Geomagnetic simulation using MHD with Adaptively Embedded PIC model

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Abstract

The MHD with embedded PIC (MHD-EPIC) model makes it feasible to incorporate kinetic physics into a global simulation. Still, this requires a large enough box-shaped PIC domain to accommodate the movement and changes of the magnetic reconnection regions over time. This wastes computational resources on simulating regions with the expensive PIC model where MHD would be sufficient to describe the physics. We have developed a new MHD with Adaptively Embedded PIC (MHD-AEPIC) algorithm that couples the BATS-R-US MHD model with the new FLexible Exascale Kinetic Simulator (FLEKS) PIC code. In the new coupled model the PIC domains can move with the magnetic reconnection regions and adapt to them with an arbitrary shape. In this work, we will first introduce the algorithms for selecting the reconnection regions in the MHD model that need to be resolved with the kinetic PIC model. Then we will compare simulations obtained with MHD-EPIC using fixed PIC regions versus MHD-AEPIC employing adaptive PIC regions to verify that the new model generates reliable results. Finally, we will apply the MHD-AEPIC model to a global magnetic storm simulation and demonstrate the improved efficiency.

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Geomagnetic storm event simulation using a global MHD with adaptively embedded particle-in-cell (MHD-AEPIC) model

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PREEVENTS

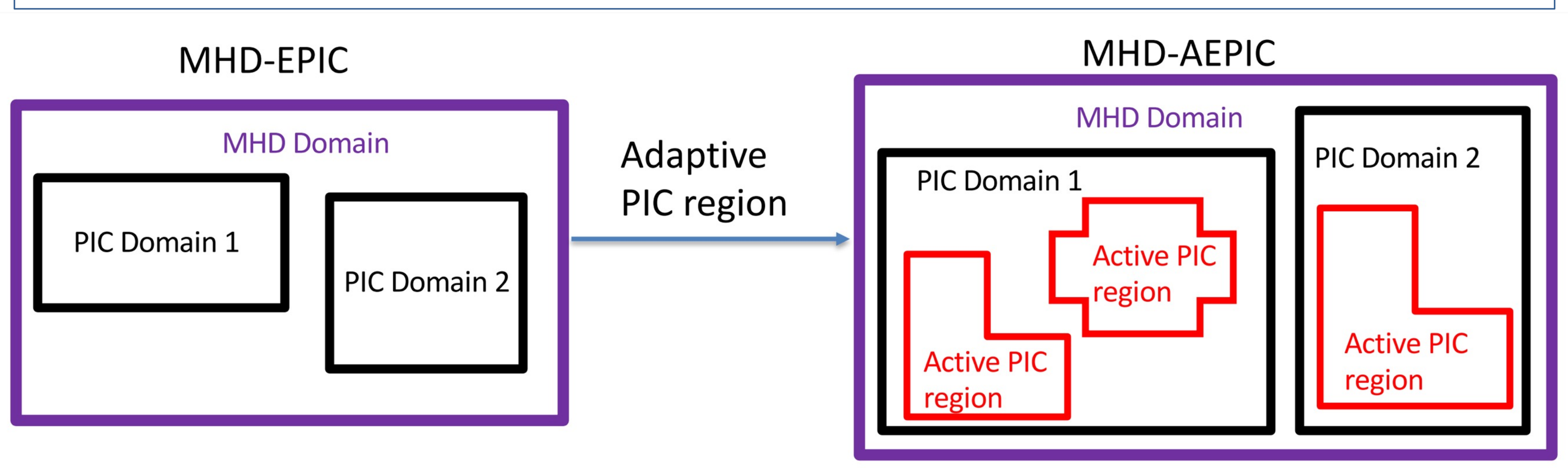
Introduction

❖ Kinetic Physics in Global Magnetosphere Simulation

- MHD-EPIC: two-way coupling between MHD and PIC models
- MHD-EPIC has been used to study the dayside magnetic reconnection (Chen et al. 2017)
- Applying MHD-EPIC to the tail is challenging: large PIC region is needed to cover the tail reconnection sites
- *MHD-AEPIC: dynamically adapt the PIC region during the runtime to minimize the computational cost*

