Erosion and Refilling of the Earth's Plasmasphere: a Machine Learning Approach

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Image credits: European Space Agency

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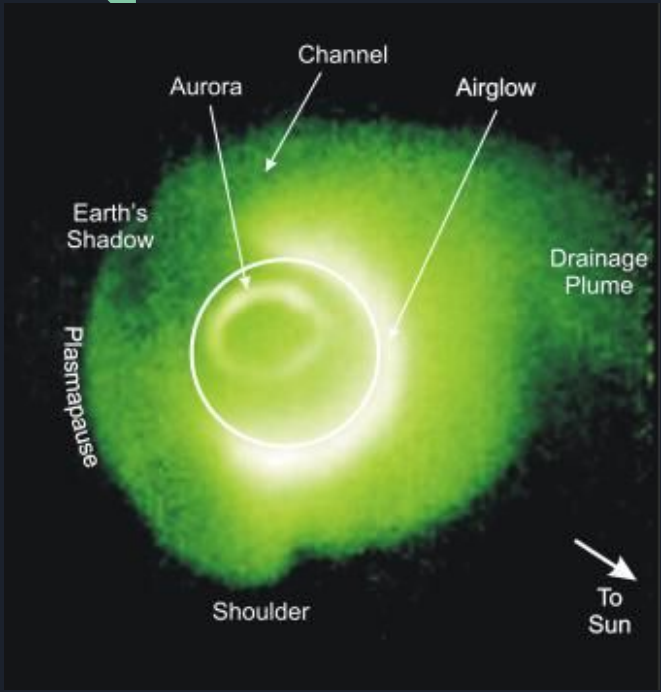
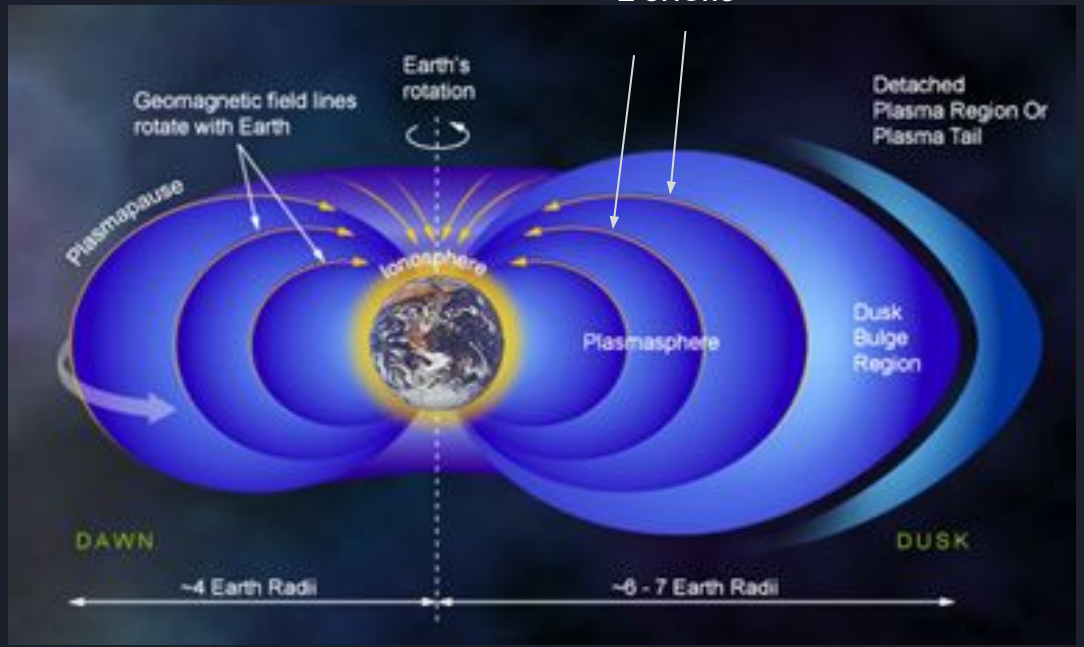
Background

Plasmasphere

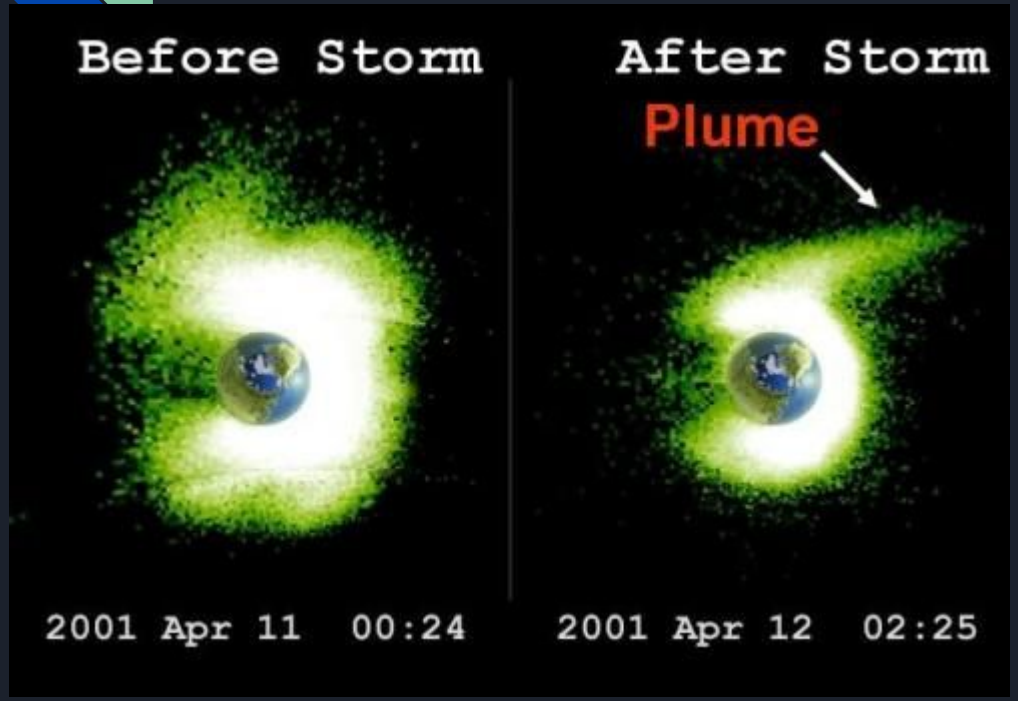


Earth's plasmasphere and plume as measured by IMAGE's EUV instrument. (From Sandel et al. 2003)



