HELLENIC REPUBLIC
National and Kapodistrian University of Athens
EST. 1837

Institute of Accelerating Systems & Applications

On the cause of relativistic electron acceleration and loss in the outer Van Allen belt

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Abstract

- This suite of studies attempts to provide answers by combining statistical studies with detailed particle and wave observations in the inner magnetosphere: (a) two detailed case-studies of events that resulted in relativistic electron acceleration and loss, respectively and (b) a superposed epoch analysis between an enhancement event group and a loss event group.
- Results during non–storm events, demonstrate that the mechanisms which enhance or deplete the electron population of the outer belt is mainly internal, and as such, are not always associated with geomagnetic storms, at least in terms of Dst (or SYM-H) index.
- Recently, the so called "two-step acceleration" scenario has been proposed and discussed by Jaynes et al., [2015] and Li et al., [2016]. By combined analysis of phase space density radial profiles and Fokker-Planck simulation, we confirm this scenario.
- The superposed epoch analysis – based on a survey of 71 geospace disturbance incidents spanning the maximum and descending phase of solar cycle 24 – indicates that these events share some common features regarding relativistic electron enhancements and losses and thus a level of repeatability exists.

Non-Storm Losses *[from Katsavrias et al., GRL2015]*

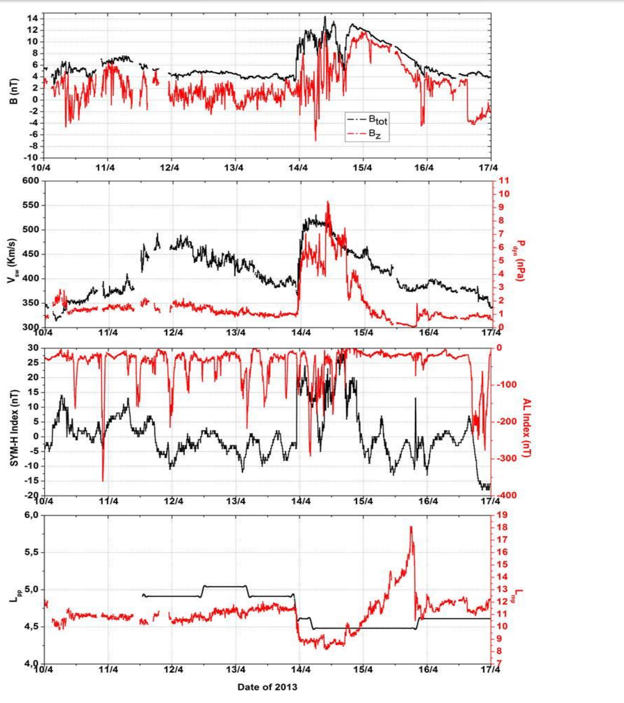
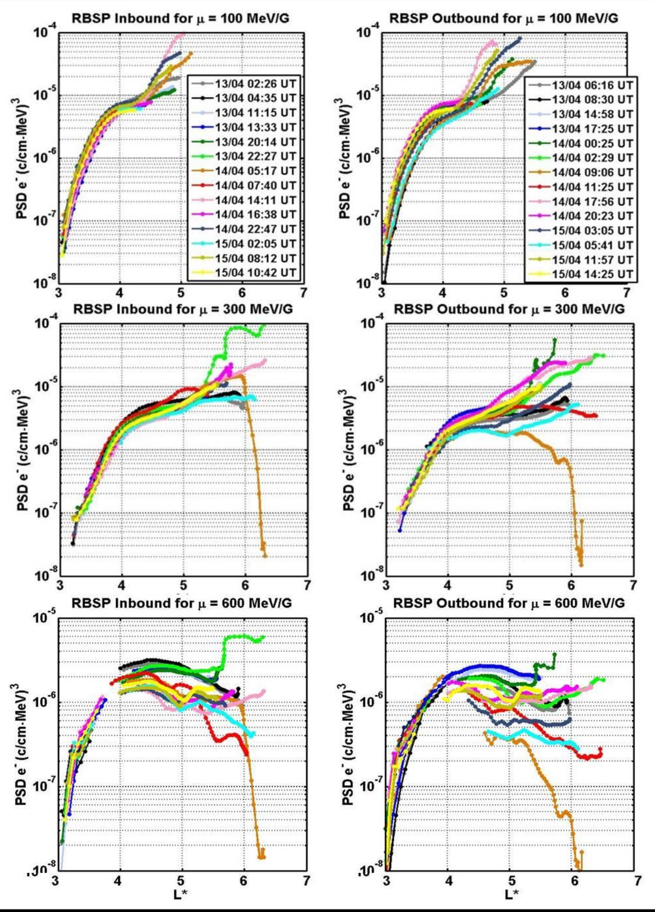


