Statistical investigation of the erosion and refilling of the plasmasphere - machine learning approach

James Lende[1], Xiangning Chu[1], Jacob Bortnik[2], Richard Denton[3], Xin Cao[1], Donglai Ma[2]

[1]Laboratory for Atmospheric and Space Physics, Boulder, CO, United States, [2]Department of Atmospheric and Oceanic Sciences, University of California Los Angeles, Los Angeles, CA, United States, [3]Department of Physics and Astronomy, Dartmouth College, Hanover, NH, United States

lende@mines.edu

Laboratory for Atmospheric and Space Physics
University of Colorado **Boulder**

1. Introduction and Background

It was previously assumed that the rate of erosion and refilling of the Earth's plasmasphere was constant for a geomagnetic storm. By utilizing a neural network, as well as density and solar wind data, we have shown that erosion and refilling is much more complex than initially thought.

- The Earth's plasmasphere is a layer of low energy charged particles, or cold plasma, that extends from the top of the ionosphere to the magnetosphere. The outer boundary, called the plasmapause, is signified by an abrupt change in plasma density.
- Geomagnetic storms, caused by solar wind and other solar activity, erode the plasmasphere, stripping its plasma and decreasing plasma density.

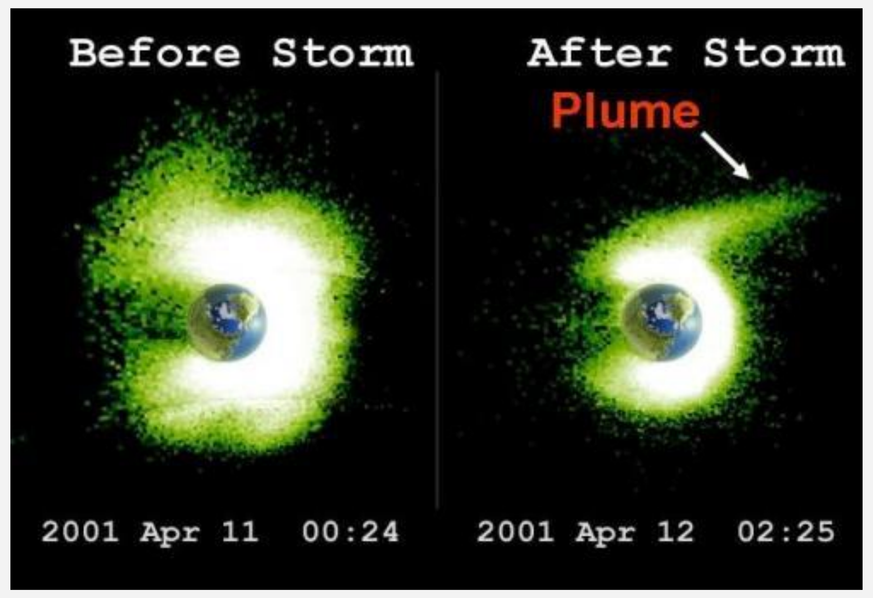

Figure 1: Plasmasphere, before and after storm (Image credits Jerry Goldstein)

- In times of low geomagnetic activity, plasma from the ionosphere is driven along magnetic field lines into the plasmasphere[1].
- Previous studies assumed a constant rate of erosion/refilling, shown in this equation from Krall's 2014 study[2]:

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

Equation 1: Refilling of the plasmasphere after Feb 2001 geomagnetic storm [Krall et al., 2014]

In this study we model the density of the plasmasphere over time and answer the question: "**how does the rate of refilling and erosion change throughout a geomagnetic storm?**"

2. Methods

We used a machine learning neural network to model the plasmaspheric density at the equatorial lines. This allowed us to find the rate of change of the density, i.e. rate of erosion and refilling. Input parameters included geomagnetic indices and solar wind features. Python was used for data analysis.

Data was gathered from the ISEE, CRRES, POLAR, and IMAGE satellite missions as well as NASA's OMNI solar wind database.