Model Description

❖ FLexible Exascale Kinetic Simulator (FLEKS, Chen et al 2021)



- Gauss' law satisfying energy-conserving semi-implicit particle-in-cell method (GL-ECSIM)
- Particle resampling: splitting and merging
- Adaptation: PIC cells can be switched on/off

❖ Identifying reconnection sites for PIC

- Current density divided by perpendicular magnetic field:

$$c_1 = \frac{j^2}{|j \times B| + j\epsilon} \Delta x > 0.4$$

- Divergence of the magnetic field curvature

$$c_2 = [\nabla \cdot (b \cdot \nabla b)](\Delta x)^2 > -0.1$$

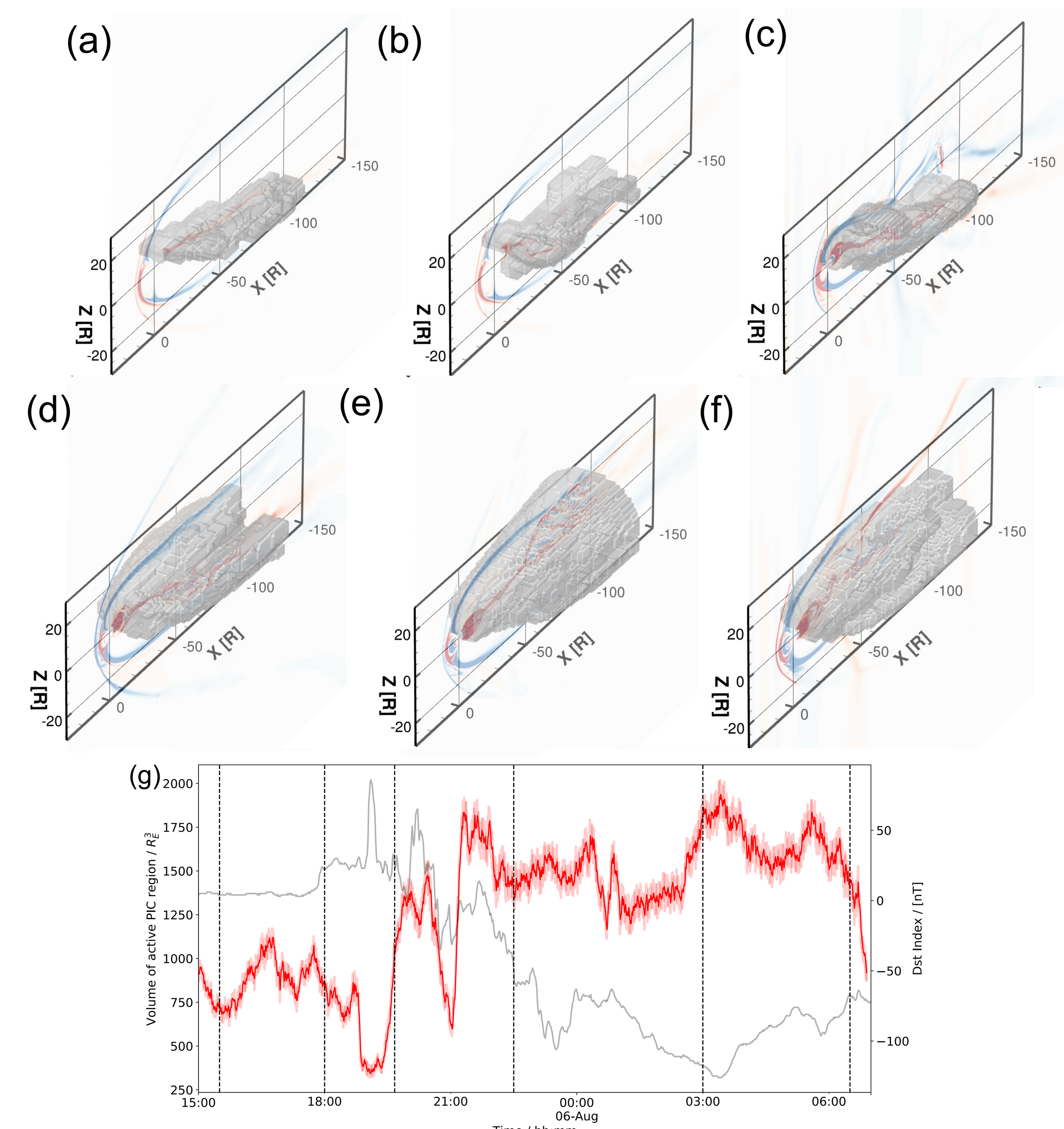
- Specific entropy

$$c_3 = \frac{p}{\rho^\gamma} > 0.02 \text{ nPa/(amu*cm}^{-3})^\gamma$$

c_1 identifies current sheet but ignores the guide field;
c_2 excludes O-lines;
c_3 restricts the PIC region to be inside the magnetosphere.

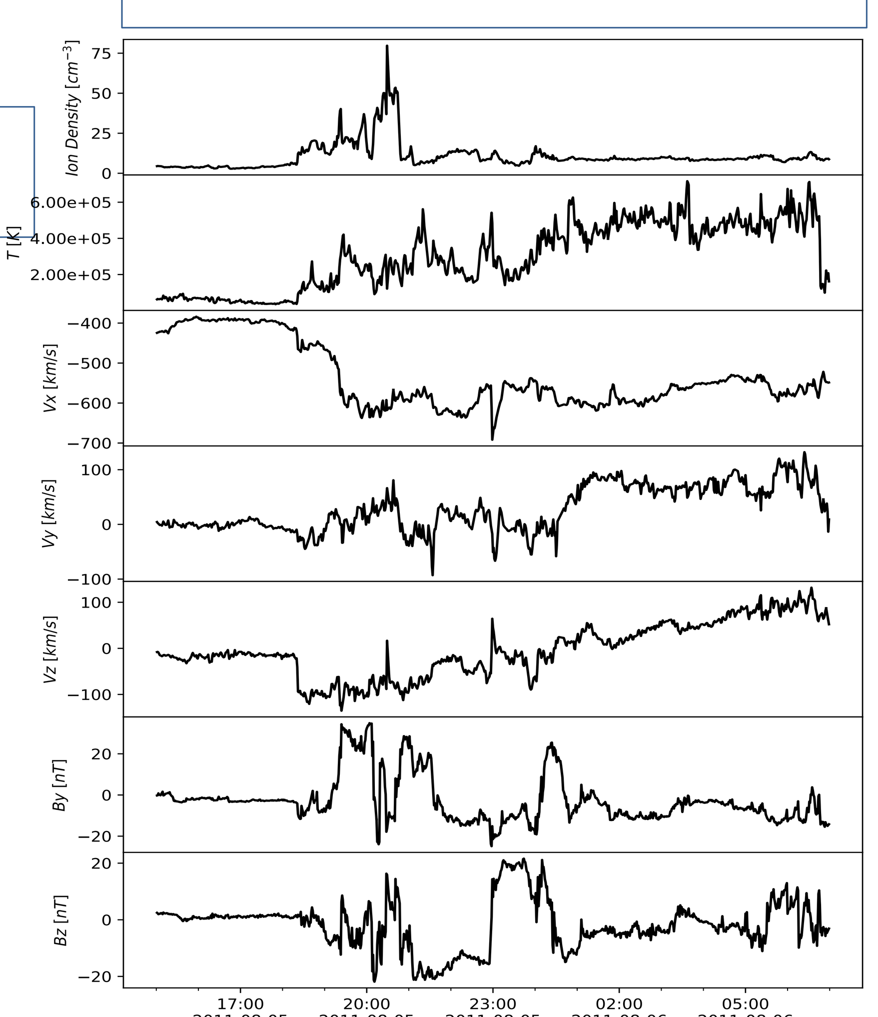
Dynamically adapting PIC domain

The grey iso-surfaces are the boundaries of the active PIC domain.



