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System Science Tools for MHD Simulations

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ABSTRACT

Modeling the global magnetosphere is important for comprehending its complex behavior and making critical weather predictions for safeguarding both individuals and space assets. While many studies focus solely on specific aspects or regions of the magnetosphere (e.g. inner magnetosphere, the radiation belts, etc.), our objective is to investigate the entire magnetosphere using systems science techniques. In this research, we employ the multi-variable canonical correlation analysis (CCA) to analyze the magnetospheric behavior and compare it directly with global magnetospheric simulations across various storm time events. To achieve this, we utilize data from the GAMERA MHD Simulation for our simulated magnetospheric inputs and draw on the OMNI datasets for our solar wind inputs. Through our analysis, we seek to determine whether the global simulation accurately replicates the real magnetospheric system and aim to propose a new validation methodology that will benefit the space physics community.

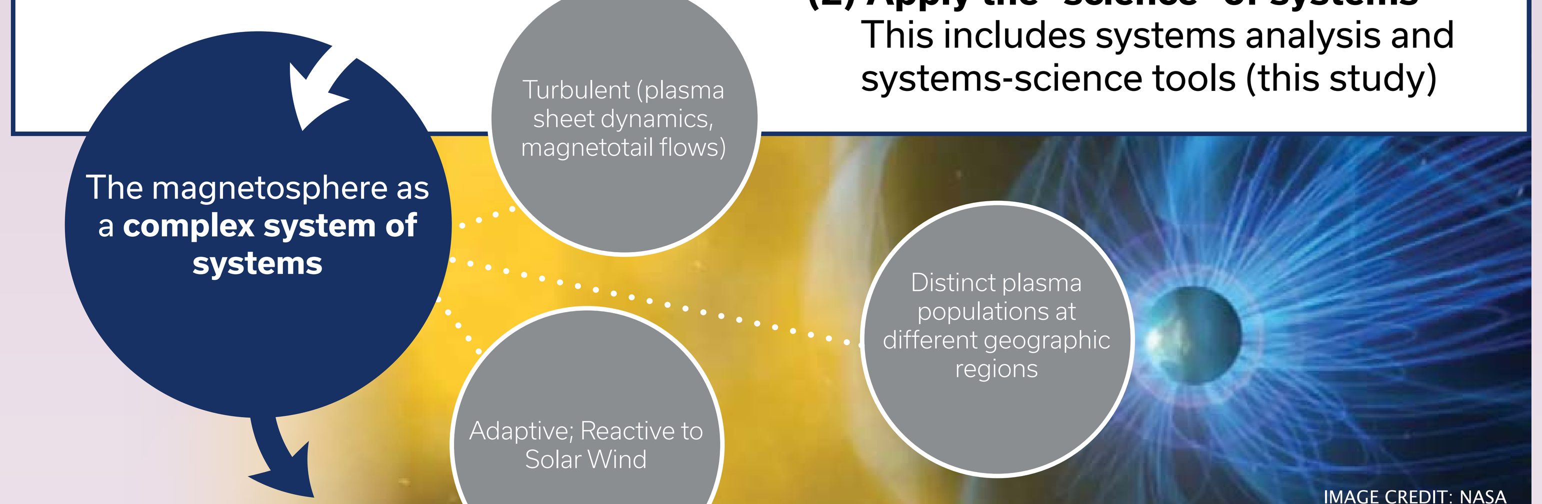
BACKGROUND: SYSTEM SCIENCE

System science is methodology that explores complex interrelated systems as a *whole* instead of focusing on a single system in order to understand physical behavior.

