Magnetospheric convection in a hybrid-Vlasov simulation

Shi Tao[1] (shi.tao@helsinki.fi), M. Alho[1], I. Zaitsev[1], M. Battarbee[1], U. Ganse[1], Y. Pfau-Kempf[3], L. Turc[1], M. Palmroth[1,2]

1: University of Helsinki 2: Finnish Meteorological Institute 3: CSC – IT Center for Science

UNIVERSITY OF HELSINKI

Funded by the European Union

European Research Council

Introduction

Magnetospheric convection is important in modulating the dynamics of the Earth's magnetosphere. One of the most extensively studied convection patterns is the Dungey cycle. It describes the large-scale circulation of magnetospheric plasma driven by reconnection at dayside and nightside of the Earth's magnetosphere. The rate of Dungey cycle convection is quantified by the following relation:

$$|\Phi_{\mathrm{D}}| - |\Phi_{\mathrm{N}}| = \frac{dF_{\mathrm{pc}}}{dt}, \tag{1}$$

where $\Phi_D(t), \Phi_N(t)$ represent the reconnection rates on dayside and nightside. F_{PC} denotes the amount of open flux in the ionosphere. Previous studies have employed an empirical equation determining the dayside reconnection rate in observations [1]:

$$\Phi_{\mathrm{D}} = L_{\mathrm{eff}}|V_x||B_z|, \quad \text{for } B_z < 0 \tag{2}$$

In addition, researchers have discovered a convection pattern that is solely induced by dayside reconnection [3]. In this study, we use a 3D hybrid-Vlasov simulation for investigating convection patterns. We also develop a new method to quantify reconnection rates with respect to MLT sectors. We found some inconsistencies between our simulation and MHD theory on convection.

Methods

We employed Vlasiator, a hybrid-Vlasov simulation tool, to model the entire Earth's magnetosphere using a solar wind input characterized by a constant southward interplanetary magnetic field (IMF) [2].

To estimate reconnection rates, we developed a method that tracks changes in closed magnetic flux using Faraday's law via Stokes' theorem:

$$\int -\frac{\partial \mathbf{B}}{\partial t} \cdot da = \int \nabla \times \mathbf{E} \cdot da = \oint \mathbf{E} \cdot dl. \tag{3}$$

This analysis is performed along a closed contour within the closed field line region. According to Equation (3), the flux change is given by the line integral of the electric field. Because the contour is closed, contributions from individual boundary segments can be evaluated separately. As Figure 1 depicts, in an MLT sector, the reconnection rate can be characterized as:

$$\Phi' = \frac{dF_{ABCD}}{dt} - \left(\int_{AB} E_r dr - \int_{CD} E_r dr + \int_{DA} rE_\theta d\theta\right). \tag{4}$$

