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Explosive Disruptions of the Magnetosphere Lead to Substorms

The mechanisms behind explosive disruptions of the Earth's magnetosphere are revealed using supercomputer simulations.

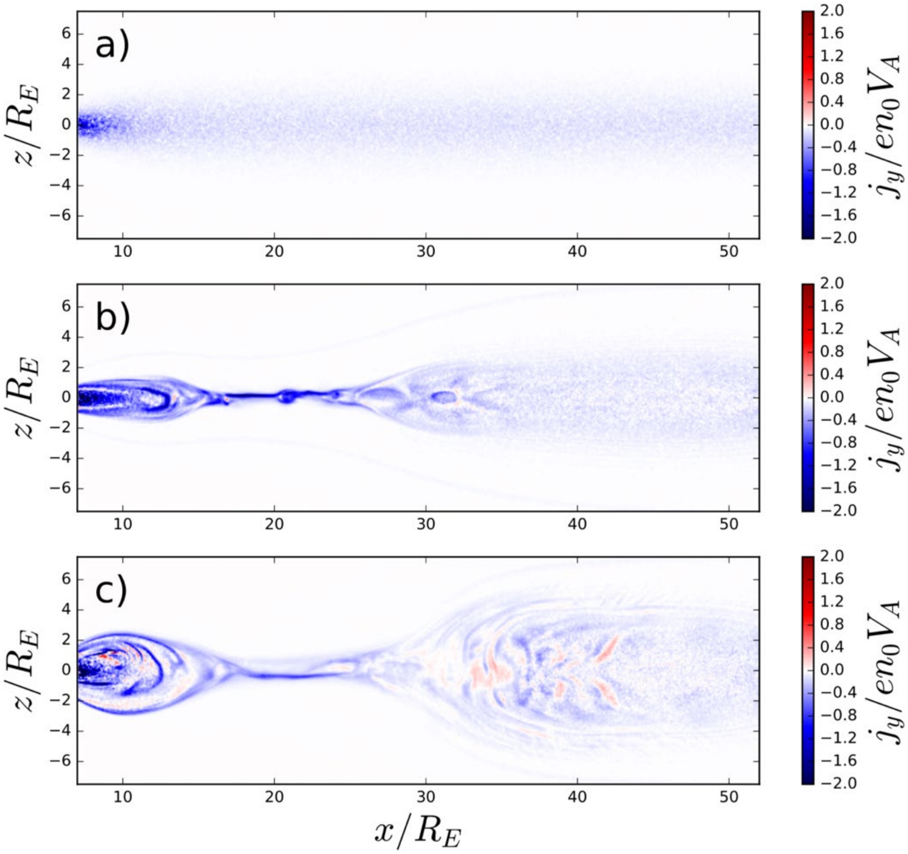

Image courtesy S. Totorica (Princeton University)

Evolution of the electrical current density in the magnetotail in a two-dimensional slice of a three-dimensional simulation at three times: a) in the quiet, undisturbed magnetotail; b) after the onset of magnetic reconnection, c) after the near-Earth disruption.

The Science

The sun constantly emits a flow of charged particles and magnetic field – a magnetized plasma – known as the solar wind. Fortunately, most of the charged particles bounce off of the Earth's magnetic field, known as the magnetosphere; otherwise, the solar wind would burn the Earth to a crisp. When the solar wind magnetic field is opposite to that of the magnetosphere, magnetic field lines in the outer magnetosphere can explosively snap apart – called magnetic reconnection – flinging charged particles and magnetic field around the Earth to the night side of the Earth's magnetic field into what is known as the magnetotail. How this eventually leads to explosive disruptions known as substorms has now been revealed by supercomputer simulations.

The Impact

Magnetospheric substorms occur daily. Bursty flows of magnetized plasma, highly energetic particles, and intense polar auroras can damage satellites and ground-based electrical infrastructure. Substorms play a key role in the response of the magnetosphere to variations in the incoming solar wind. Understanding the dynamics of substorms is critical for the development of accurate models to predict space weather events and mitigate their deleterious effects on critical infrastructure.

Summary

Magnetic field lines are like elastic strings, and when they snap charged particles are accelerated to high energy. But this in itself does not explain the substorms. Computer simulations that follow the trajectories of billions of particles in the Earth's magnetosphere and magnetotail and compute their self-consistent electromagnetic forces show that when there is too much plasma pressure pushing against the magnetic field, the magnetic field lines develop an unstable oscillation known as a "ballooning instability", which was first discovered in fusion-energy relevant magnetized plasmas. This causes turbulence, and leads to the particle acceleration in substorms.

Researchers have long known that the magnetic field reversal across the magnetotail current sheet plays an important role, and so do the plasma flows that are revealed by satellite observations. Magnetic reconnection is widely believed to play an important role in the disruption of the magnetotail. Our novel simulations are the first to start from an exact "kinetic" equilibrium, so that the calculation starts from a state for which the electric and magnetic forces on the particles are balanced. The formation of instabilities can then be carefully observed. The calculation captures the distant tail current sheet and the near-Earth dipole magnetic field, which is known from satellite observations to play an important role. The simulations reproduce features observed by satellites with unprecedented accuracy, and reveal a new mechanism for substorm onset: plasma flows produced by reconnection are disrupted in the near-Earth region by the three-dimensional ballooning instability.

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Publications

S. Totorica, A. Bhattacharjee, "Interplay of Three-Dimensional Instabilities and Magnetic Reconnection in the Explosive Onset of Magnetospheric Substorms," *to be submitted to Physical Review Letters* (2020).