We tested the most relevant parameters from the 4 satellites and found through a correlation heatmap that R, MLT, and MLAT correlated best with density (logNe).

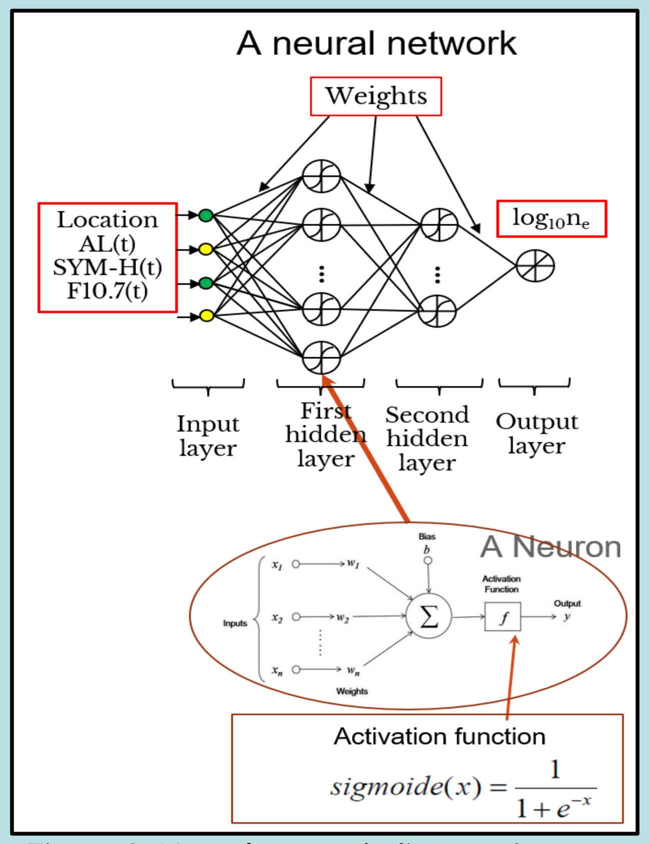

Figure 2: Neural network diagram for model [Chu et al,. 2017]

3. Results

Before training the model, we found the input parameters that were most effective in predicting plasma density. We found that AE_index had the highest correlation with predicting plasma density in the model. We also tested the optimal time length of data to be used. Figure 3 shows that 2.5 days is the optimal length for the time series.

After training the model, the correlation coefficient between the test data set and the output data set was roughly 0.95. This means that over 90% of the data's features were captured by the model.

From the models predicted data, we made 2 contour plots in Python accompanied by solar wind parameters shown in figures 4 and 5. The two figures cover different time ranges of space weather events. The top two plots in each figure show the proton density, flow speed, Sym-H index, and adjusted AL index over time. The third plot shows equatorial plasma density at each L-shell for the time range, while the bottom plot shows the equatorial erosion and refilling rate at each L-shell from the same date range. The erosion/refilling plot was made by taking the derivative of density over time.

The plots show high plasma density near the Earth (lower L-shells) and many fluctuations in density, as well as many fluctuations in erosion/refilling rates.

