ADVANCED SPACE WEATHER MODELING

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EXECUTIVE SUMMARY

Our effort aims to achieve a breakthrough advance in the understanding of space weather. The most destructive forms of space weather are due to 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

Major space weather events are caused by large-scale expulsions of magnetized plasma from the Sun, which are known as coronal mass ejections (CMEs) and that typically travel to Earth in one to three days. These eruptions occur frequently, as often as several times per day during solar maximum, and cause geomagnetic storms by triggering sudden reconfigurations of the magnetosphere by magnetic reconnection. Extreme space weather events are caused by the most energetic CMEs, which drive sudden and extensive changes in the Earth's magnetic field producing among other effects large-scale electric impulses that can melt transformers and cause cascading blackouts. Repair times for replacing the high-voltage transformers is estimated to be several months.

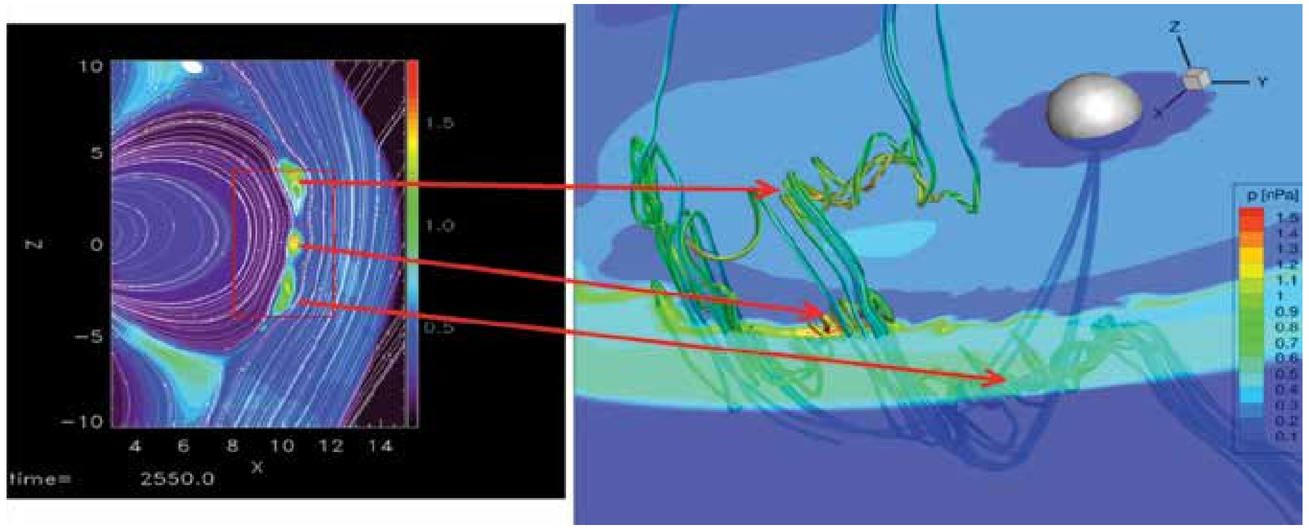

Figure 1: MHD-EPIC simulation of the Earth's magnetosphere. Left panel: 2D cut; color represents pressure with projected field lines. The MHD simulation extends to 256RE; red box indicates the embedded PIC model (4REx6REx6RE). Right panel: 3D structure of a magnetic flux rope formed by magnetic reconnection. Field line colors represent plasma pressure.

Being able to predict extreme space weather is a challenging task that requires both accurate simulations of CME structures when they reach Earth and the response of the magnetosphere. The magnetic reconnection process that lies at the heart of space weather events depends on the magnetic field carried by the coronal mass ejection as well as on the plasma processes happening at kinetic scales. Accurate modeling of magnetic storms, therefore, requires prediction of the interplanetary magnetic field of CMEs and an accurate model for the reconnection process. Our proposed research addresses both of these crucial issues.

METHODS & CODES

We combine the efficiency of global fluid-type models with the physical capabilities of 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 with 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 12x24 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 on coronal or photospheric conditions.

RESULTS & IMPACT

We have used this unique opportunity to simulate space weather events with the MHD-EPIC model, where the reconnection is handled by a kinetic PIC code. With this approach, we focused on modeling of the fundamental process of reconnection and its impact on the global dynamics. Currently, the MHD-EPIC model is the first three-dimensional global study of the complex process reconnection process using a high-fidelity kinetic model for the magnetic reconnection. We also made breakthrough advances in simulating flux emergence at active-region scale in spherical geometry. This work addresses the most salient questions of space weather.

WHY BLUE WATERS

Our project uses the Blue Waters petascale computing facility 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 a whole 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 with embedded PIC model and gain a better understanding of the intricate interaction between the small kinetic scales and the global scales that result in magnetospheric storms.

PUBLICATIONS AND DATA SETS

Chen, Y., et al., Extended Magnetohydrodynamics with Embedded ParticleinCell (MHDEPIC) Simulation of Earth's Magnetopause reconnection. GEM 2016, Santa Fe, N.M., June 19–24, 2016.

Toth, G., et al., Scaling the ion inertial length and its implications modeling reconnection in global simulations. MMS Workshop, Boulder, Colo., June 6–8, 2016.

Manchester, W., B. van der Holst, and G. Toth, Simulating Solar Active Regions. LWS Technical Interchange Meeting, Mountain View, Calif., May 30–June 2, 2017.