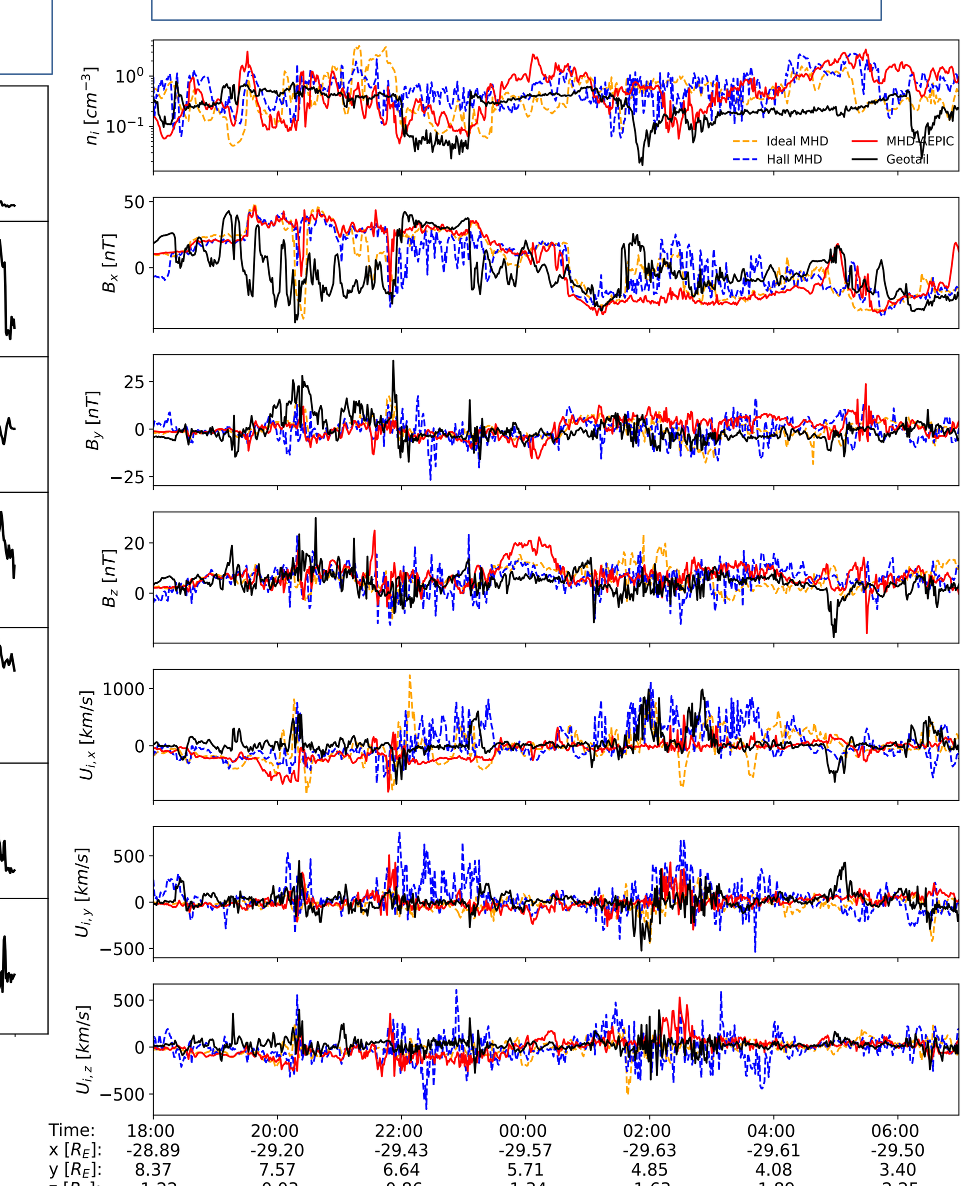
Geomagnetic Storm Simulation

❖ Selected storm event: 2011-08-05