Figure 1. An ICME on April 13 increased the solar wind speed to ~520 km/s and pressure to ~9.5 nPa. Its geomagnetic response was only an interval of weak substorm activity (AL_{min} ~ -300 nT) while the Sym-H index was continuously positive during April 14.



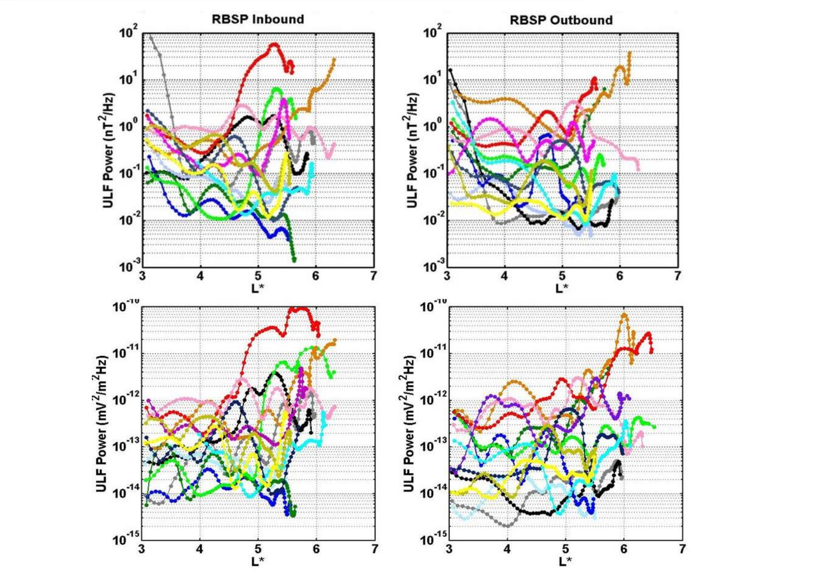


Figure 2 (left) & 3 (above). Electron PSD with μ > 300 MeV/G exhibits a strong dropout which coincides with the maximum compression of the magnetopause and a two-orders of magnitude enhancement of the Pc5 wave power. This combination suggests that the outward diffusion driven by the Pc5 waves can cause rapid losses to the outer boundary even during geospace disturbances with limited compression of the magnetopause and continuously northward IMF.