With systems science, there two components to be considered:

(1) Apply system thinking
One must account for all parts and connections, with diverse expertise

(2) Apply the "science" of systems
This includes systems analysis and systems-science tools (this study)



MOTIVATIONS & OVERVIEW

The overall goal of this project is to perform multi-variable correlation analysis to analyze the behavior of the magnetosphere and compare it side-by side with the behavior of global magnetospheric simulations

- Studying the global magnetosphere is becoming increasingly important in the field of space science.
- Comparisons and validation of Magnetospheric codes have typically focused on one aspect or region (e.g. GEM challenges)
- As a community, we need a tool to be able to analyze the codes in all their complexity.
- We can consider the magnetosphere to be a **complex, system of systems** that is qualified to be studied using **System Science methods** (One form of these methods is a **correlation analysis**).

This proposes **two main objectives** of this study:

⋆ Understand if the global simulation behaves as the real system does

⋆ Propose a new validation methodology for the space physics community

EVENT STUDY: 2008, 2013 STORMS

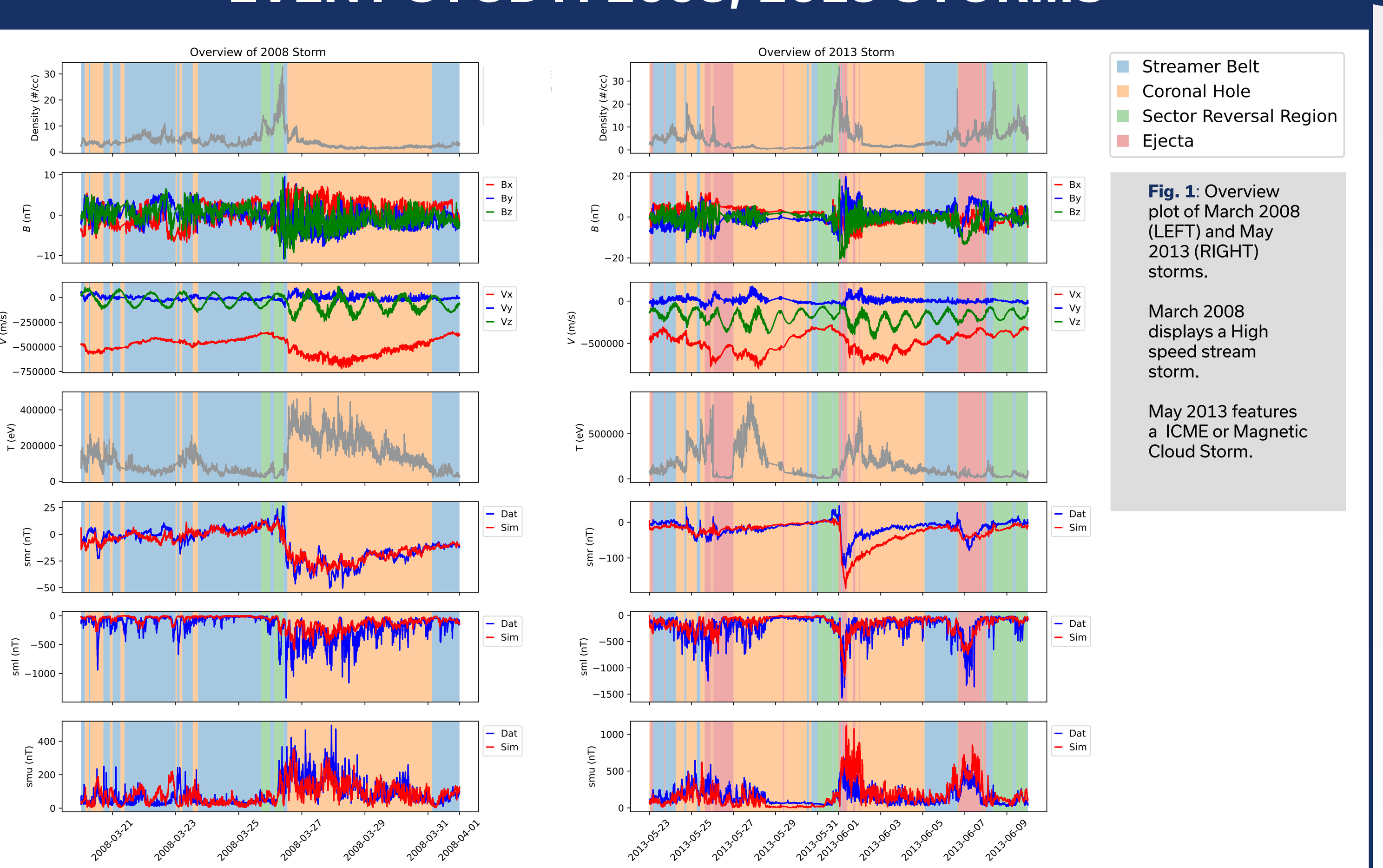


Fig. 1: Overview plot of March 2008 (LEFT) and May 2013 (RIGHT) storms.