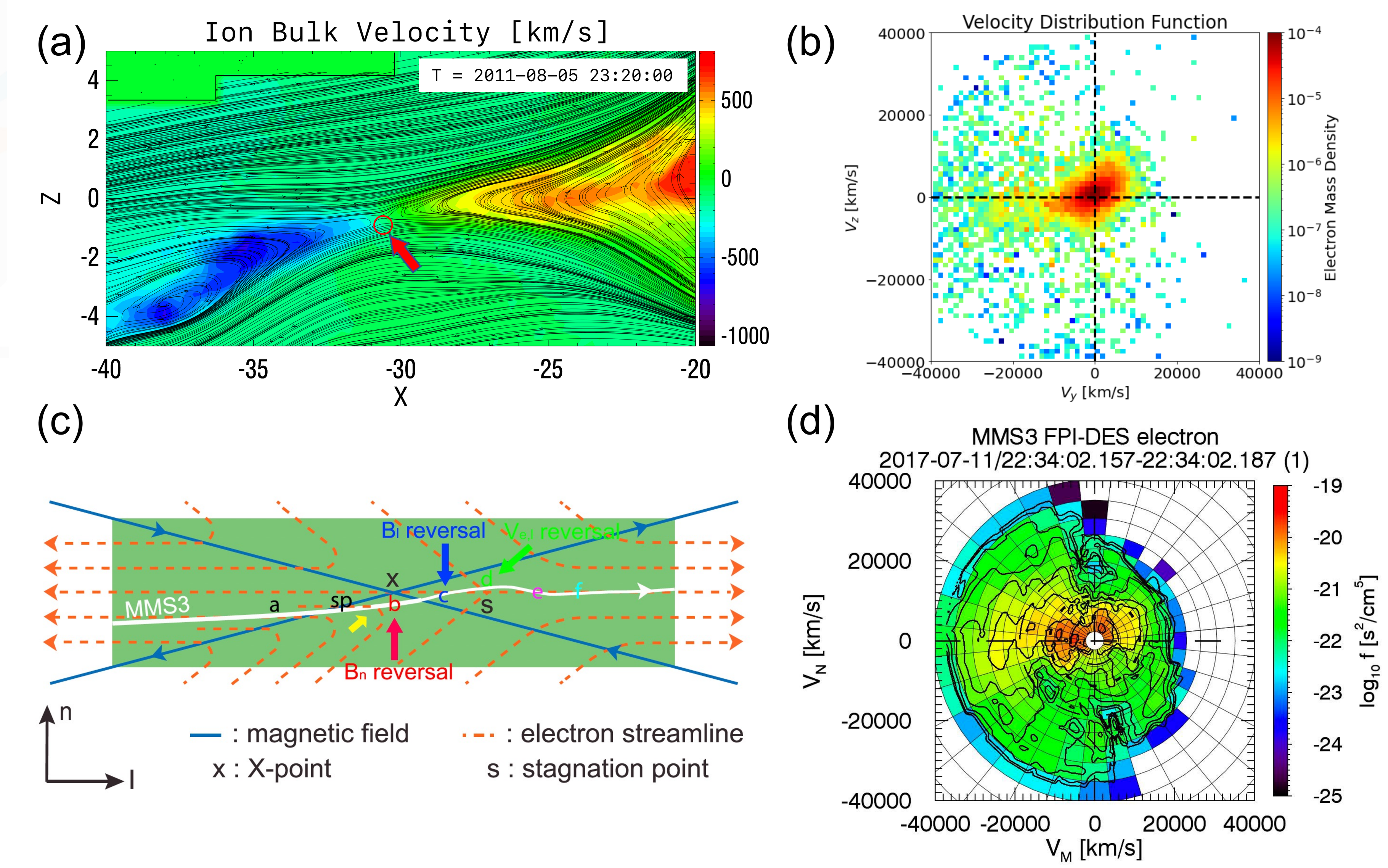
Two southward turnings of IMF happen at 18:30 on 2011-08-05 and 6 hours later.