Main body of plasmasphere, plasmapause, and ionosphere. (NESTA)

Plasmasphere



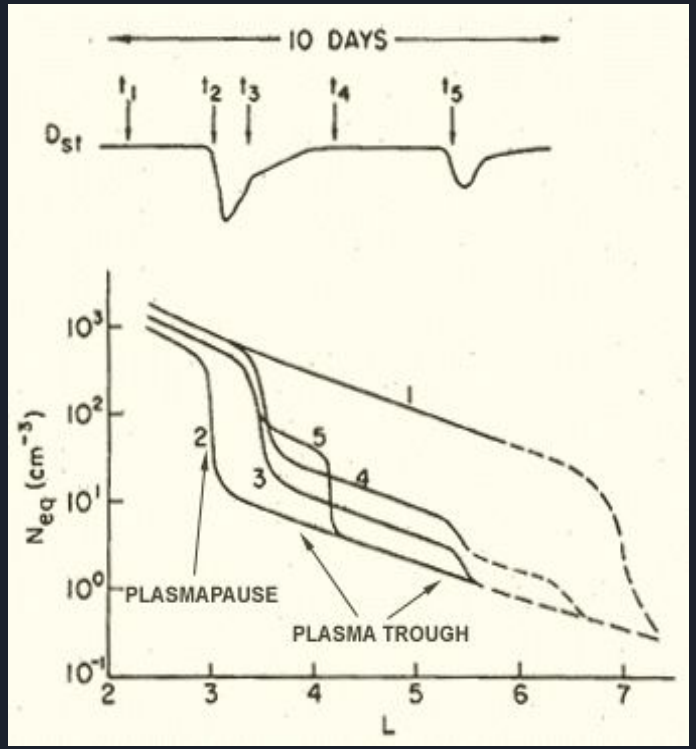
Plasmasphere, before and after storm (Image credits Jerry Goldstein)

Aurora or "northern lights" are the result of magnetic storms. (USGS)

Plasmaspheric Dynamics

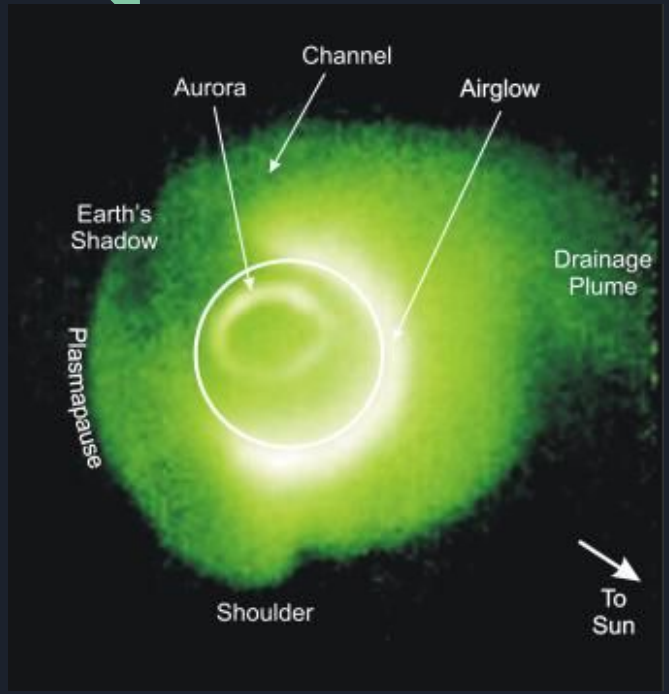
Plasma density profiles

1. Quiet time
   - Saturated plasmasphere
   - Plasma diffusive equilibrium with the ionosphere
2. Erosion
   - Plasma lost to dayside magnetopause
   - Plasmapause contraction
   - Plasmaspheric plume
3. Refilling
   - Plasma outflow from the ionosphere along field lines
   - DST is same as 2, but density profiles are different
4. Refilled
   - Plasma density increases and plasmapause moved outward



Carpenter and Park [1973]

Plasmasphere



Earth's plasmasphere and plume as measured by IMAGE's EUV instrument. (From Sandel et al. 2003)

- Radiation belt physics
  - Killer electrons
- Magnetosphere-Ionosphere coupling
  - Magnetic reconnection
- Wave propagation
  - Communication disruption
    - GPS signals
- Power grid outages

Unsolved problems in plasmasphere refilling

[Gallagher and Comfort 2016]

1. It has been shown that the thermosphere can have a significant influence on the plasmasphere. Where and when does the thermosphere influence refilling [*Krall et al*., 2014]?
2. Where and when do changes in ionospheric chemistry significantly influence refilling [*Krall and Huba*, 2013; *Huba and Krall*, 2013]?
3. With what efficiency does photoelectron heating influence refilling [*Comfort*, 1996; *Krall et al*., 2014]?
4. Do the physical processes operating during refilling change in significance as refilling progresses [*Lawrence et al*., 1999; *Su et al*., 2001]?
5. What is the role of mass and how does that change during refilling [*Singh and Horwitz*, 1992; *Sandel*, 2011]?
6. What high altitude processes influence refilling [*Singh and Horwitz*, 1992; *Singh*, 1996; *Khazanov*, 2011; *Khazanov et al*., 2012]?
7. Boundaries in plasma properties are often not boundaries in plasma processes, such as convection. What is the significance of the overlap in plasma populations that are a consequence of these dynamic processes? Do plasma of different origins, properties, and processes confuse our picture of plasmaspheric refilling [*Chappell et al*., 2008]?