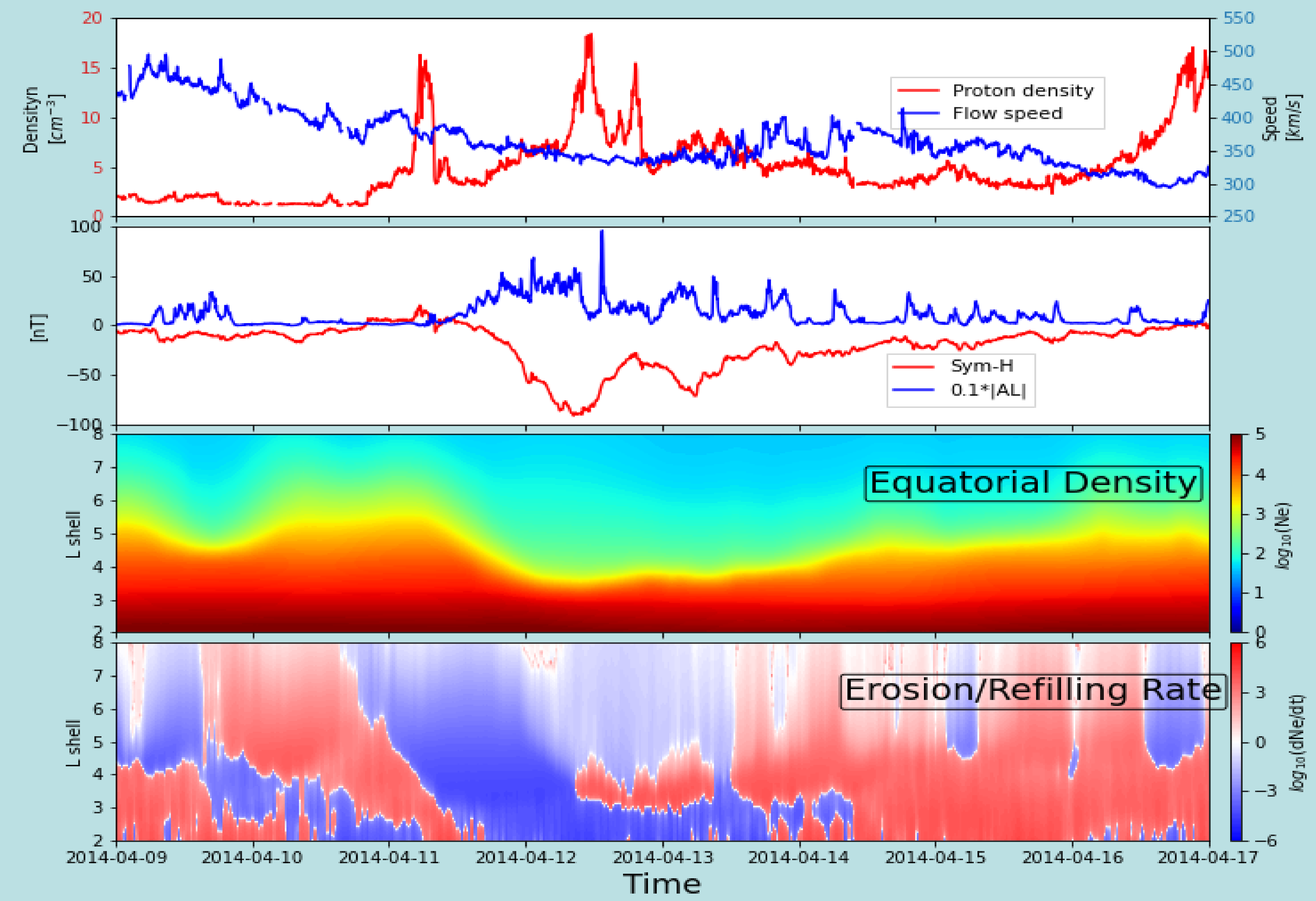

Figure 4: Equatorial plasma density over time vs. L shell, with erosion/refilling rate over time vs L shell from August 2014 space weather storm.

