Modeling H+ and O+ Pressure in the Plasma Sheet During Storms and Substorms with Machine Learning

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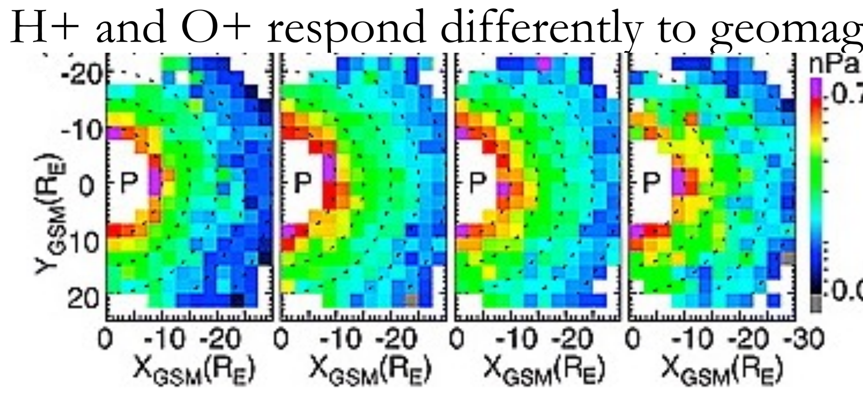
1. Introduction: Plasma Sheet Pressure

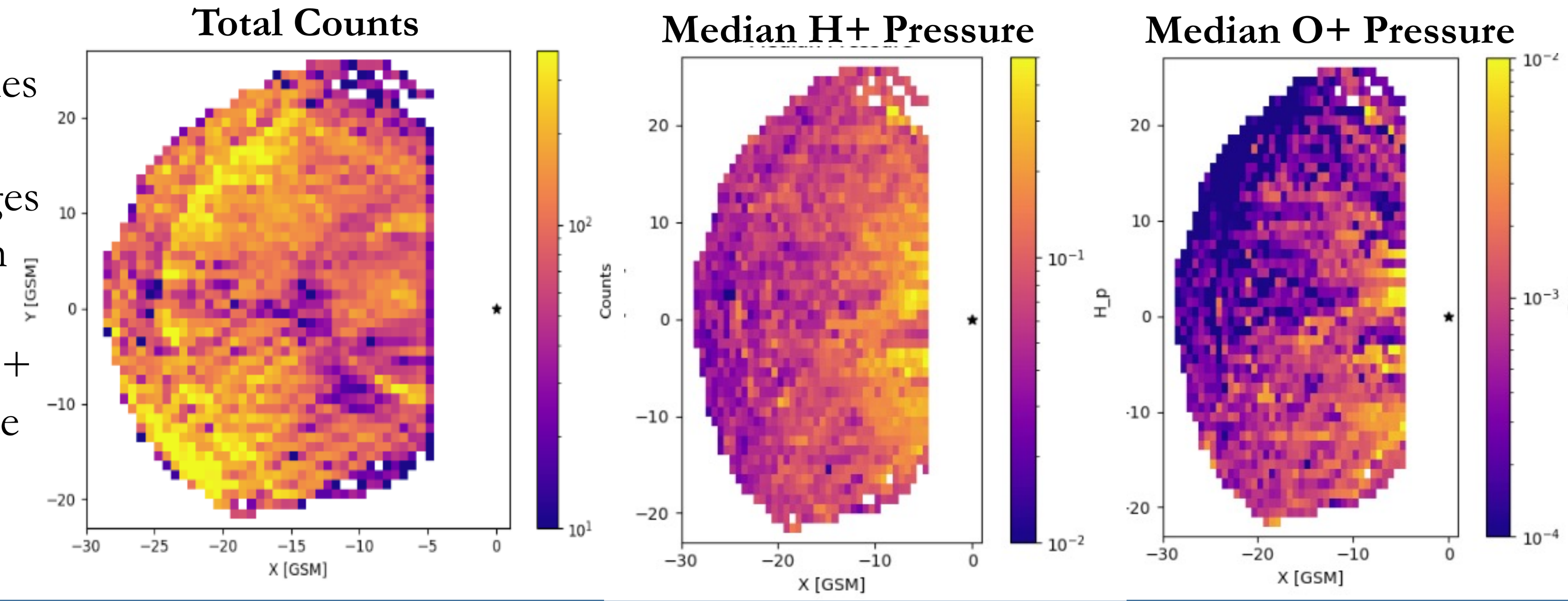
- Plasma in the plasma sheet comes from two main sources: the ionosphere and the solar wind
  - H+ in the plasma sheet can come from either source, while the O+ is mostly associated with the ionospheric source
  - Measuring O+ levels in the plasma sheet describes the contribution of ionospheric sources
- **How does the plasma sheet change during storms and substorms?**
  - We develop a machine learning model to predict pressures in the plasma sheet during storms
- Test how H+ and O+ respond differently to geomagnetic index inputs