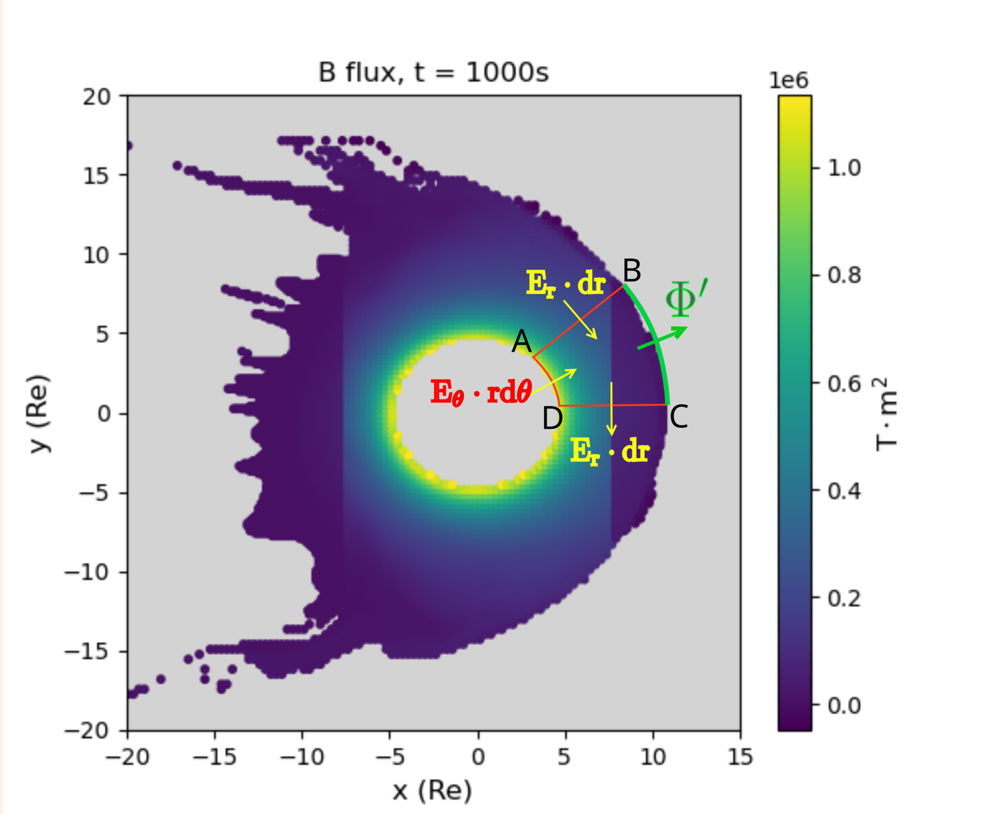

Figure 1: Magnetic flux in the closed field line region on the equatorial plane at 1000 s in the simulation. The grey area shows open field lines. ABCD marks a closed region, with arrows indicating flux flow across its boundaries.

Results

- We validate our new method to quantify reconnection rates in different Magnetic Local Time (MLT) sectors.

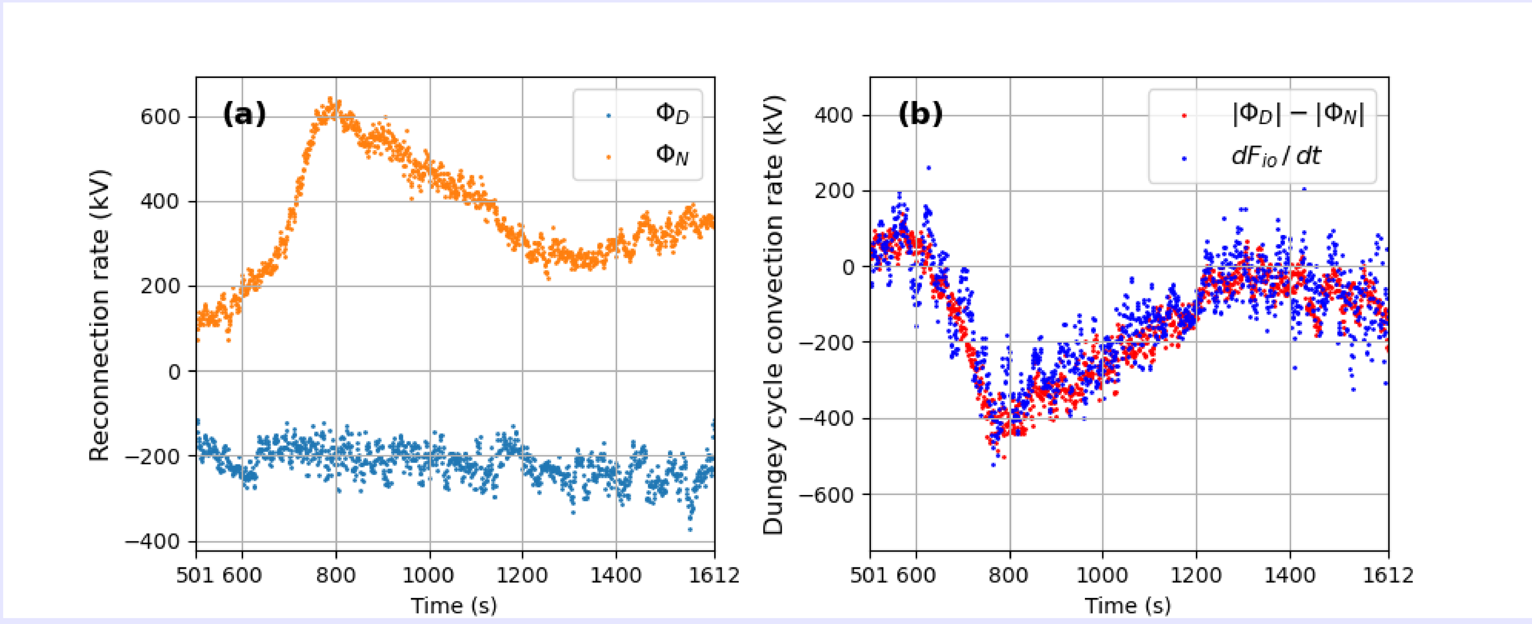

Figure 2: Panel (a): Dayside and nightside reconnection rate.
Panel (b): Dungey cycle convection rate (red dots) compared with the open flux change rate (dark blue dots).

- We find a fluctuation of dayside reconnection rate despite the constant solar wind input.