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Unsolved problems in plasmasphere refilling

[Gallagher and Comfort 2016]

$$dn_e/dt = 3.81\,(6.8/L)^{4.94}\,\mathrm{cm}^{-3}\,\mathrm{day}^{-1}.$$

[Krall et al., 2014]

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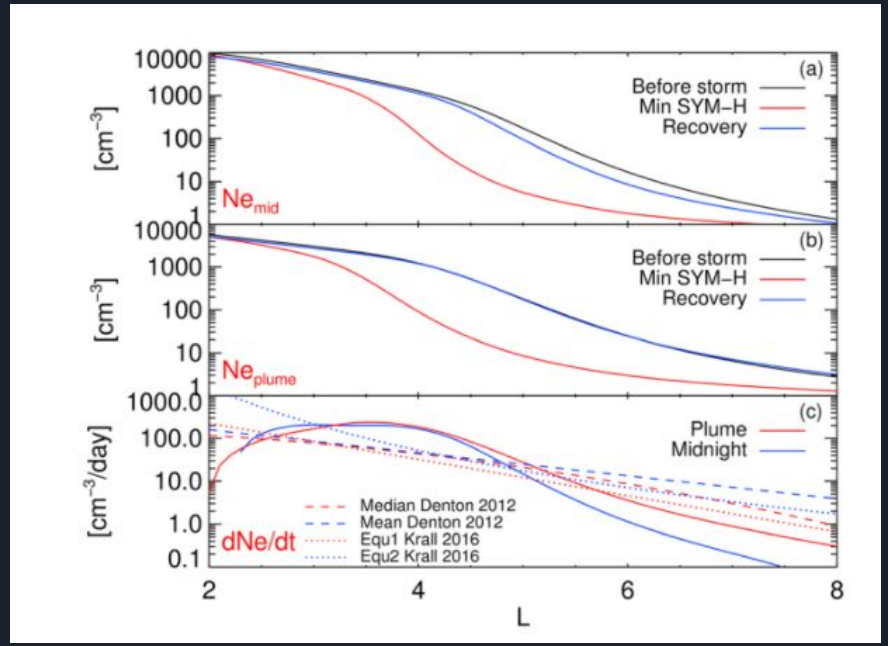
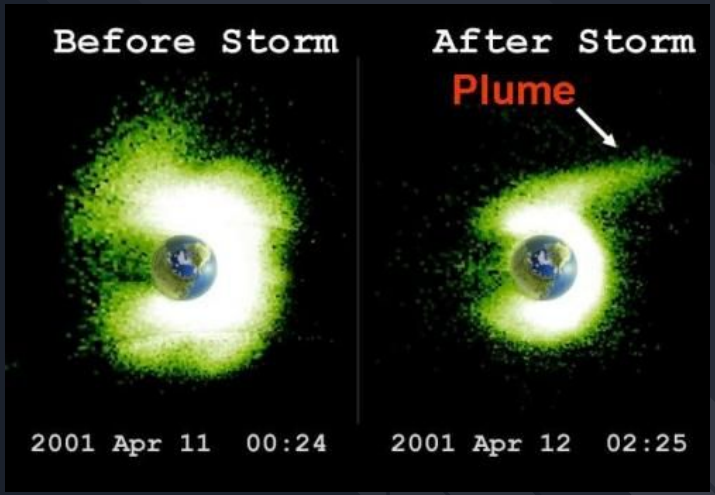


[Chu et al., 2017]

Purpose and Objectives

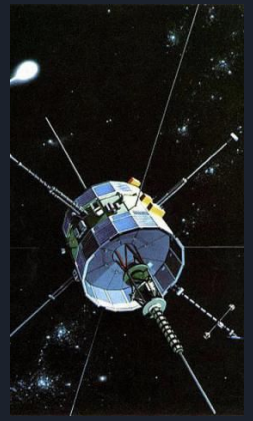


Refilling rate is not constant, how does it change throughout a storm?

Methodology

- Determine which data matters most
- Find solar wind parameters that contribute to the model and apply them
- Train the model
- Graph density and erosion/refilling rates from predicted data

Density Data



International Sun-Earth Explorer (1978-1988), ISEE

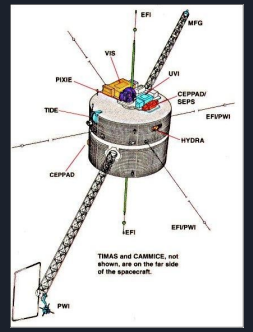


Illustration of the POLAR spacecraft (image credit: NASA)

