Abstract

Collisionless shocks are powerful particle accelerators found across the Universe. Using *in-situ* satellite data and theoretical advances, we establish a multiscale shock acceleration framework for relativistic electrons. Our findings show that suprathermal seeded electrons injected at ~1 keV are accelerated in foreshock transients to relativistic energies, refining our understanding of shock acceleration and the origins of electron cosmic rays.

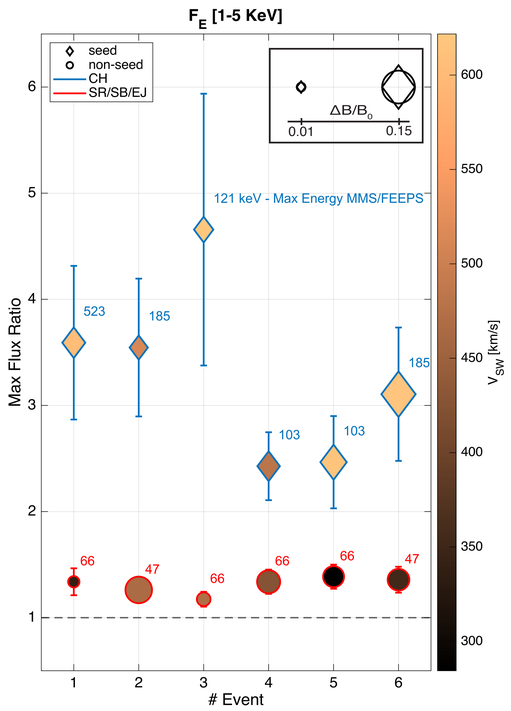
Datasets & Method

THC: Upstream of the bow shock at lunar orbit, observing solar wind properties and **B** discontinuities.

MMS: Close to Earth's bow shock, measuring Foreshock transients, highlighting energetic (>100 keV) and relativistic electrons.

Statistics

Statistical Analysis of seeded and non-seeded events. All foreshock transients with 100> keV electrons are associated with fast solar wind conditions and a 1-10 keV seed electron population.



Work is accepted in *Nature Communications*, ask me for the latest preprint ☺

Electron injection threshold and acceleration processes at Earth's foreshock transients

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Relativistic electrons linked to ~1keV seeded electrons and fast (coronal hole) solar wind conditions

Figure 1: Overview observations

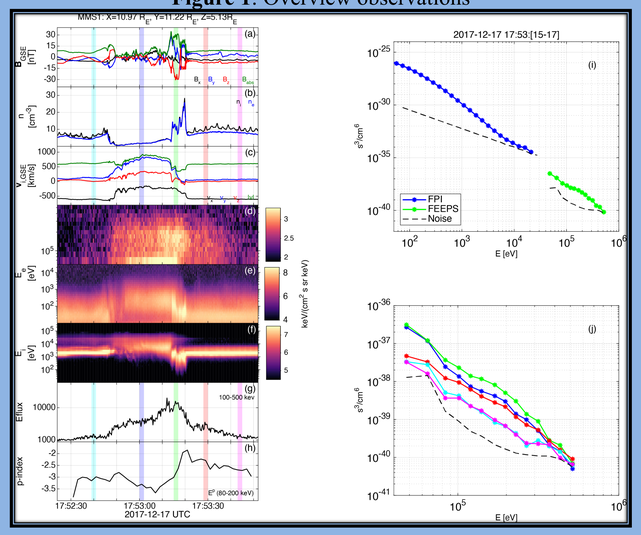

Figure 1 shows high-energy electrons (> 511 keV) in a foreshock transient. The green shaded area highlights a compressive edge forming a localized shock, while the purple area reveals a low-density plasma core with high-amplitude electromagnetic waves. These features enable efficient scattering and multiple shock crossings, producing a harder energy spectrum (p~2) than expected for standard DSA.

Figure 2: Detailed plot and wave analysis

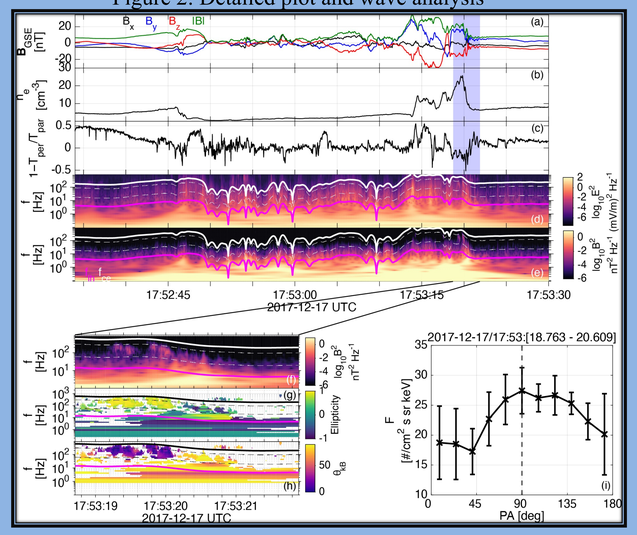

Figure 2 highlights key processes reinforcing shock acceleration. In the compressive region of the foreshock transient, high-frequency, high-amplitude non-linear electromagnetic waves interact with local electron populations, amplifying their energy through wave-particle interactions. The wave characteristics, including narrowband frequencies (0.1–1 f_{ce}), right-hand polarization, and parallel propagation, enable cyclotron-resonant acceleration, producing perpendicular pitch angle distributions (PADs) consistent with theoretical models.

Summary & Discussion

1) **Relativistic Electron Framework**: We showed that low electron injection thresholds (~1–5 keV) originating from fast solar wind conditions can drive relativistic electrons at Earth's foreshock transients.

2) **Key Observations**: Fast solar wind conditions consistently enable foreshock transients to produce suprathermal electrons, explaining past observations of energetic electrons (e.g., Wilson et al., 2016, and Liu et al., 2019).

3) **Generalization**: The model can be applied across planetary systems, scaling with system size. Larger systems like Jupiter could support MeV electron acceleration, consistent with previous findings.

4) **Potential Astrophysical Relevance:** Planetary bow shocks interacting with stellar winds may contribute to the cosmic ray electron spectrum. Specifically from stellar systems containing ultra-hot Jupiters.

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Reinforced Shock Acceleration

We show that electron acceleration at planetary bow shocks involves processes from global system scales (fast solar wind) to kinetic scales (wave-particle interactions), collectively enabling particles to reach relativistic energies.

At Earth's bow shock, a low injection threshold (~1–5 keV) driven by fast solar wind conditions allows these mechanisms to produce relativistic electrons.

Schematic

Below is a schematic illustrating how fast solar wind conditions (right/blue path) lead to energetic electrons forming at foreshock transients, while slow solar wind conditions (left/red path) lack a seed population, resulting in no energetic events at Earth's foreshock.