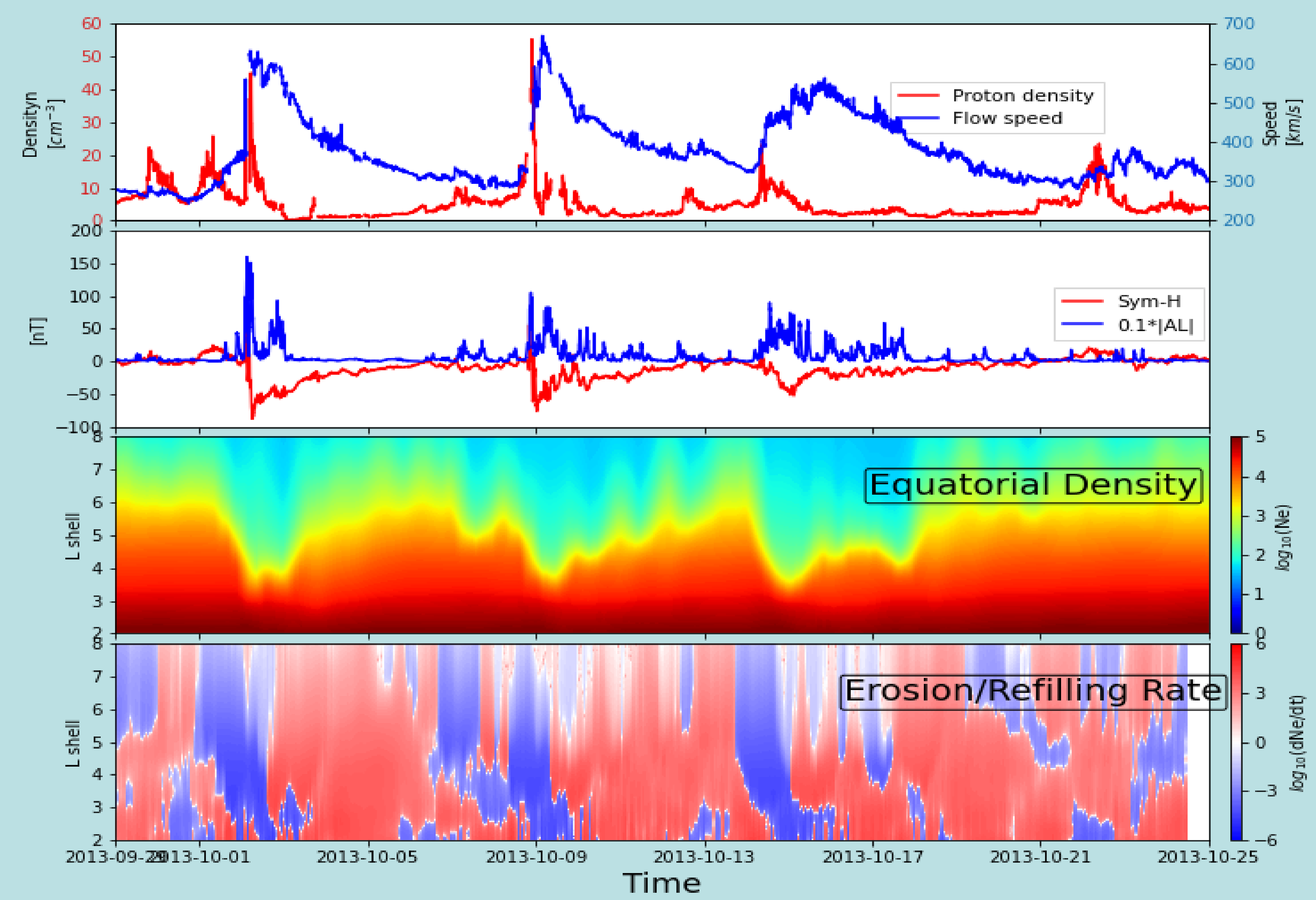

Figure 5: Equatorial plasma density over time vs. L shell, with erosion/refilling rate over time vs L shell from 2013 September-October space weather storms.

4. Conclusions

The results of this project show that the erosion and refilling rates of the plasmasphere are not constant through a geomagnetic storm as was previously assumed, but are actually much more complex.

From our initial question, "how does the rate of refilling and erosion change throughout a geomagnetic storm", our results conclude: the density of the plasmasphere changes in many ways not yet understood.

The fluctuations in the erosion and refilling rates suggest that the controlling mechanism is (1) in the time scale of a geomagnetic storm and (2) related to the extra electric field due to a set of substorms [Chu et al., 2017].