March 2008 displays a High speed stream storm.

May 2013 features a ICME or Magnetic Cloud Storm.

METHODOLOGY: CANONICAL CORRELATION ANALYSIS

The method of **Canonical Correlation Analysis (CCA)** takes two state vectors (SW, ER) and seeks to find linear combinations of these vectors such that they have the maximum correlation to each other.

SYSTEM DRIVER: SOLAR WIND VARIABLES

Solar wind data is provided by the **OMNI database**

Inputs:
D: density
B$_z$: z-component of magnetic field
|*V*|: magnitude of the velocity

State Vector (t = timesteps) $SW_{\text{(input)}} = m \times t$

SYSTEM RESPONSE: MAGNETOSPHERIC VARS.

Magnetospheric data is provided by the **GAMERA MHD Simulation**

Inputs:
smr: symmetric ring current index
sml: max westward auroral electrojet strength
smu: max eastward auroral electrojet strength

State Vector (t = timesteps) $ER_{\text{(input)}} = n \times t$

Vector Transformation

Solar Wind scalar state variable $SW_{\text{CCA}} = 1 \times t$

Solar Wind scalar state variable $ER_{\text{CCA}} = 1 \times t$

Maximize the correlation between the scalar state variables via SVD of the *n* x *m* cross correlation matrix

Output: Canonical Covariate Pair (latent) – linear combination of the set of original variables with maximized correlated state variables and weights that relate the state vector to the new state scalars