Two-step Acceleration *[from Katsavrias et al., JGR2019a]*

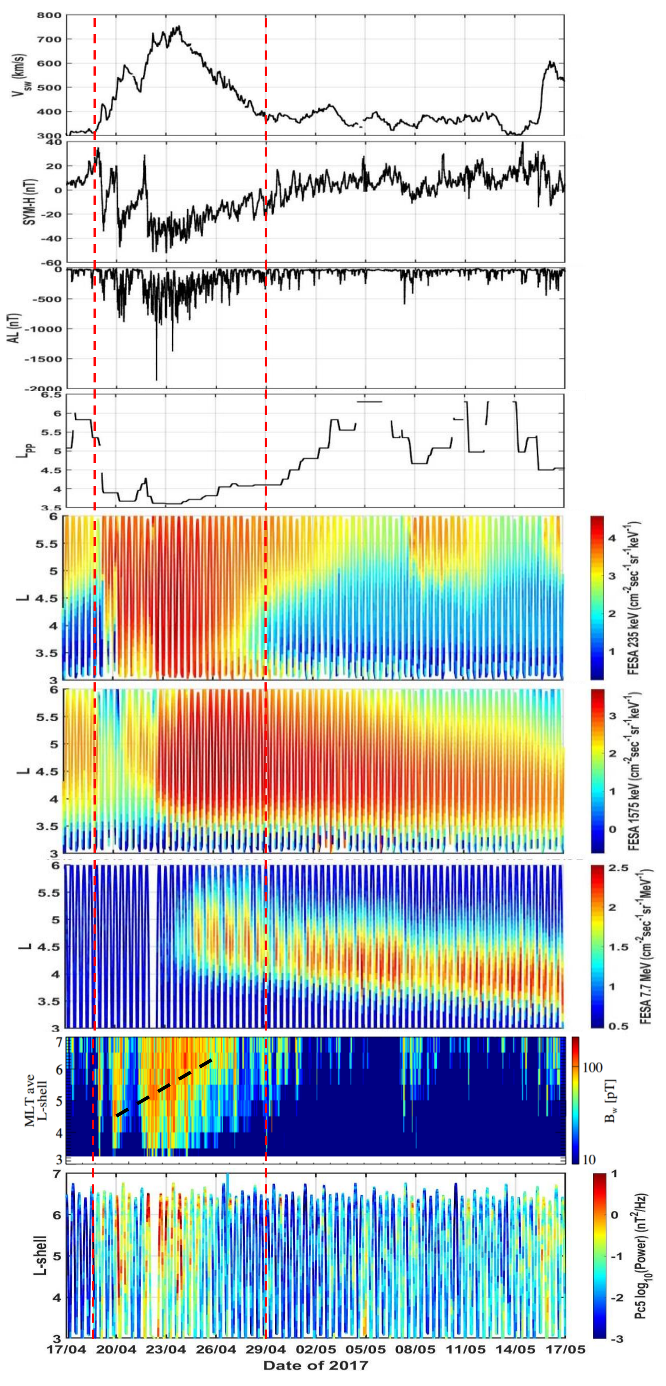


Figure 4 (left). Two consecutive HSSs on April 19 and 21, 2017 increased the solar wind speed to ~800 km/s and generated a series of intense substorm activity with AL_{min}~-2000 nT and a weak storm.

Nevertheless, this **weak geomagnetic storm** with Sym−Hmin ≈ −50nT, resulted in a **relativistic and ultra–relativistic electron enhancement of two orders of magnitude similar to the St. Patrick's event of 2015**, the strongest storm (Sym−Hmin ≈ −235nT) seen over the past decade *[Baker et al., 2016]*.