Wang et al. (2006)

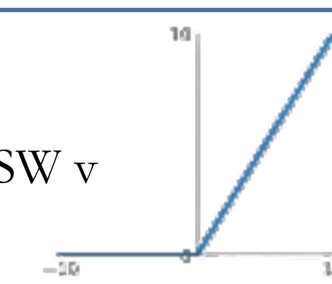
2. Introduction: MMS Data

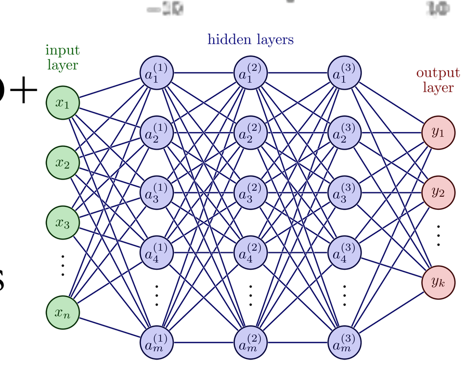
- MMS/HPCA data—satellite 1 *[Young et al., 2016]*
  - Measures major ion species' 3D distributions at energies 1 eV-40 keV
  - 2 minute averaged pressure data at HPCA energy ranges during times when MMS was in the plasma sheet from 2016-2024+
- Data preparation and model training are separate for H+ and O+
- Data limited to plasma sheet observations and validated to create machine learning inputs
- Total data numbers: H+: 174,985; O+: 117,285



3. Methodology: Artificial Neural Network (ANN)

- Model input layer
  - Spacecraft positions: GSM coordinates (xyz)
  - Solar activity indices: Kp, f10.7, SME, SML, SMU, SW v and p, IMF B_z, 7 day histories
- Hidden layers
  - 2 hidden layers to model H+, one to model O+
  - Activation function: reLU
- Output layer
  - Returns predicted pressure for given positions
  - Activation function: reLU

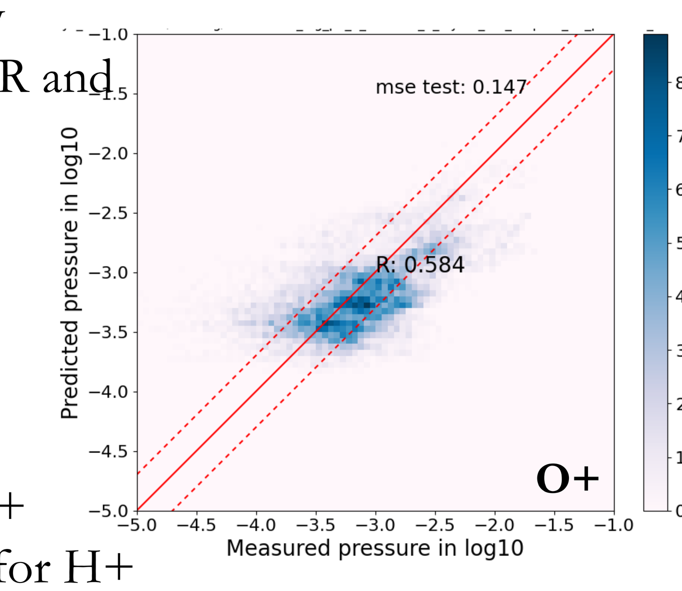




- Model performance evaluated by Pearson's correlation coefficient R and mean squared error (MSE):

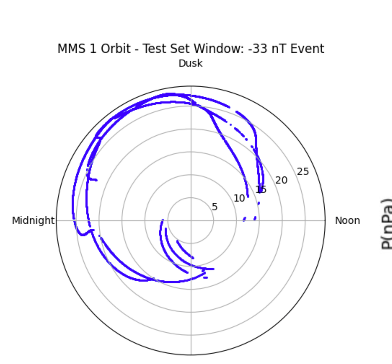
$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i-\bar{x})^2}\sqrt{\sum_{i=1}^{n}(y_i-\bar{y})^2}}$$

