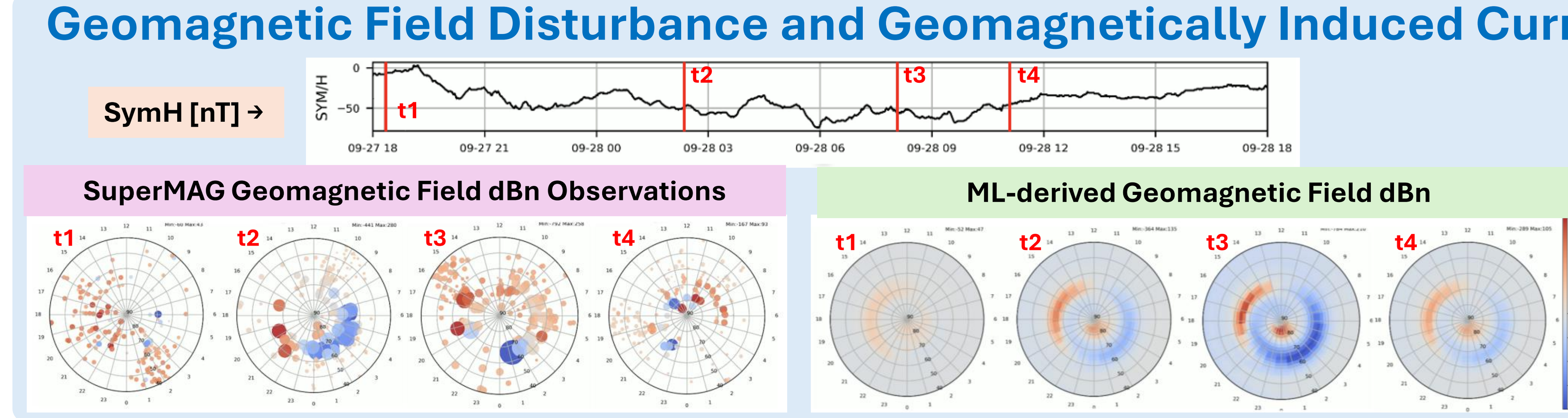
- The RANDM model predicts global thermospheric density at 400km altitude, providing key insights into the LEO environment.
- Thermospheric density along the two LEO orbits significantly increases during a storm, causing substantial drag.

Global Thermosphere Density at LEO ➡

Geomagnetic Field Disturbance and Geomagnetically Induced Currents (GICs)

SymH [nT] →

SuperMAG Geomagnetic Field dBn Observations | **ML-derived Geomagnetic Field dBn**



- The RESGEO model predicts global geomagnetic field variations during a storm.
- It captures enhanced storm-time disturbances, indicating elevated risk of GICs and power outages.