Substorm dynamics in MHD: Statistical validation tests and paths for improvement

John Haiducek[1], Daniel Welling[2], Steven Morley[3], Agnit Mukhopadhyay[4], Xiangning Chu[5], Joseph Helmboldt[1], Joseph Huba[6], and Natalia Ganushkina[4]

[1]US Naval Research Laboratory
[2]University of Texas at Arlington
[3]Los Alamos National Laboratory
[4]University of Michigan Ann Arbor
[5]University of California Los Angeles
[6]Syntek Technologies

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Abstract

Magnetohydrodynamic (MHD) models have been used for nearly four decades to study the dynamics of magnetospheric substorms. However, until recently no demonstration has been made that MHD models can consistently reproduce substorm onset times in a statistical sense. To test whether MHD can reproduce observed substorm onset times, we developed a procedure for identifying substorm onsets that can be applied both to observational data and to MHD output. Our substorm identification procedure aims to improve upon existing methods of substorm identification by using multiple types of observations to corroborate each identified substorm. Using this procedure, we identified over 100 substorms from the period 1-31 January 2005. Using this list of substorm onset times, we show that the MHD model has weak, but statistically significant skill in predicting substorm onset times. We explore paths to improving the ability of the MHD model to predict substorm dynamics by testing different configurations of the MHD model.

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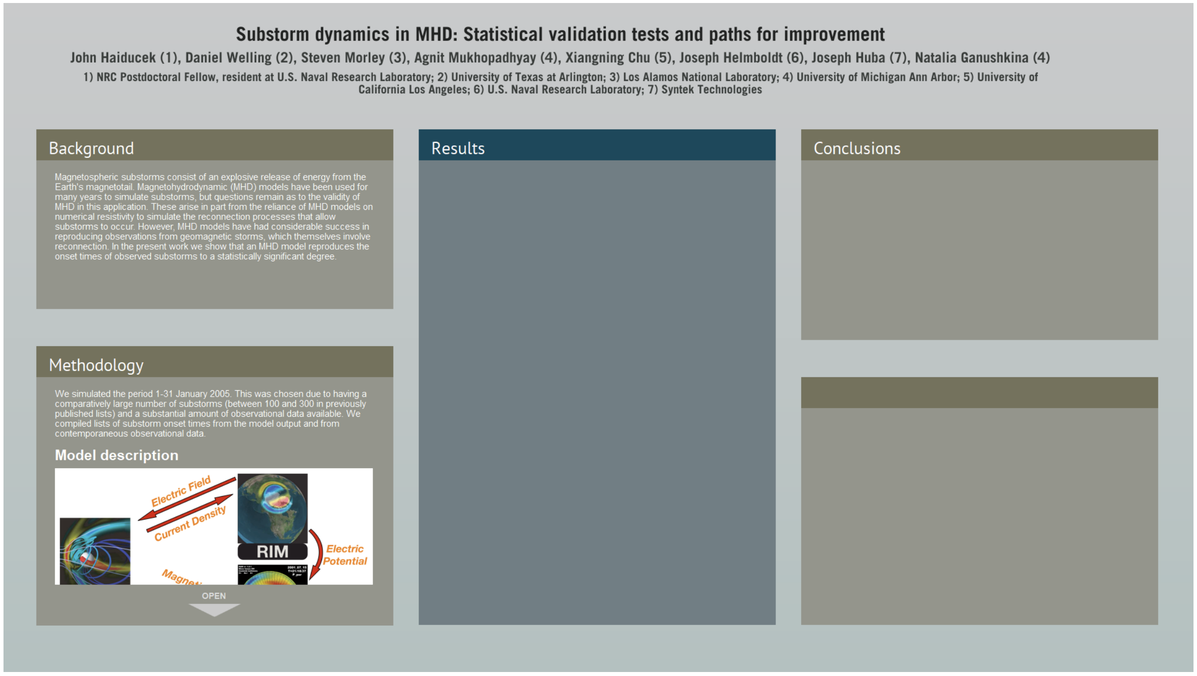

