First full global 6D hybrid-Vlasov simulation of the near-Earth space

Minna Palmroth (1,2), Urs Ganse (1), Yann Pfau-Kempf (1), Markus Battarbee (1), Maxime Grandin (1), Andreas Johlander, Lucile Turc (1), Maxime Dubart (1), Kostis Papadakis (1)

(1) University of Helsinki, Finland
(2) Finnish Meteorological Institute, Helsinki, Finland

Space weather refers to the potentially harmful environmental conditions within the near Earth space, driven by variations in the solar wind and affected by the dynamics of the Earth's magnetic domain, the magnetosphere. Among the most unpredictable space weather phenomena are *substorms*, periods of magnetospheric energy loading and unloading, which can lead to spacecraft failure. Substorms have been investigated from 1960s with tens of spacecraft costing billions, however, even constellations have failed to understand the cause of substorms due to the inherently local nature of measurements. Decades-long debate exists between two competing models for the substorm onset, caused by either an instability-driven current disruption, or magnetic reconnection.

Space weather simulations are typically based on magnetohydrodynamics (MHD), or ion kinetic physics, while electron-kinetic physics within the global context is still a distant dream for the modellers. The MHD approach is computationally not extremely complex and can be executed in all three spatial dimensions (3D). However, the MHD approach neglects kinetic physics, which is at the heart of the substorm process, especially in terms of reconnection and 3D instabilities occurring in the magnetospheric tail. The first ion-kinetic 3D simulations have been carried out with the noisy particle-in-cell approach using a very coarse grid, a low number of particles, and a down-scaled dipole representing a Mercury-type configuration. The Vlasov-hybrid approach is a noise-free ion-kinetic approach, but so far it has been 5D (including 2D real space and 3D ion velocity space).

Vlasiator is the world's first and so far the only global simulation based on the hybrid-Vlasov approach that simulates the ion distributions accurately without noise. The simulation has, for computational reasons, been so far executed in 2D real space. Even so, the global 5D Vlasiator results have shown without a doubt that ion-kinetic effects cannot be neglected from the large scales, as small-scale phenomena affect large scales and vice versa. This scale coupling leads to phenomena that are not predicted using local simulations without proper boundary conditions, or with spacecraft measurements lacking the global context.

This project carries out the world's first 6-dimensional ion-kinetic global magnetospheric simulation, accurate both locally and globally. We will investigate unambiguously for the first time the timing of magnetospheric tail reconnection relative to the instability development. Our results help to understand the unpredictable substorms, with technological and societal impacts in interpreting spacecraft measurements, and devising new missions and instruments. A growing demand exists to understand spacecraft environments as the utilisation of space is in rapid increase, with markets worth billions. Our efforts are a significant contribution to these ends.