Investigating Electron Energization in a Chain of Flux Ropes in Earth's Magnetotail and its Implications for Space Weather

Earth's magnetosphere is constantly shaped by the solar wind, a stream of charged particles flowing from the Sun. On the night side of Earth, this interaction stretches the magnetosphere into a long tail, known as the magnetotail. Within this region, magnetic structures with twisted bundles of magnetic field lines called flux ropes often form due to multiple x-line reconnection. These structures accelerate particles, energizing electrons and ions and playing an important role in space weather. While scientists know that flux ropes can energize particles, exactly *how* this happens is still not fully understood.

In this study, we used data from NASA's Magnetospheric Multiscale (MMS) mission — a set of four spacecraft flying in close tetrahedral formation — to study a chain of four small flux ropes in the magnetotail. Using high-resolution magnetic field and particle data, we analyzed the structure of each flux rope and examined how electrons gained energy within the flux ropes. There are three main mechanisms through which electrons can get energized. 1) Direct acceleration by the parallel electric field, 2) Betatron acceleration which occurs due to the gradient of the magnetic field and 3) Fermi acceleration which is caused by the curl of the magnetic field. Our results show that Fermi acceleration is the dominant process energizing electrons, with Betatron acceleration also playing a significant role. We also found that although only a small fraction of the electrons reach suprathermal energies, yet the suprathermal electrons contribute to ~30% of the total energy density.

These findings help us understand how flux ropes accelerate electrons, even to suprathermal energies. The electrons energized within these flux ropes feed into a broader population of energetic particles in the near-Earth plasma sheet. During geomagnetic substorms, these energetic electrons can be injected into the inner magnetosphere and contribute to enhancements in the outer radiation belt which can be the most hazardous regions for orbiting spacecraft. High-energy electrons in the outer radiation belt can penetrate satellite shielding, damage onboard electronics, and pose risks to both robotic and crewed missions.