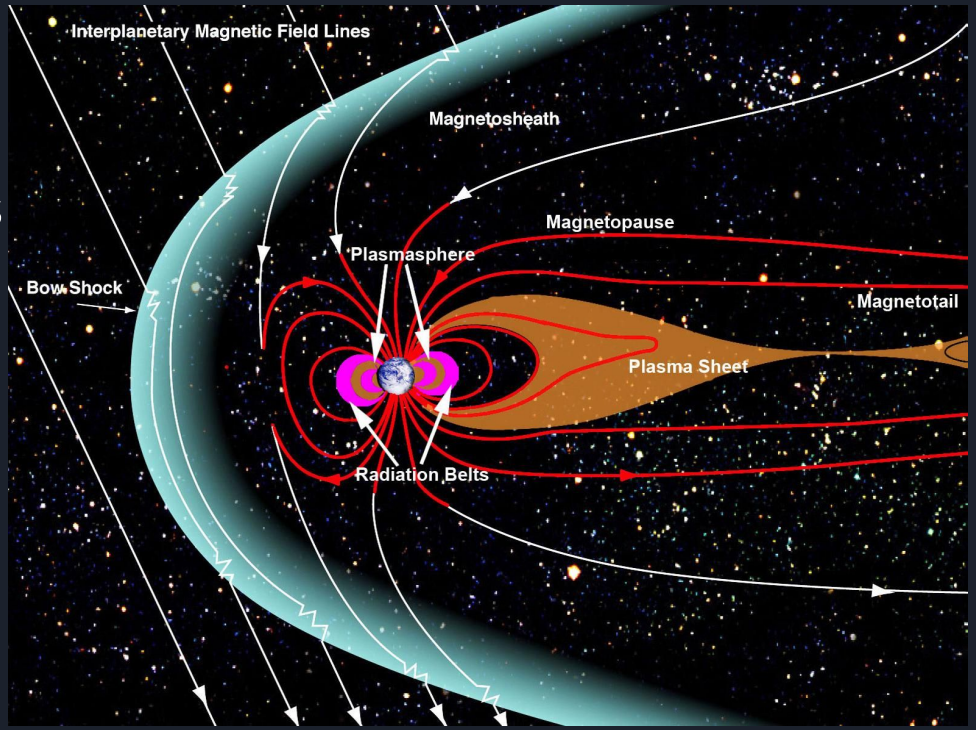
The Global Geospace Science Polar (1996-1997), POLAR

Combined Release and Radiation Effects Satellite (1990-1991), CRRES

Imager for Magnetopause-to-Aurora Global Exploration (2000-2005), IMAGE

OMNI Data

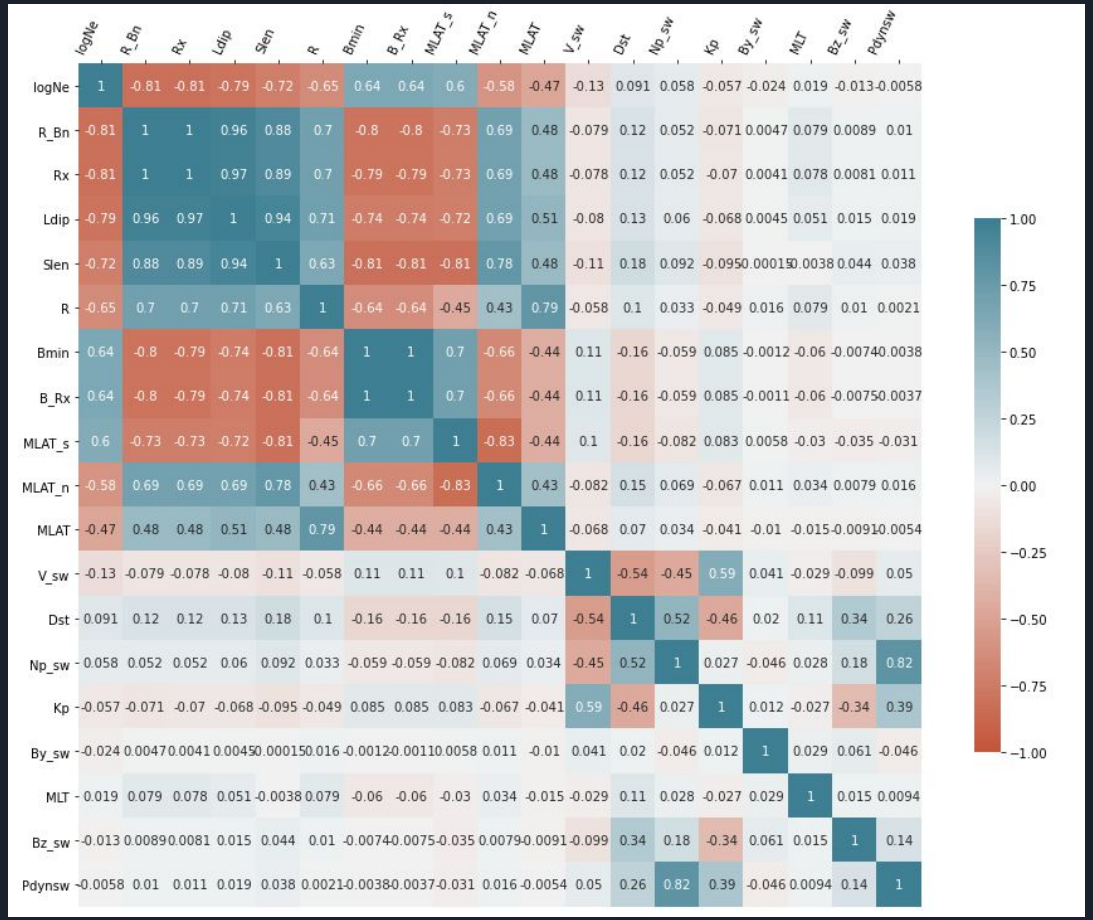
- Solar wind data
- Geomagnetic indices
- Multiple data resolutions
  - 1 min, 5 min, 1 hr



