MULTISCALE SPACE WEATHER SIMULATIONS

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EXECUTIVE SUMMARY

Our efforts aim to achieve a breakthrough advance in the understanding of space weather. The most destructive forms of space weather are caused by major solar eruptions: fast coronal mass ejections (CMEs) and eruptive X-class flares. These destructive events originate with magnetic fields emerging from the solar interior, forming the active regions from where CMEs erupt into the heliosphere. Upon impacting the Earth, interplanetary CMEs impact the magnetosphere and produce geomagnetic storms. This process is controlled by the microphysics of magnetic reconnection. Our goal is to answer the most salient questions of space weather: how the buildup of magnetic energy results in solar eruptions, and how magnetic reconnection results in geomagnetic storms.

RESEARCH CHALLENGE

Our research solves fundamental problems in plasma physics, solar physics, and magnetospheric physics that relate to magnetic field energization and reconnection. Consequently, the results are significant to solar and plasma scientists, as well as magnetosphere and space weather scientists.

METHODS & CODES

Our approach combines the efficiency of global fluid-type models with the physical capabilities of computationally expensive but physically accurate local kinetic models. The resulting magnetohydrodynamic with embedded particle-in-cell (MHD–EPIC) model is 100 to 10,000 times more efficient than a global kinetic model. In addition, we found that the kinetic scales can be artificially increased, which can dramatically—by many orders of magnitude—reduce the computational cost of the embedded PIC model. Fig. 1 shows an MHD–EPIC simulation of the magnetosphere of Earth.

The flux emergence and CME initiation simulations are carried out with our high-resolution MHD code BATS–R–US in a variation called the Spherical Wedge Active Region Model (SWARM). The simulation domain extends from the convection zone into the corona with spherical wedge grid geometry and a domain the size of an active region. SWARM models the upper convection zone extending from a depth of 0.95 Rs to a height of 1.25 Rs, and extending 12 × 24 degrees, large enough to encompass a solar active region. Spherically adaptive grids allow us to greatly reduce the number of computational cells while also resolving the photosphere. Using SWARM, we have performed rigorous flux-emergence calculations and the formation of active regions with no *ad hoc* assumptions about coronal or photospheric conditions.

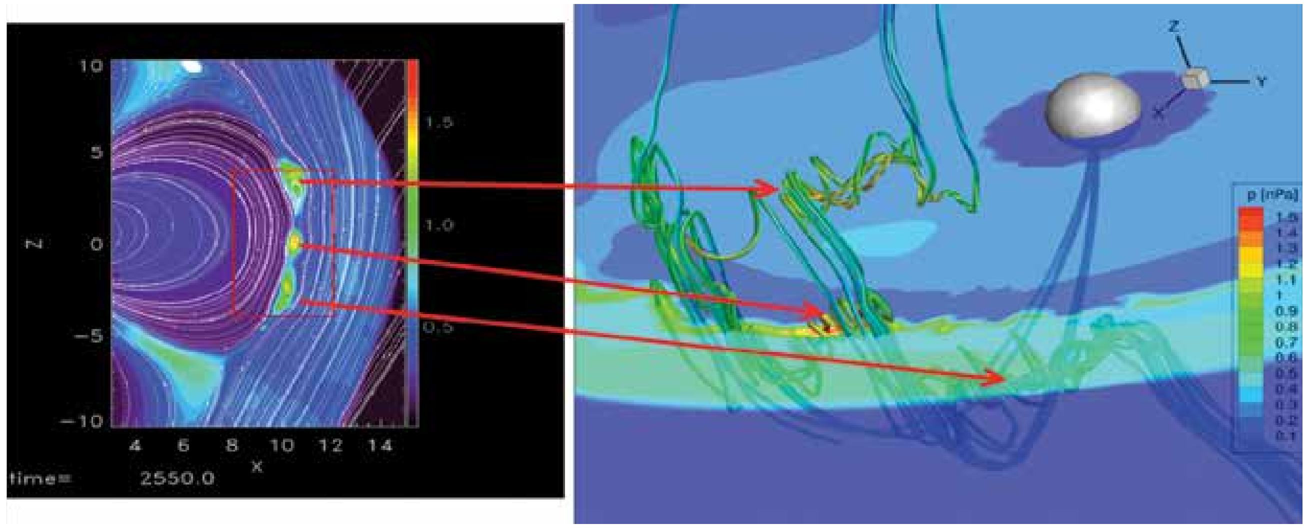

Figure 1: MHD–EPIC simulation of the Earth's magnetosphere. Left: color image represents pressure with projected field lines. The MHD simulation extends to 256Re; the red box indicates the embedded PIC model (4Re × 6Re × 6Re). Right: simulated flux transfer event where a magnetic flux rope is formed by magnetic reconnection. Field line colors represent plasma pressure.

RESULTS & IMPACT

We have used this unique opportunity to simulate space weather events using the MHD with Embedded Particle-in-Cell (MHD-EPIC) model, where the reconnection is handled by a kinetic PIC code. With this approach, we focused on modeling the fundamental process of reconnection and its impact on global dynamics. Currently, the MHD–EPIC model is the first three-dimensional global study of the complex reconnection process using a high-fidelity kinetic model for the magnetic reconnection. We also made breakthrough advances in simulating flux emergence at an active-region scale in spherical geometry—simulations that will produce eruptions, most notably flares and coronal mass ejections. This research addresses the most salient question of space weather: how the buildup of magnetic energy results in solar eruptions.

WHY BLUE WATERS

Our project uses the Blue Waters petascale computing resource to perform unprecedented space weather simulations. This capability allows us to simulate magnetic flux emergence from the convection zone into the corona to form active regions that may result in coronal mass ejections. Using Blue Waters allows us to model an entire active region with sufficient grid resolution to capture magnetic energy buildup. Blue Waters also allows us to model the reconnection process in the magnetosphere with the MHD–EPIC model and gain a better understanding of the intricate interaction between small kinetic and global scales that result in magnetospheric storms.

PUBLICATIONS & DATA SETS

Toth, G., et al., Scaling the ion inertial length and its implications for modeling reconnection in global simulations. *Journal of Geophysical Research*, 122 (2017), p. 10336.

Chen, Y., et al., Global three-dimensional simulation of Earth's dayside reconnection using a two-way coupled magnetohydrodynamics with embedded particle-in-cell model: initial results. *Journal of Geophysical Research*, 122 (2017), p. 10318.

Manchester, W., et al., Coupled Simulations of Magnetic Flux Emergence. In preparation (2018).