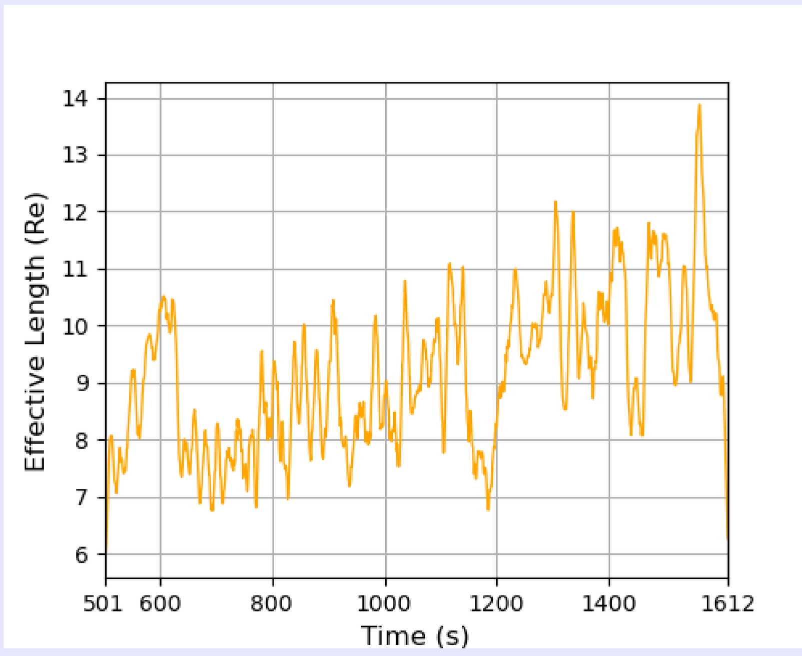

Figure 3: Dayside reconnection effective length varies between 6 $\mathrm{R_E}$ to 14 $\mathrm{R_E}$.

- We show that dayside reconnection is associated with enhanced azimuthal convection events.

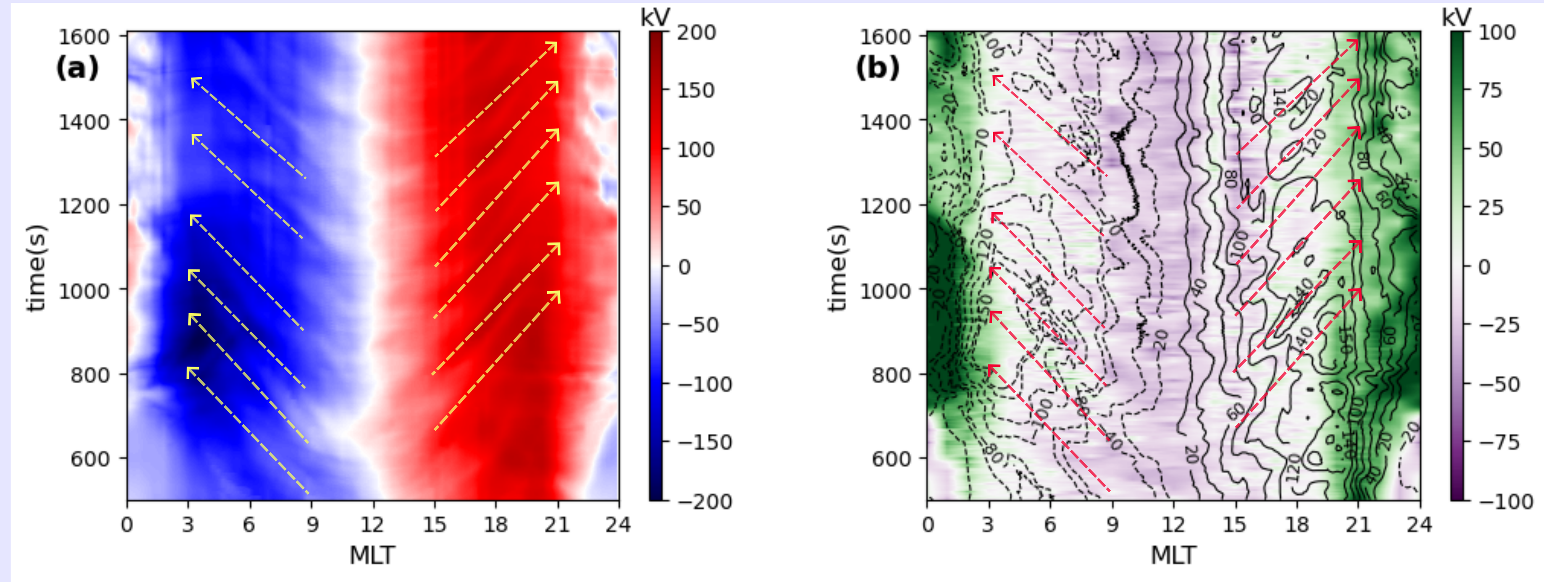

Figure 4: Panel (a):Keogram of azimuthal convection rate on the equatorial plane with time and MLT values. Panel (b): The reconnection rates with a 1-hour MLT resolution.