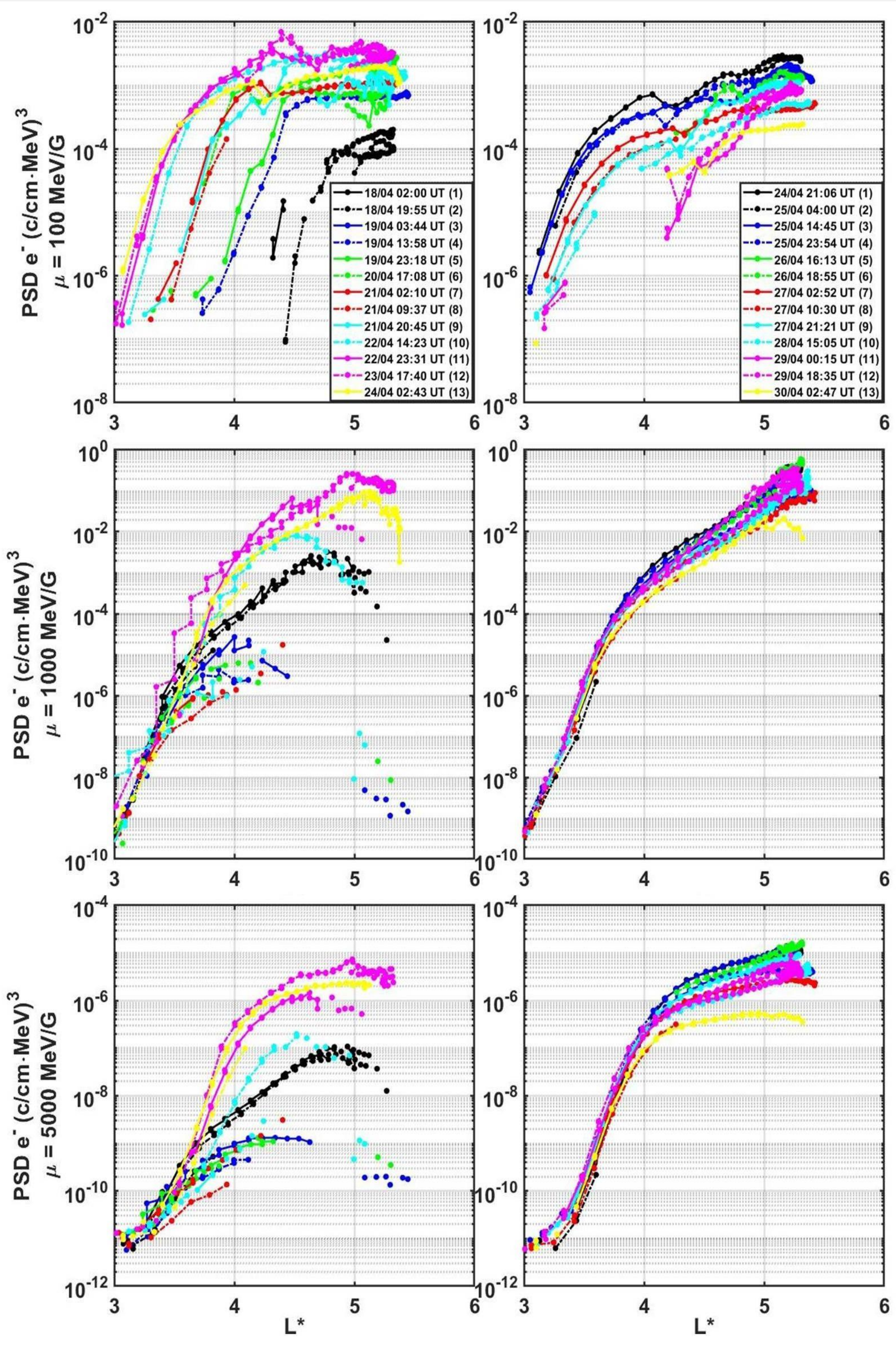
This enhancement appeared to energies up to 10 MeV and was **not recorded at geosynchronous orbit** (as in St. Patrick's event) where most space weather monitoring data, which are used for issuing alerts, are collected.

Chorus and Pc5 wave activity also exhibit significant enhancements in a broad L-shell range during the April 20-25 time period.

Figure 5 (right). Time evolution of near–equatorial mirroring electron PSD as a distribution of L* for three fixed values of μ (100, 1000 and 5000 MeV/G) and K≤ 0.03 $G^{1/2}R_E$ for the April 18–29, 2017 time period.