Heatmap

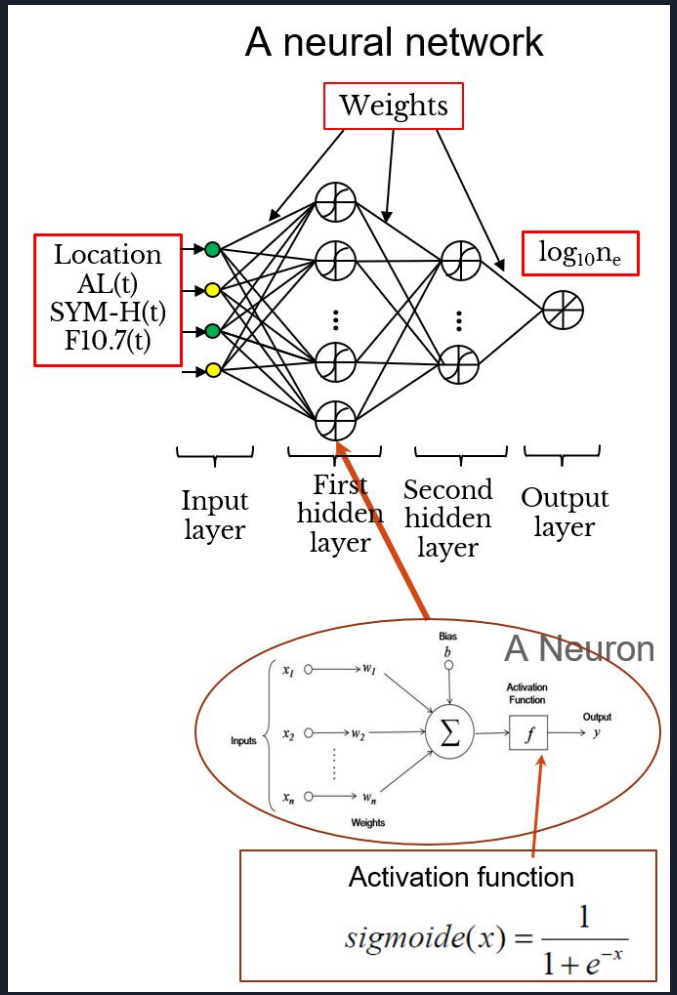
- Shows correlation between parameters
- We want what is most important for density
- Positional parameters are most correlated
  - R, MLT, MLAT

POLAR Satellite Correlation Heatmap



Neural Network

- Input/output
  - Time series of solar wind and geomagnetic indices
  - Predict the log10(Ne)
  - 3 hidden layers, sigmoid activation function



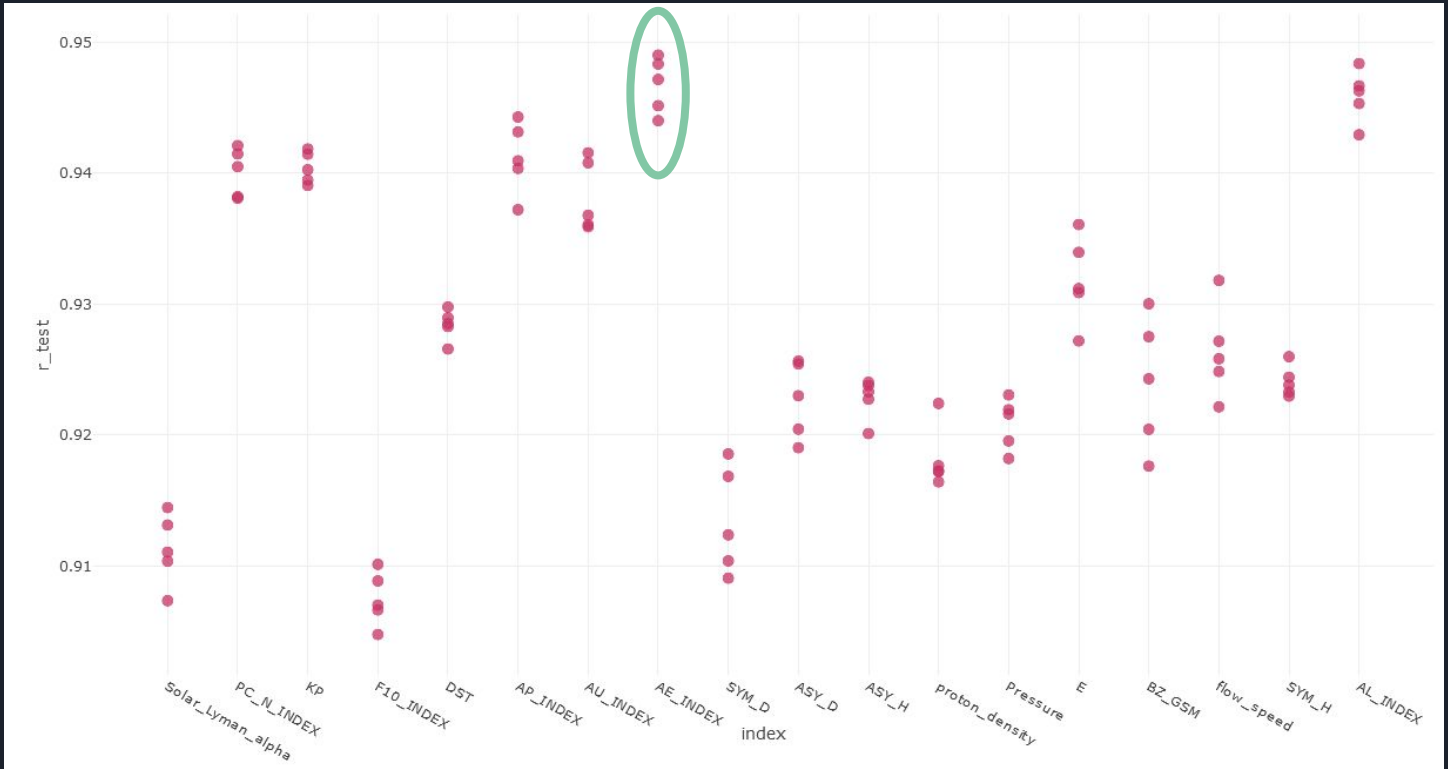
[Chu et al,. 2017]