John Haiducek (1), Daniel Welling (2), Steven Morley (3), Agnit Mukhopadhyay (4), Xiangning Chu (5), Joseph Helmboldt (6), Joseph Huba (7), Natalia Ganushkina (4)

1) NRC Postdoctoral Fellow, resident at U.S. Naval Research Laboratory; 2) University of Texas at Arlington; 3) Los Alamos National Laboratory; 4) University of Michigan Ann Arbor; 5) Laboratory for Atmospheric and Space Physics, University of Colorado Boulder; 6) U.S. Naval Research Laboratory; 7) Syntek Technologies

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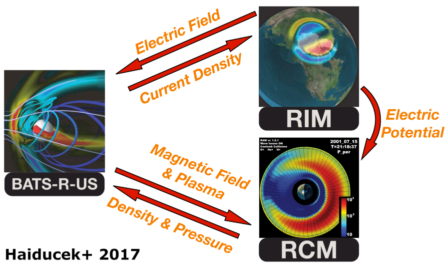
BACKGROUND

Magnetospheric substorms consist of an explosive release of energy from the Earth's magnetotail. Magnetohydrodynamic (MHD) models have been used for many years to simulate substorms, but questions remain as to the validity of MHD in this application. These arise in part from the reliance of MHD models on numerical resistivity to simulate the reconnection processes that allow substorms to occur. However, MHD models have had considerable success in reproducing observations from geomagnetic storms, which themselves involve reconnection. In the present work we show that an MHD model reproduces the onset times of observed substorms to a statistically significant degree.

METHODOLOGY

We simulated the period 1-31 January 2005. This was chosen due to having a comparatively large number of substorms (between 100 and 300 in previously published lists) and a substantial amount of observational data available. We compiled lists of substorm onset times from the model output and from contemporaneous observational data.

Model description



The simulation was performed with the Space Weather Modeling Framework (Toth+ 2005, 2012) with the following components:

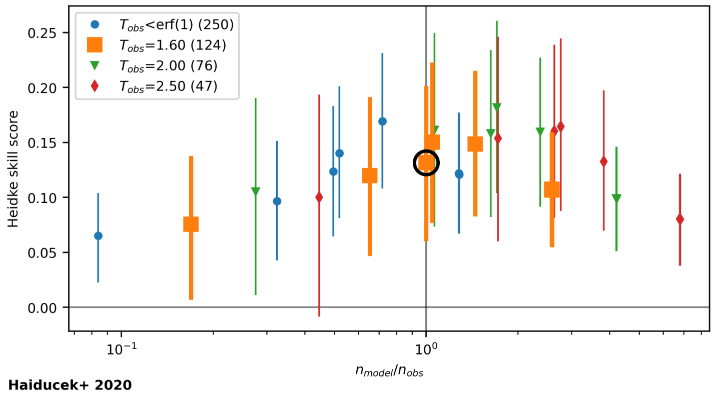
- Block Adaptive Tree Solar-wind Roe-type Upwind Scheme (BATS-R-US) MHD solver (De Zeeuw+ 2000; Powell+ 1999)
- Ridley Ionosphere Model (Ridley+ 2003, 2004)
- Rice Convection Model (Sazykin 2000; Toffoletto+ 2003; Wolf+ 1982) for the inner magnetosphere

Substorm identification

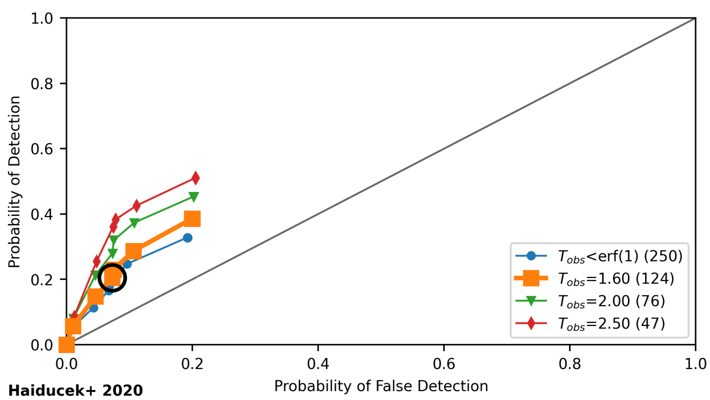
All of the available observational datasets have limitations resulting from the placement and availability of observing equipment. At the same time, most of the signatures commonly used to identify substorms can be produced by other magnetospheric processes. As a result, no single dataset is completely reliable for determining when a substorm has occurred. To address this, we developed a procedure for combining lists of substorm onsets from multiple sources.