The electron PSD for 1000 MeV/G , exhibits **rising peaks** at L* ≈ 4.5 from April 22 which moved to L* ≈ 5.2 until April 24 (orbits 10–13) indicating **local heating processes.**

The electron PSD for 5000 MeV/G, exhibits continuously positive gradients throughout the whole period of interest, indicating that **inward radial diffusion** could be the dominant mechanism for this acceleration**.**



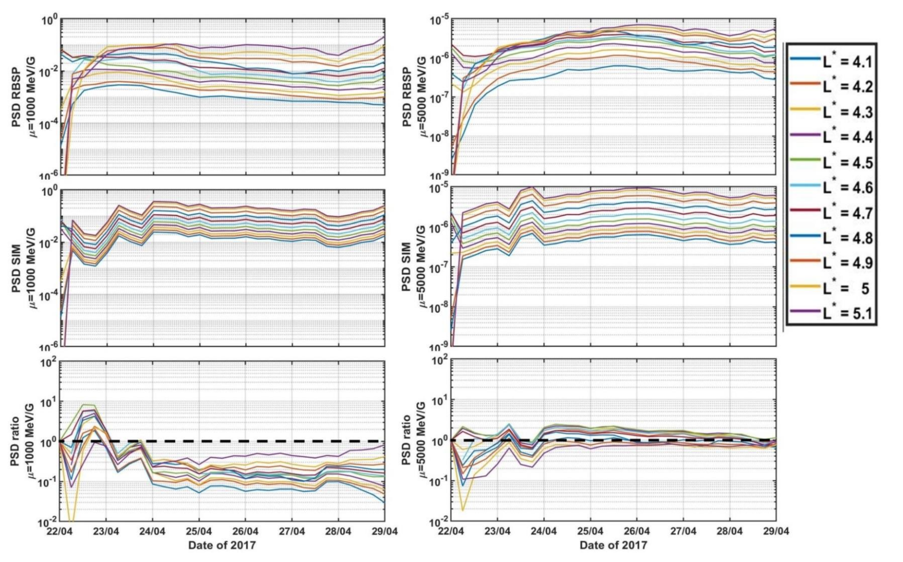
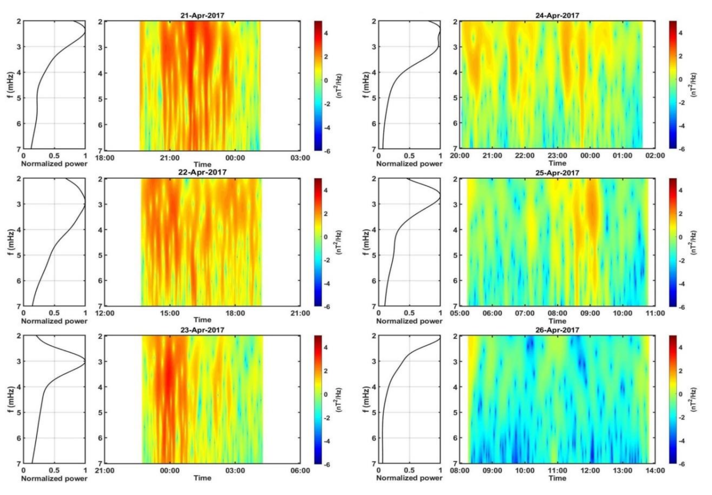
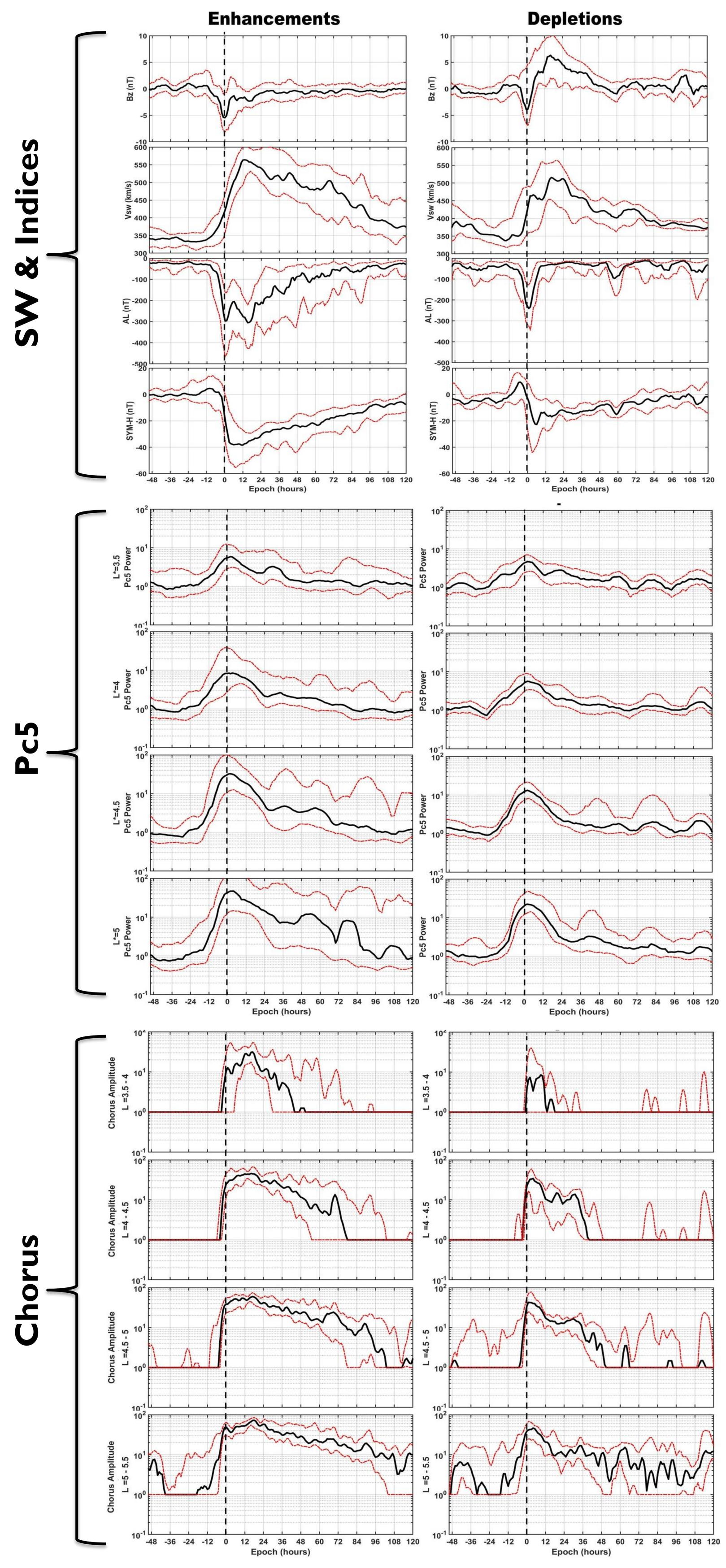