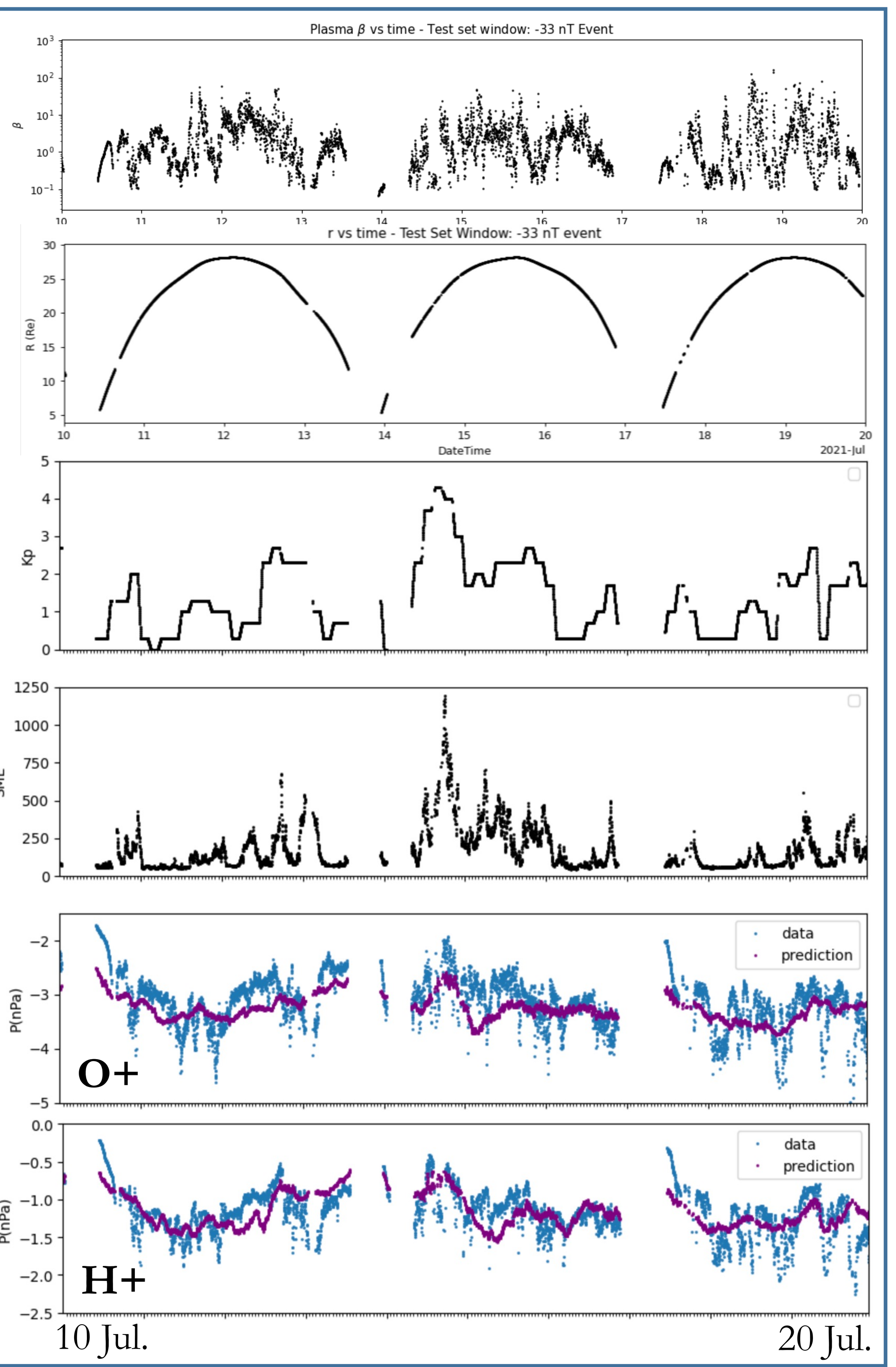
- Uncertainties cover factor of 10
- "Leave one feature out" testing indicates solar indices are most important for creating a good O+ model and solar wind moments for H+



4. Model Validation: Test Set Model Evaluation

- Model prediction for a -33 nT minor storm from the test set period (05/01/2021 to 08/01/2021)
- In general, the model performs well to within minor deviations
- Model tracks changes due to solar activity well
- Low sensitivity to shorter-term variations in pressure