Neural Network

- Model: Group K-fold cross validation - splitting data into daily chunks
- Train (60%), Validation (20%) and Test (20%)
- Early stopping and dropout to minimize overfitting
- MSE on test dataset can represent predictive ability

Initial Results

Finding best parameters



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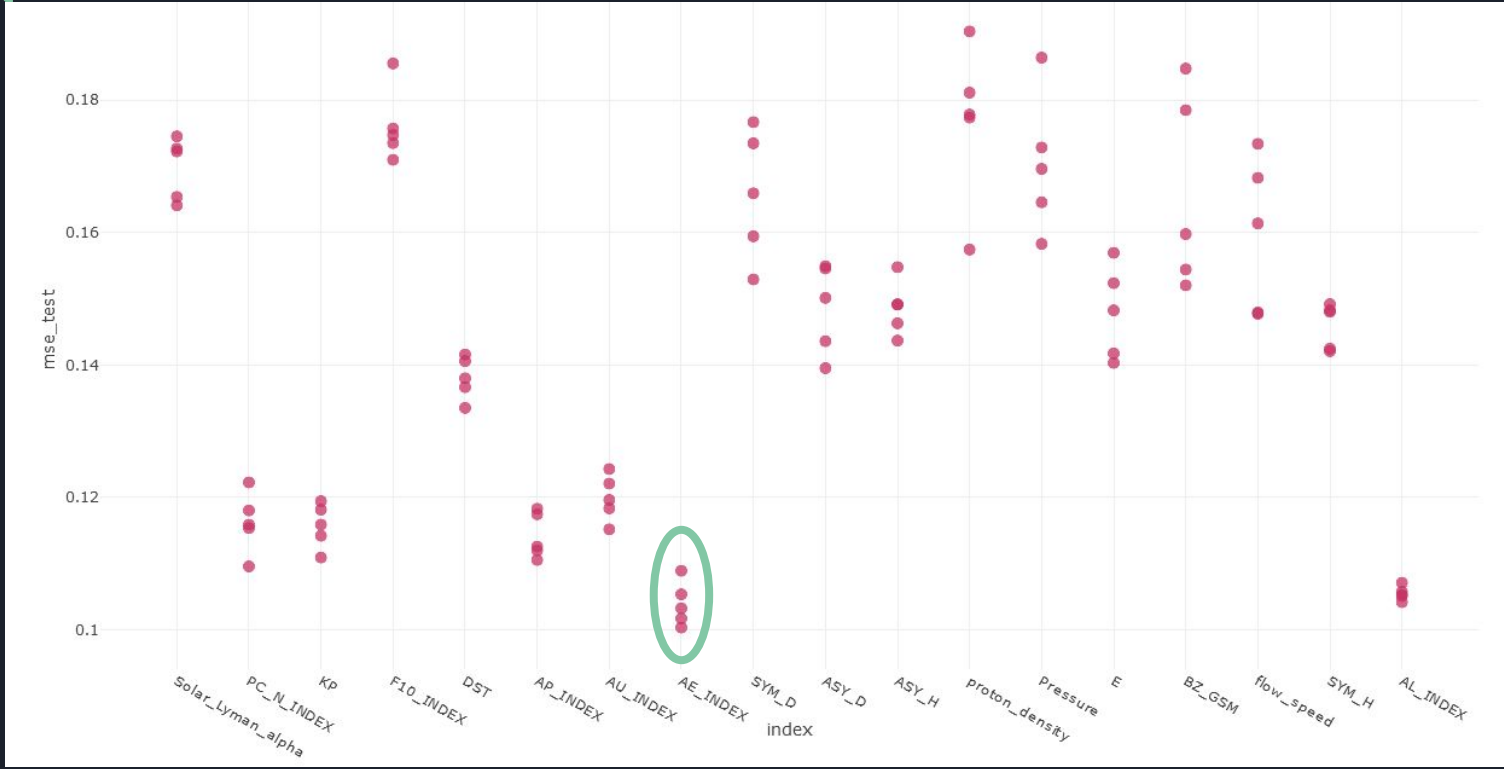