This project is a great example of how machine learning can be applied to space weather in order to expand on previous assumptions and explore new areas.

5. Future Work

For future work on this project:

- Model parameters should be tuned more optimally
- Potentially combination of 3 or more solar wind features to predict data
- Test different activation functions for the layers of the neural network
  - ReLU
- Substorm research
  - look further into mechanisms that control erosion and refilling

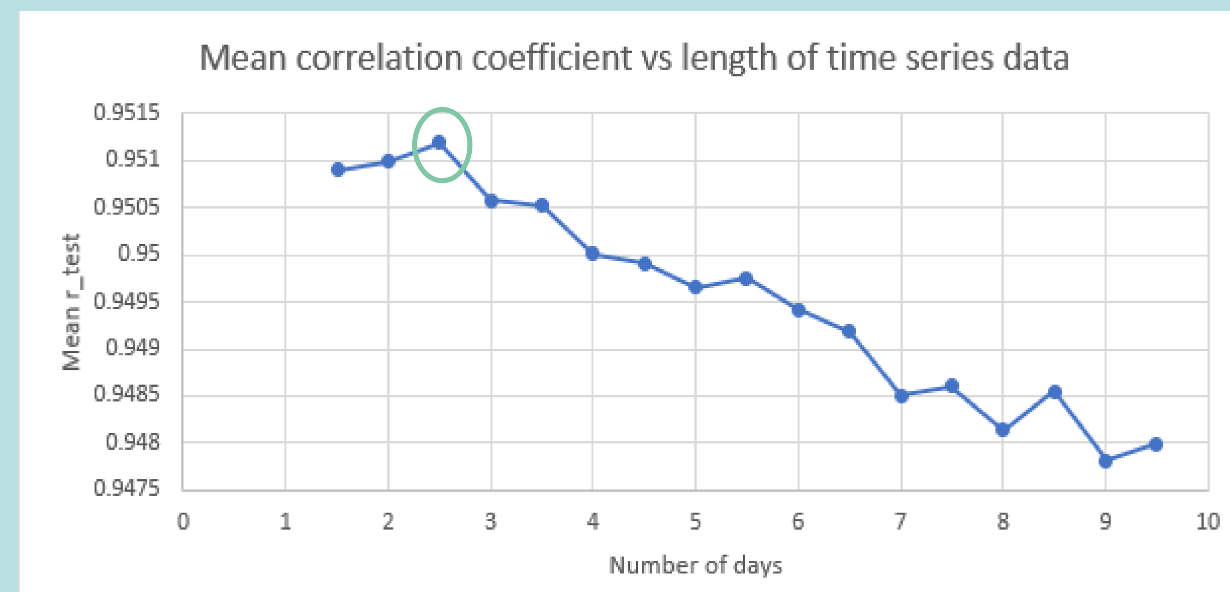

Figure 3: Mean correlation coefficient vs length of time series data used

References

[1]Chatterjee, K., Schunk, R.W. The development and validation of a 'flux-corrected transport' based solution methodology for the plasmasphere refilling problem following geomagnetic storms. *Earth Planets Space* **72,** 26 (2020). https://doi.org/10.1186/s40623-020-01150-0

[2]Krall, J., Huba, J. D., Jordanova, V. K., Denton, R. E., Carranza, T., and Moldwin, M. B. (2016), Measurement and modeling of the refilling plasmasphere during 2001, *J. Geophys. Res. Space Physics*, 121, 2226– 2248, doi:10.1002/2015JA022126.

[3]Chu, X. N., Bortnik, J., Li, W., Ma, Q., Angelopoulos, V., and Thorne, R. M. (2017), Erosion and refilling of the plasmasphere during a geomagnetic storm modeled by a neural network, *J. Geophys. Res. Space Physics*, 122, 7118– 7129, doi:10.1002/2017JA023948.

Acknowledgements

This research was supported by the National Science Foundation REU program, award #1659878.