❖ Geotail observation

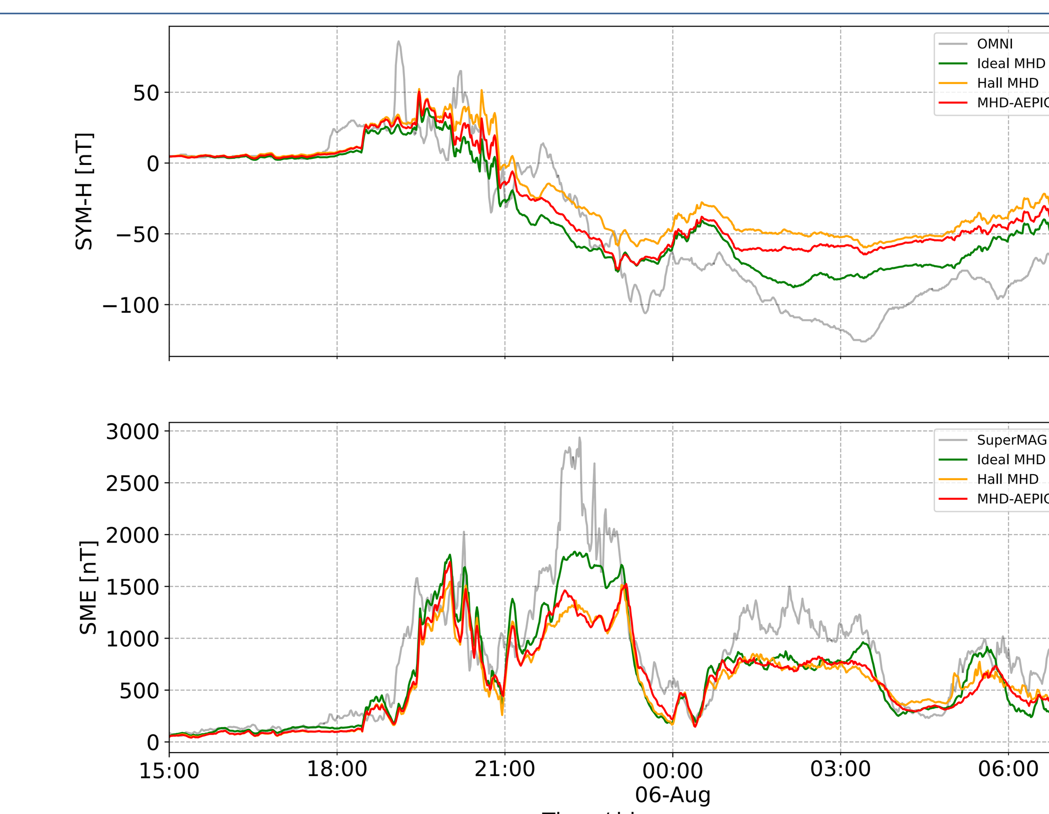


Results

❖ Reconnection event & Electron Velocity Distribution



❖ Dst Indexes from different models



Conclusions

- A brand new MHD with adaptively embedded particle-in-cell (MHD-AEPIC) model is introduced
- The new model makes it possible to perform a geomagnetic storm event simulation with electron physics for the first time
- The 16 h storm event takes ~255 h on 5600 CPU cores, the average volume of the active PIC patches is 1280 R_E^3, which is ~0.2% of a fixed PIC box: -100 < x < -10, -40 < y, z < 40 R_E
- The model results have good agreement with observations from the electron scale to the global scale

References

1. X. Wang, Y. Chen, and G. Toth. Global magnetohydrodynamic magnetosphere simulation with an adaptively embedded particle-in-cell model. Earth and Space Science Open Archive, page 21, 2021 doi:10.1002/essoar.10508044.2
2. Y. Chen, G. Toth, H. Zhou, and X. Wang. FLEKS: A flexible particle-in-cell code for multi-scale plasma simulations. Earth and Space Science Open Archive, page 27, 2021 doi:10.1002/essoar.10508070.1

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