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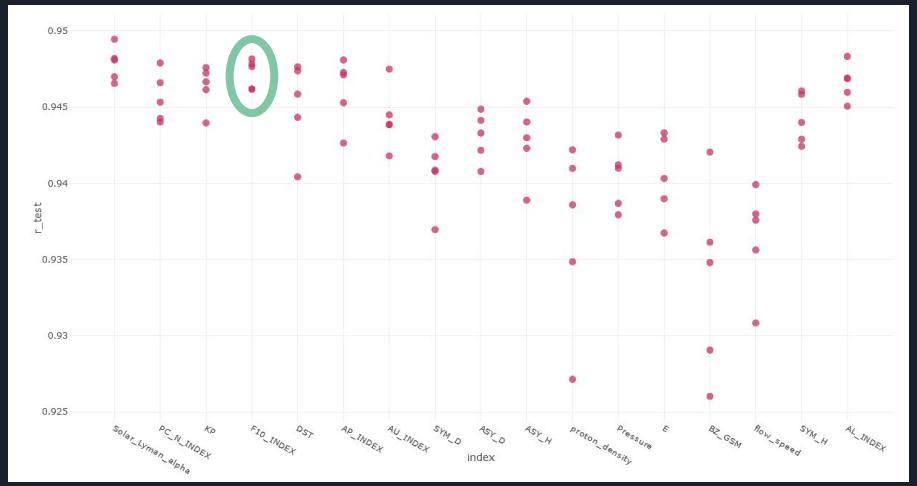
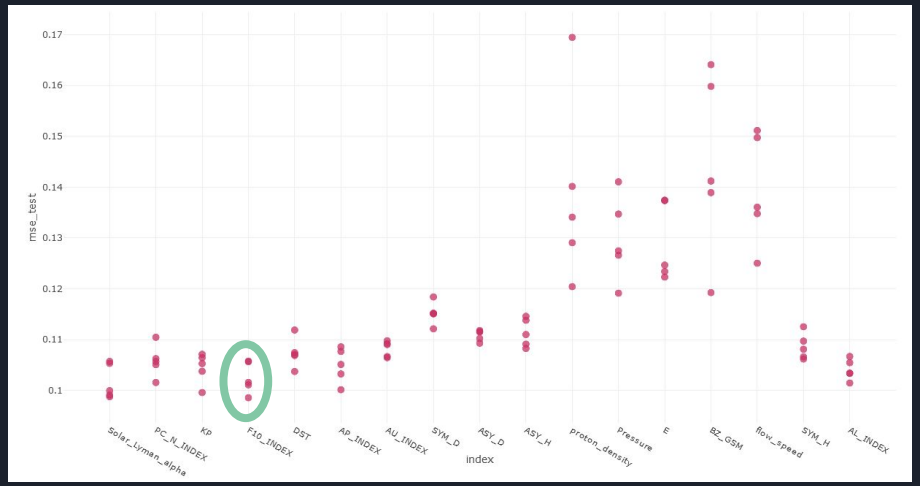
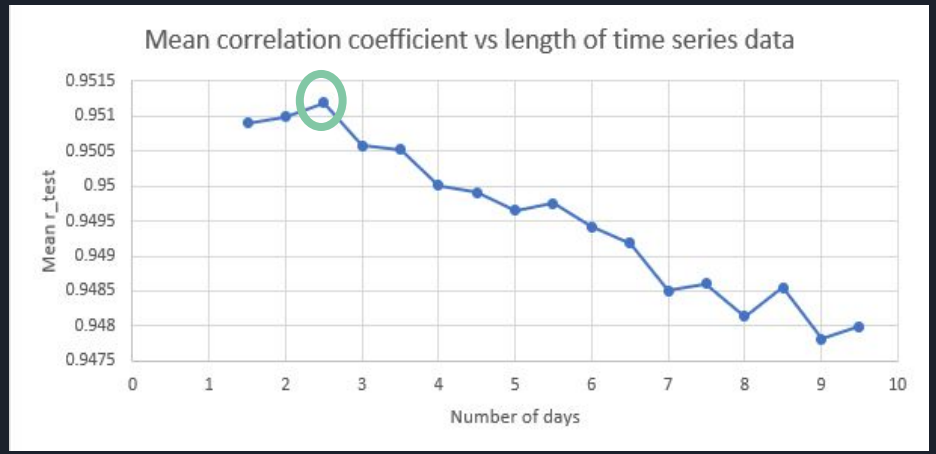
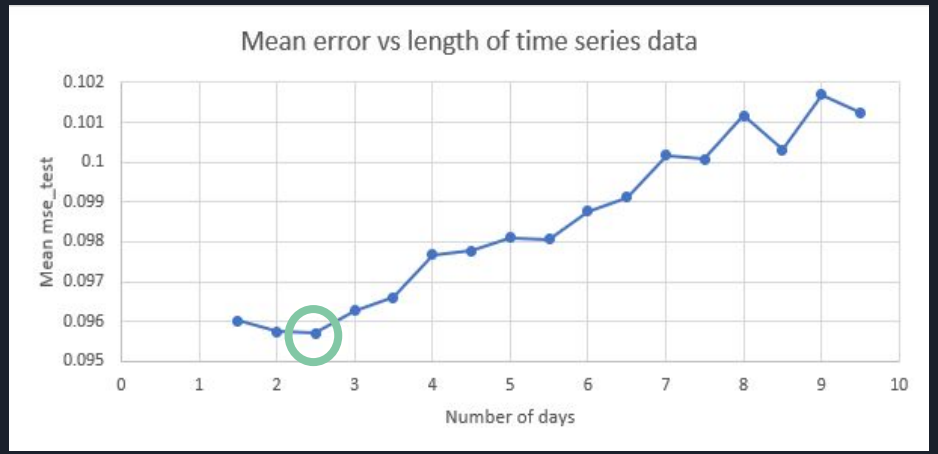