[VIDEO] https://www.youtube.com/embed/UBzfGN8K2pE?rel=0&fs=1&modestbranding=1&rel=0&showinfo=0

MHD PREDICTION OF SUBSTORM ONSETS

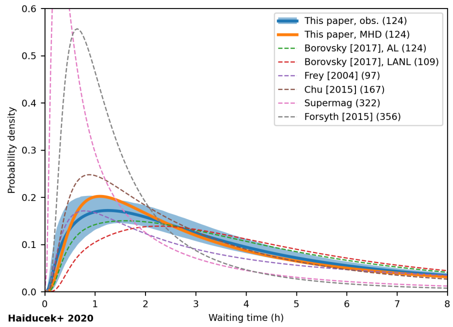


We computed Heidke skill scores (above) for forecast of substorm onset within a 30 minute window, shown here as a function of frequency bias (the ratio of modeled to observed substorms) for a variety of threshold choices. Values greater than zero represent a skillful forecast; a perfect forecast would have a skill score of one. Error bars denote 95% confidence interval. The skill scores obtained are consistently positive for a wide range of selection parameters. These results show that the MHD model predicts substorms with a skill better than random chance.

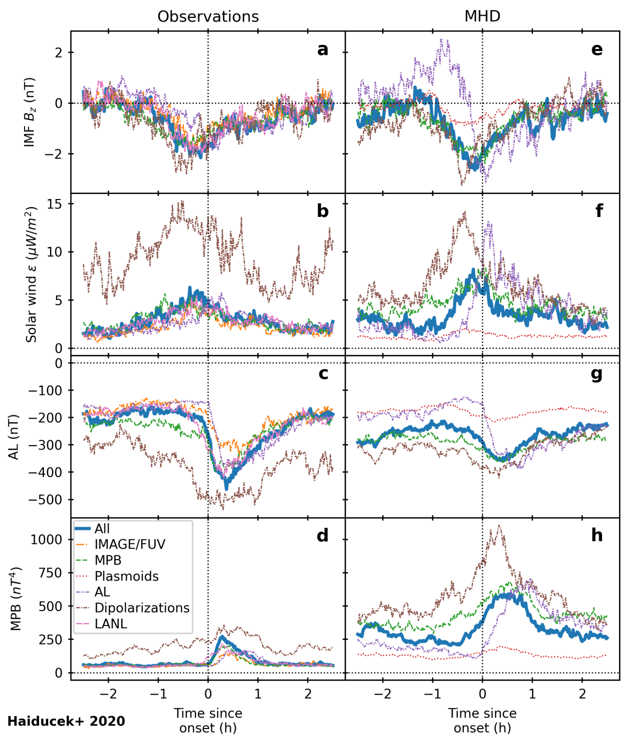


Receiver operating characteristic (ROC) curves for forecast of a substorm within a 30-minute window, showing the probability of detection (POD)as a function of probability of false detection (POFD). showing several choices of identification threshold for observed substorms. A perfect forecast would produce a constant POD of 1. The truncation of the curve at POFD~0.2 is a consequence of the procedure used to identify substorms from the data.