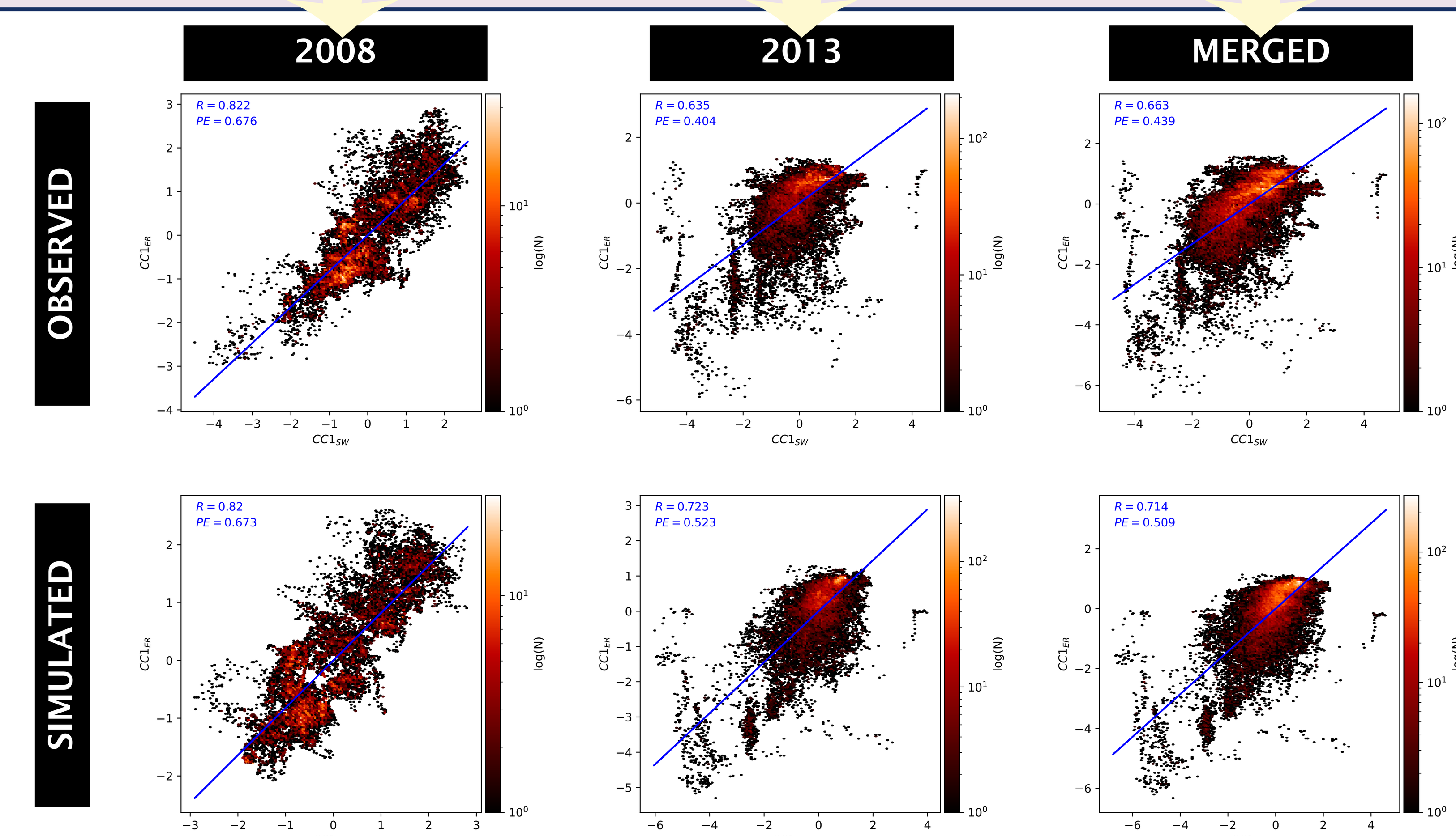


Fig. 2: Plots of the first canonical covariates (CC1) for the solar wind (SW) and magnetospheric (ER) variables for different storms with both observed and simulated data.

CONVERGENCE STUDY

How much data is needed to converge on the coefficients of CCA?