Initial Results

Finding best time range





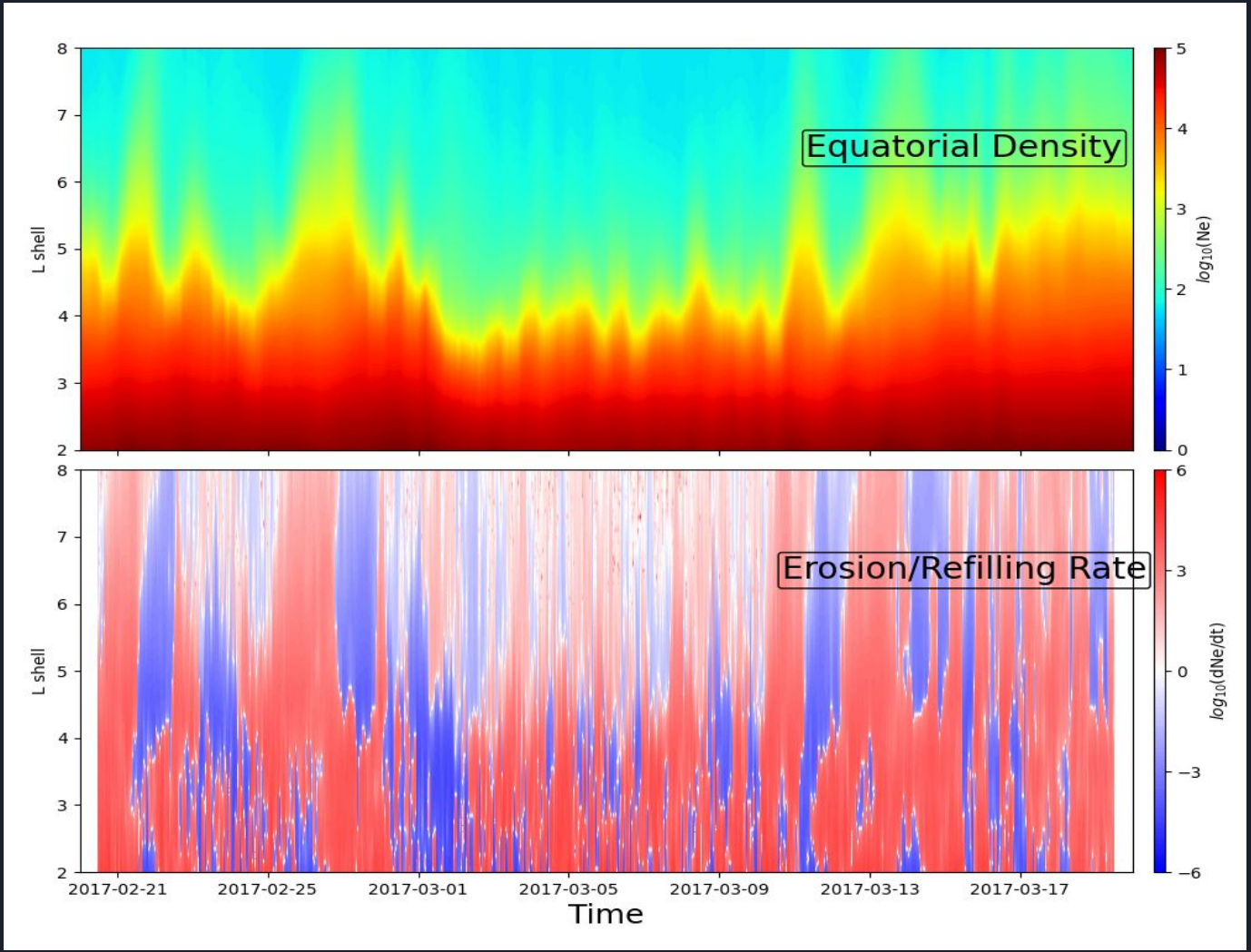
Model Results

Top:

- Density over time at each L shell

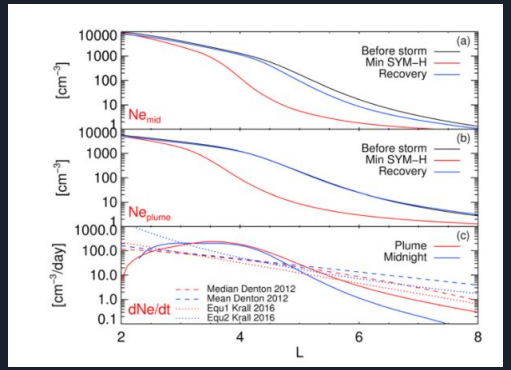
Bottom:

- Erosion/refilling rate



Final Takeaways

Previous Assumptions



[Chu et al., 2017]

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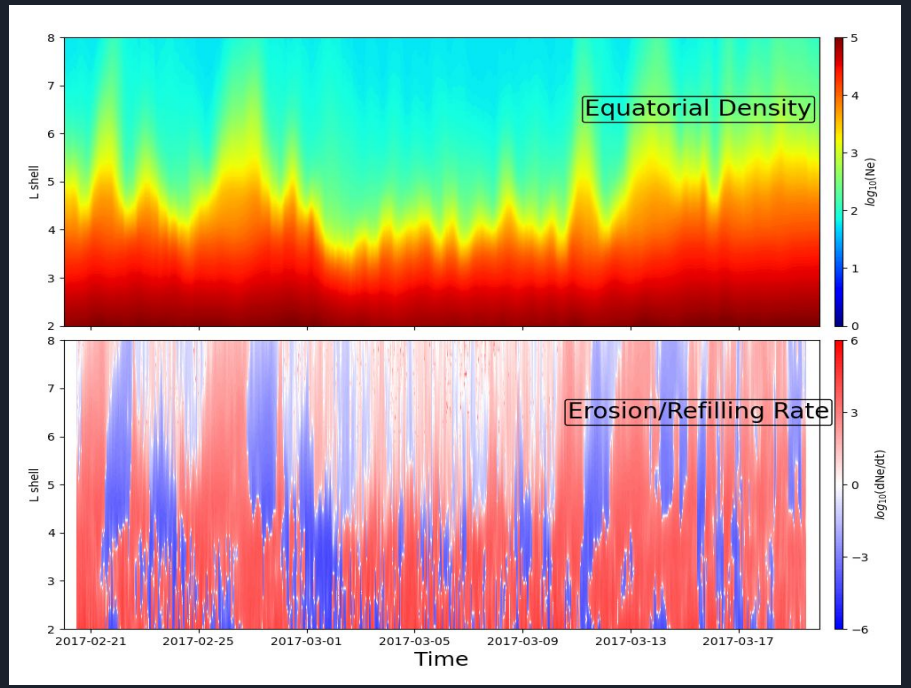
Project Results



Future Work

- Tuning model parameters exactly
  - Length of time series used
  - Most effective solar wind parameters
    - 3 parameter combination
- Substorm research

Acknowledgements

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Questions?