SUBSTORM TIMING AND CHARACTERISTICS

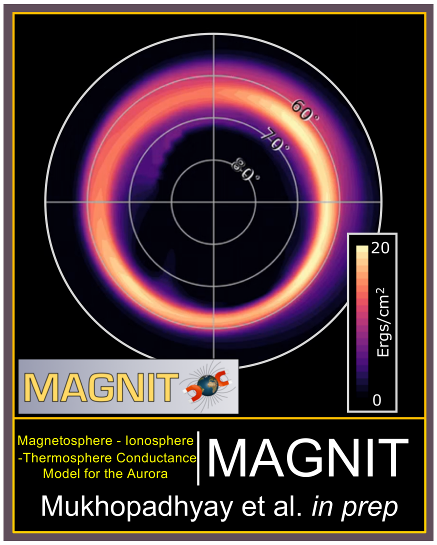


Distributions of substorm waiting times from our work and from previous work covering the same time period. Parenthesized numbers in the legend denote the number of substorms in each dataset. We adjusted the tuning parameters of our selection procedure so that it produces a distribution near the median of the previously published datasets.

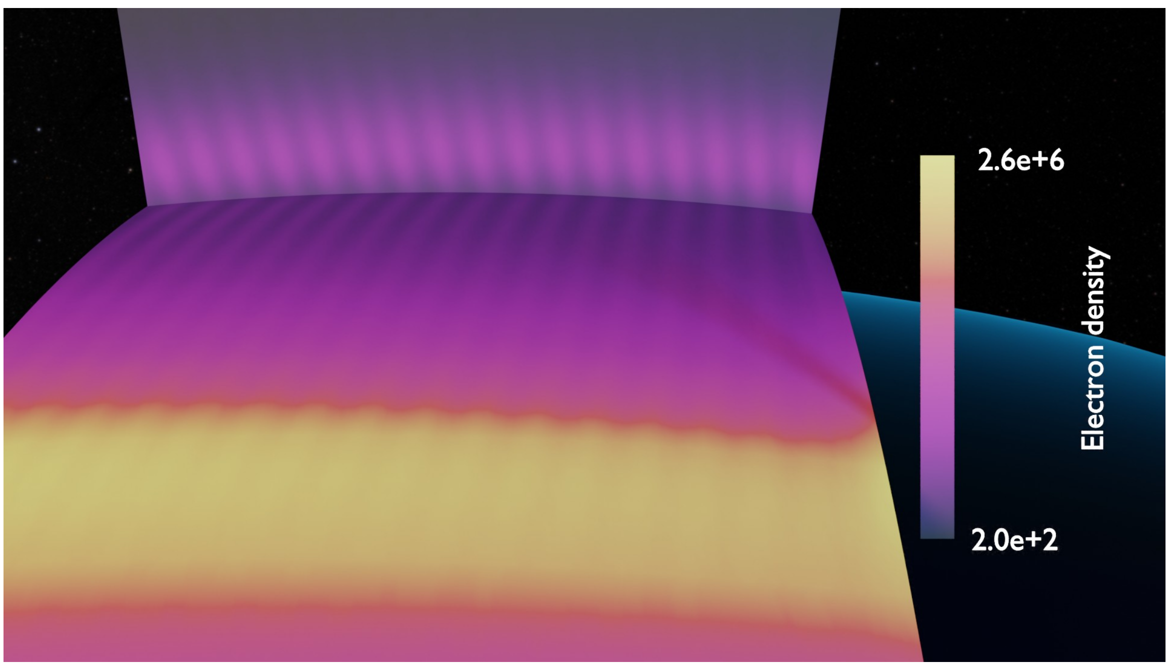


Superposed epoch analysis of solar wind driving parameters IMF Bz and epsilon, and geomagnetic response parameters AL index and midlatitude positive bay (MPB) index. These plots demonstrate that the model exhibits qualitatively correct behavior with respect to substorm dynamics.

PATHS FOR IMPROVEMENT



The model tends to produce a weaker AL response and greater cross-polar cap potential compared to observations, suggesting that the ionospheric conductivity in the model may be incorrect. We are currently testing the new Magnetosphere - Ionosphere-Thermosphere Conductance Model for the Aurora (MAGNIT) to see how it affects substorm dynamics.



Data assimilation of magnetospheric and ionospheric observations could yield additional improvements. We are developing a new data assimilation system, which is now being tested on SAMI3 (SAMI3 is Another Model of the Ionosphere 3D).