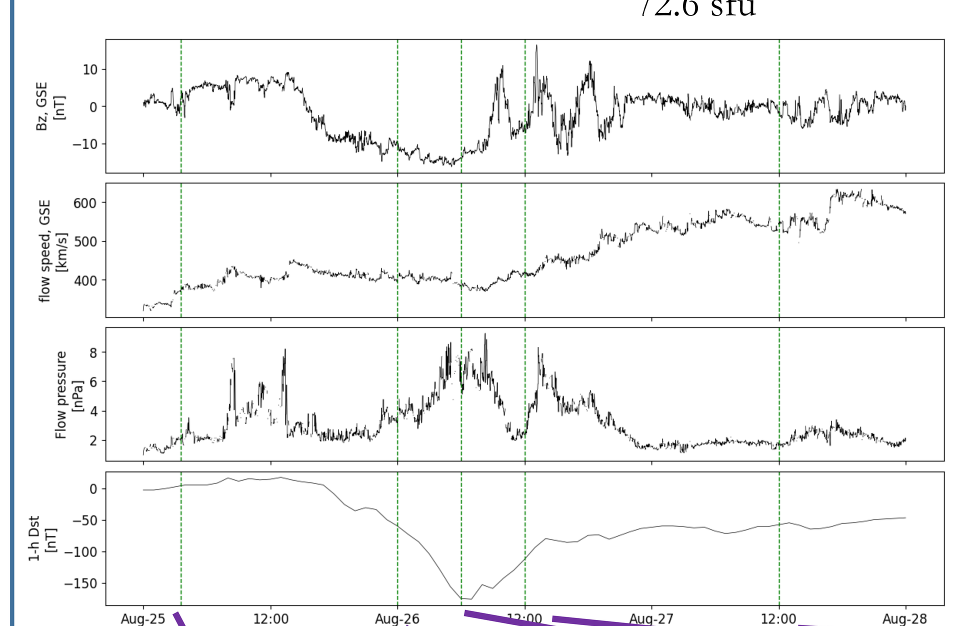




5. Scientific Results: Example Storm Model Predictions

Strong storm: Aug. 26, 2018 (min. Dst: -174 nT)

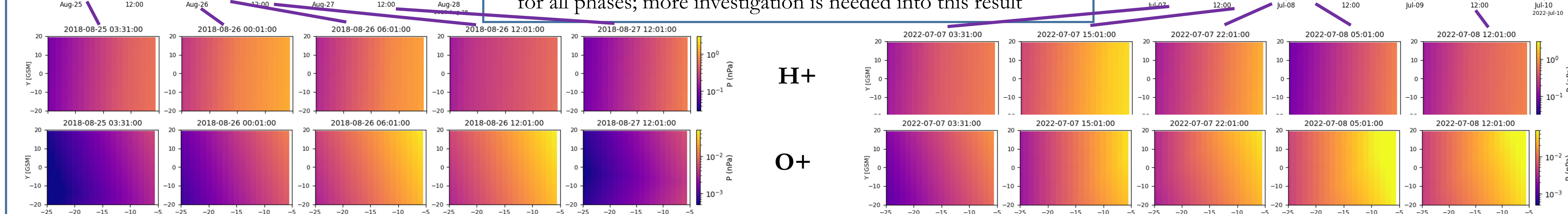
- Mixed storm
- Maximum f10.7: 72.6 sfu



- Model predicts the equatorial plasma sheet pressures during storm phases
- Both H+ and O+ pressures increase during both storms (agrees with statistical study) *[Liao et al., 2024]*
- A clear spatial decrease in pressures with radial distance from the Earth is also shown (agrees with statistical study) *[Liao et al., 2024]*
- The H+ pressure enhancement occurs earlier in the storm than O+ enhancement, but O+ enhancement is stronger
- O+ enhancement lingers into late recovery phase, while H+ pressure decreases faster
- The O+ pressure shows a weak cross-tail asymmetry developing towards dusk
- Model predicts higher O+ pressure during the moderate storm for all phases; more investigation is needed into this result

Moderate storm: July 07, 2022 (min. Dst: -80.48 nT)

- CIR/SIR storm
- Maximum f10.7: 135 sfu



6. Conclusions

- H+ and O+ pressure ML models track geomagnetic activity well
- H+ enhancement comes earlier in storms than O+ enhancement
- Duskside O+ asymmetry in agreement with Liao et al. (2024)

7. Future Work

- Continue to improve model performance
- Extend model to predict density and temperature in the plasma sheet
- Expand training set with Cluster/CODIF

Acknowledgements

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