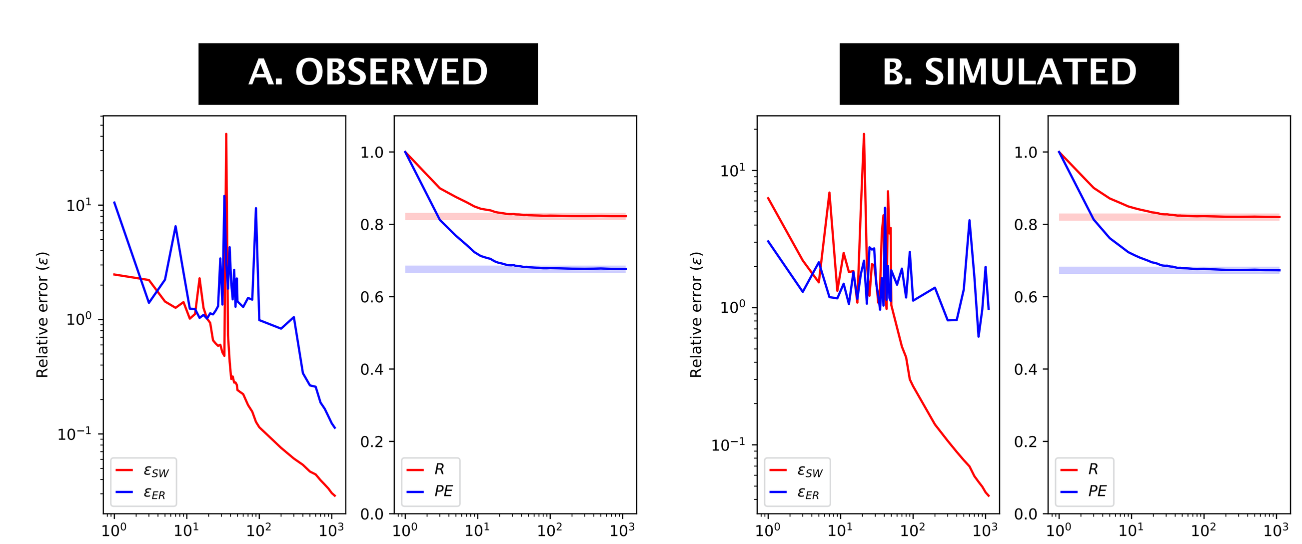


Fig. 3 (A,B):

(LEFT) Plot of relative error for the SW vars (red) and the ER vars (blue) for CCA per *N* number of points.

(RIGHT) Plot of Pearson's correlation coefficient (R, Red) and the prediction efficiency PE (blue) per *N* number of points Shaded region is about +/- 1% of actual value.

See convergence on order of 10's.

Only a small portion of the data is needed to converge!

GAMERA: Developed by the Center for **Geospace Storms (CGS)**

MHD simulation tool that improves upon Lyon-Fedder-Mobarry (LFM) code with many applications in heliophysics. Available variables include SuperMag indices, cross polar cap, and ring current total energy density.

Some **notable features** include:
- High-degree optimization
- OpenMP parallelism
- Easy adaptation to different geometries and initial/boundary conditions

Learn more here

FILTERING THE DATASET

Can we predict driver-response behavior by filtering the dataset by specific conditions?