ABSTRACT

Magnetohydrodynamic (MHD) models have been used for nearly four decades to study the dynamics of magnetospheric substorms. However, until recently no demonstration has been made that MHD models can consistently reproduce substorm onset times in a statistical sense. To test whether MHD can reproduce observed substorm onset times, we developed a procedure for identifying substorm onsets that can be applied both to observational data and to MHD output. Our substorm identification procedure aims to improve upon existing methods of substorm identification by using multiple types of observations to corroborate each identified substorm. Using this procedure, we identified over 100 substorms from the period 1-31 January 2005. Using this list of substorm onset times, we show that the MHD model has weak, but statistically significant skill in predicting substorm onset times. We explore paths to improving the ability of the MHD model to predict substorm dynamics by testing different configurations of the MHD model.

REFERENCES

De Zeeuw, D. L., Gombosi, T. I., Groth, C. P. T., Powell, K. G., & Stout, Q. F. (2000). An adaptive MHD method for global space weather simulations. IEEE Transactions on Plasma Science, 28(6), 1956–1965. https://doi.org/10.1109/27.902224

Haiducek, J. D., Welling, D. T., Ganushkina, N. Y., Morley, S. K., & Ozturk, D. S. (2017). SWMF Global Magnetosphere Simulations of January 2005: Geomagnetic Indices and Cross-Polar Cap Potential. Space Weather, 15(12), 1567–1587. https://doi.org/10.1002/2017SW001695

Haiducek, J. D., Welling, D. T., Morley, S. K., Ganushkina, N. Y., & Chu, X. (2020). Using Multiple Signatures to Improve Accuracy of Substorm Identification. Journal of Geophysical Research: Space Physics, 125(4), e2019JA027559. https://doi.org/10.1029/2019JA027559

Powell, K. G., Roe, P. L., Linde, T. J., Gombosi, T. I., & De Zeeuw, D. L. (1999). A Solution-Adaptive Upwind Scheme for Ideal Magnetohydrodynamics. Journal of Computational Physics, 154(2), 284–309. https://doi.org/10.1006/jcph.1999.6299

Ridley, A. J., Gombosi, T. I., De Zeeuw, D. L., & DeZeeuw, D. L. (2004). Ionospheric control of the magnetosphere: Conductance. Annales Geophysicae, 22, 567–584. https://doi.org/10.5194/angeo-22-567-2004

Ridley, A. J., Richmond, A. D., Gombosi, T. I., Zeeuw, D. L. D., & Clauer, C. R. (2003). Ionospheric control of the magnetospheric configuration: Thermospheric neutral winds. Journal of Geophysical Research: Space Physics, 108(A8), 1328. https://doi.org/10.1029/2002JA009464

Sazykin, S. Y. (2000). Theoretical Studies of Penetration of Magnetospheric Electric Fields to the Ionosphere. Utah State University.

Toffoletto, F., Sazykin, S., Spiro, R., & Wolf, R. (2003). Inner magnetospheric modeling with the Rice Convection Model. Space Science Reviews, 107(1–2), 175–196. https://doi.org/10.1023/A:1025532008047

Tóth, G., Sokolov, I. V., Gombosi, T. I., Chesney, D. R., Clauer, C. R., De Zeeuw, D. L., Hansen, K. C., Kane, K. J., Manchester, W. B., Oehmke, R. C., Powell, K. G., Ridley, A. J., Roussev, I. I., Stout, Q. F., Volberg, O., Wolf, R. A., Sazykin, S., Chan, A., Yu, B., & Kóta, J. (2005). Space Weather Modeling Framework: A new tool for the space science community. Journal of Geophysical Research: Space Physics, 110(A12), A12226. https://doi.org/10.1029/2005JA011126

Wolf, R. A., Harel, M., Spiro, R. W., Voigt, G.-H., Reiff, P. H., & Chen, C.-K. K. (1982). Computer simulation of inner magnetospheric dynamics for the magnetic storm of July 29, 1977. Journal of Geophysical Research, 87(A8), 5949–5962. https://doi.org/10.1029/JA087iA08p05949