- We demonstrate that the plasma does not flow along the flux tube entropy isocontours near the reconnection region and at the terminator, contrary to what was expected from previous work [4].

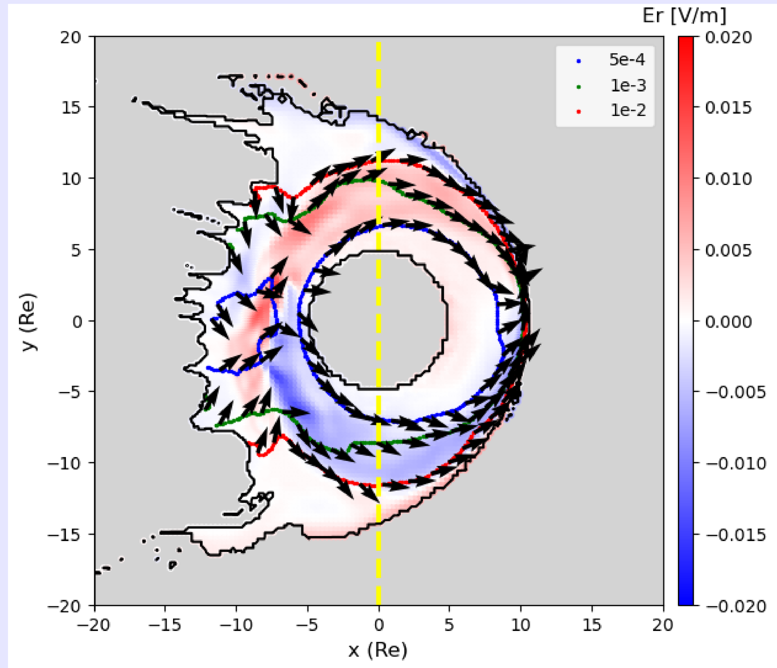

Figure 5: Colors depict the radial electric field component in the closed field line region. We show three flux tube entropy isocontours here, in $\mathrm{nPa(R_E/nT)^{\frac{5}{3}}}$. The yellow dashed line indicates terminator and arrows are bulk velocities along the isocontours.

References

[1] Milan, S. E., Provan, G., & Hubert, B. (2007). Magnetic flux transport in the Dungey cycle. *J. Geophys. Res. Space Phys.*, *112*(A1).

[2] Palmroth, M., et al. (2018). Vlasov methods in space and astrophysics. *Living Rev. Comput. Astrophys.*, *4*(1).

[3] Dai, L., et al. (2024). Global magnetosphere convection from dayside reconnection. *Nat. Commun.*, *15*(1), 639.

[4] Wolf, R. A., et al. (2009). Entropy and plasma sheet transport. *J. Geophys. Res. Space Phys.*, *114*(A9).

Acknowledgments

The work is funded by the European Union (ERC grant WAVESTORMS - 101124500). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Council Executive Agency. Neither the European Union nor the granting authority can be held responsible for them. ST acknowledges the Research Council of Finland grant numbers 336805 and 352846 (FORESAIL), 335554 (ICT-SUNVAC), and 345701 (DAISY). MA acknowledges the Research Council of Finland grant numbers 352846 and 361901, and the Inno4Scale project via European High-Performance Computing Joint Undertaking (JU) under Grant Agreement No 101118139. The JU receives support from the European Union's Horizon Europe Programme. LT acknowledges support from the Research Council of Finland (grant number 322544). MP acknowledges the Research Council of Finland grant numbers 347795, 345701, 352846, and 361901. YP scknowledges the Research Council of Finland grant number 339756 (KIMCHI). The work of MB and UG are supported by the EuroHPC "Plasma-PEPSC" Centre of Excellence (grant number 4100455) and the Research Council of Finland matching funding (grant number 359806). MB acknowledges the Research Council of Finland grant number 352846. The authors thank the Finnish Computing Competence Infrastructure (FCCI), the Finnish Grid and Cloud Infrastructure (FGCI) and the University of Helsinki IT4SCI team for supporting this project with computational and data storage resources. The authors wish to acknowledge CSC – IT Center for Science, Finland, for computational resources. The simulation presented in this work was run on the LUMI-C supercomputer through the EuroHPC project Magnetosphere-Ionosphere Coupling in Kinetic 6D (MICK, project number EHPC-REG-2022R02-238).