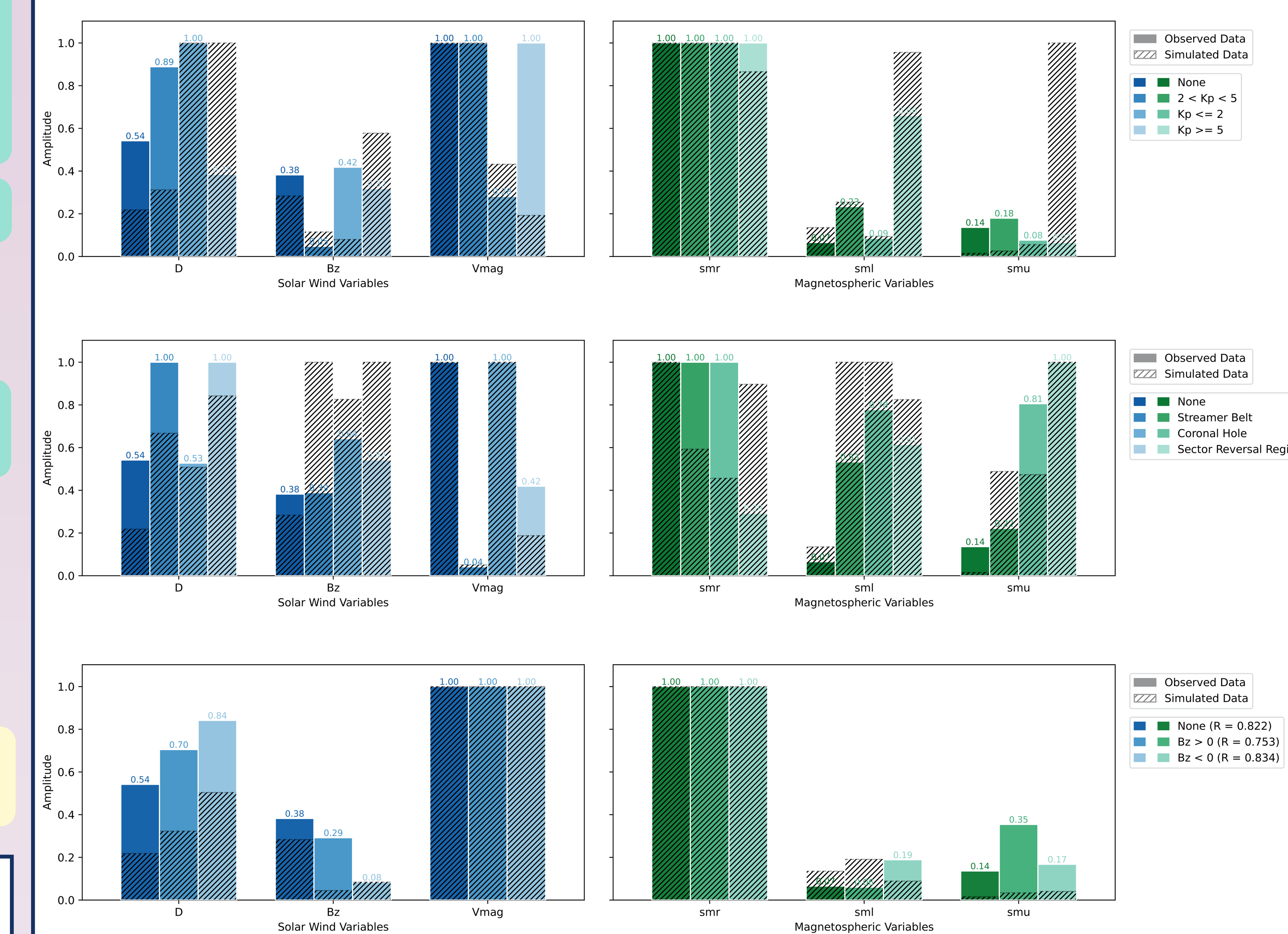


Fig. 4: Plot of CCA output amplitude weights comparing observed and simulated filtered data variables of 2008 storm. Data is filtered by Kp (TOP), Solar Wind Type (MIDDLE), and interplanetary magnetic field (IMF, BOTTOM).

The **amplitude** is the normalization of the weights by dividing all the weights by the maximum, such that the highest weight is 1.

Correlation coefficient with filter was greater (R>8.22) for both observation and simulation for Kp[2:5], Sector Reversal Region SW Type, and low IMF (Bz<0).

VARIABLE CORRELATION

Can we quantify individual correlations to determine if the same variables drive CCA in both our observations and simulations?

	CC1 (Solar Wind)			CC1 (Magnetopsheric)		
Var	**R (DATA)**	**R (SIM)**	**% Error**	**R (DATA)**	**R (SIM)**	**% Error**
D	-0.68	-0.55	19.12	-0.56	-0.45	19.64
Bz	-0.47	-0.47	0	-0.39	-0.39	0
V	0.92	0.96	4.35	0.75	0.79	5.33
smr	-0.81	-0.82	1.23	-0.99	-1	1.01
sml	-0.48	-0.63	31.25	-0.58	-0.77	32.76
smu	0.46	0.47	2.17	0.56	0.58	3.57

Agreement: *V* and *smr* are the top drivers in both observed and sim. data

CONCLUSION & FUTURE WORK

FUTURE WORK
- Obtain **more storm data** and a create larger merged dataset for analysis
- In addition, play around with more and less variable inputs (*not all magnetospheric variables were tested*!)
- Explore different MHD simulations outside of GAMERA
- Implement time lag
- Explore **non-linear methods**, such as **Deep CCA**

CONCLUSIONS
Are the same variables driving the simulation and the observed data? Yes, mostly.

- The 2008 storm outperformed the 2013, but both storms found general overall agreement in the weights for the unfiltered real (observed) and simulation data.
- Filtering the data provided more clues on what is driving our model with better agreement.

Propose a new validation methodology for the space physics community
- The systems science methods used in this project provide a viable pathway for setting a community standard in model validation
- Additionally, these methods can help dissect where simulations may fail/ have deficiencies

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