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MEDIA CONTACTS
Saralyn Stewart
(512) 694-2320
stewart@physics.utexas.edu

Fusion Power Plants and Geomagnetic Storms Share an Intriguing Secret

Scientists find striking similarities in the way plasma electrons interact with twisty magnetic fields inside fusion energy devices and in the Earth's magnetosphere.

LONG BEACH, Calif. — One of the main reasons life on Earth is possible is the Earth's magnetic field, which shields our planet from a stream of charged particles (called a plasma) coming from the sun. The Earth's magnetic field acts as a shield for most of these charged particles. The sun, however, regularly emits solar flares, powerful bursts of plasma that are among the most energetic events in our solar system, releasing enough energy to power Earth for 200,000 years. The electrons accelerated in these events can rearrange and bypass the Earth's magnetic field, damaging satellites, disrupting communication and GPS systems, and threatening astronaut safety. The same effect occurs in fusion power plants, where controlling runaway electrons - fast, high-energy electrons that can form during the disruption of the magnetic field within the fusion devices - is a major barrier to harnessing the power of the sun on Earth. The key similarity is that both in the lab and in space, the magnetic field rearranges itself into a shape called a magnetic island (Figure 1, plot on the left) that acts as a vortex, trapping particles inside of itself.

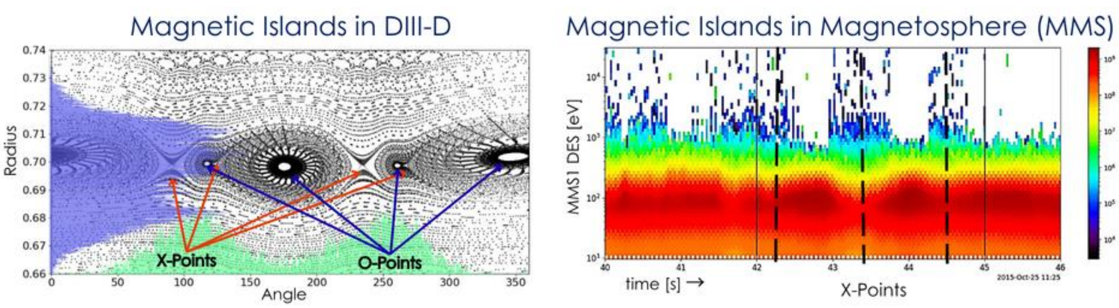

Figure 1: The plot on the left shows a magnetic island in DIII-D during a structural change that causes smaller islands to emerge. Histograms are plotted over the magnetic structure where here peaks correspond to where electrons are likely to end up in the radial (blue) and angular (green) directions. These histogram peaks are analogous to the red color on the MMS plot to the right. The plot on the right shows the number of electrons of different energies detected as the MMS spacecraft was passing through a magnetic island in the Earth's magnetosphere. Red color in this plot indicates more electrons, while the blue color indicates less electrons. Here eV is the unit of electron energy, where higher energy corresponds to greater temperature.

Motivated by these observations, a group of scientists from Auburn University and University of California San Diego led the first direct laboratory-to-space comparison of plasma electron dynamics in magnetic islands, aiming to understand which processes are universal and scalable between the two. Using the DIII-D national fusion device, researchers created and manipulated magnetic islands in a controlled way using different coils. Like their magnetosphere counterparts, islands created in DIII-D can trap and accelerate electrons. By controlling the islands, the scientists were able to show how these electrons escape this confinement. Both lower energy plasma electrons and energetic "fast" electrons become concentrated around the centers of those islands. Then, when the scientists made the islands undergo a structural change by splitting them into new smaller islands, the fast electrons burst out.

Simulations of these processes showed that electrons' ability to escape varies dramatically depending on where in the island they start. Near the center of the island, called the O-point, electrons remain trapped, unable to escape the confinement of the island. Near the island's crossing points, or X-points, electrons find "highways" that let them escape outward more easily. When the island splits into smaller structures, new X-points appear, creating additional escape routes. This transition makes electron motion irregular, a pattern scientists call superdiffusion. These results demonstrate how the shape of the magnetic field determines whether electrons stay confined or break free.

The comparison with NASA's MMS mission, a multi-spacecraft initiative focused on studying changes in the Earth's magnetosphere, revealed the same pattern. Higher densities of background electrons appear near island centers (Figure 1, dense red color regions in the right figure), and spikes of energetic electrons occur at the island X-points where magnetic field lines twist (high energy electrons shown in blue color in the right figure). Together, the lab and space results show that magnetic islands act like electron traps and launch pads, confirming that the same physics governs plasmas in vastly different environments.

"Seeing similar physics in a magnetic confinement fusion device and in Earth's magnetic field is remarkable," said Jessica Eskew, a graduate student from Auburn University and lead author of the study. "It shows that we can reproduce space plasma phenomena in a controlled laboratory setting, helping us make progress in both fusion energy and space weather research."

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Contacts:

Jessica Eskew, Auburn University, jre0039@auburn.edu
Sydney Battles, Auburn University, slb0091@auburn.edu
Evdokyia Kostadinova, Auburn University, egk0033@auburn.edu
Dmitri Orlov, University of California San Diego, orlov@fusion.gat.com

Abstract

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