Figure 6 (top) & 7 (bottom). 1-D Fokker-Planck simulation fails to reproduce the PSD_{RBSP} relativistic electrons μ=1000 MeV/G. On the other hand, PSD_{SIM} for μ=5000 MeV/G exhibits negligible deviations from the PSD_{RBSP}. The latter – combined with the continuously positive gradients – suggests that inward diffusion process driven by the enhanced Pc5 activity . Also note that the peak in the power spectral density (below) is, roughly, in the 2–3.5 mHz frequency range. The latter includes the 2.3–3 mHz frequency range, which corresponds to the drift frequency of near–equatorial electrons with μ =1000 MeV/G.



Superposed Epoch Analysis *[from Katsavrias et al., JGR2019b]*



Event Selection

- Average solar wind conditions at least 12 hours before the start of the event:

V_{sw} < 400 km/s	P_{sw} < 3 nPa	SYM-H > -20 nT	AL > -300 nT	-5 < Bz < 5 nT

- 71 events during the RBSP era (9/2012 – 4/2018) spanning the maximum/declining phase of Solar cycle 24.

Net Effect Statistics

Enhancements	$PSD_{Post}/PSD_{Pre} \geq 6$
Depletions	$PSD_{Post}/PSD_{Pre} \leq 1/4$
No Change	$1/4 < PSD_{Post}/PSD_{Pre} < 6$

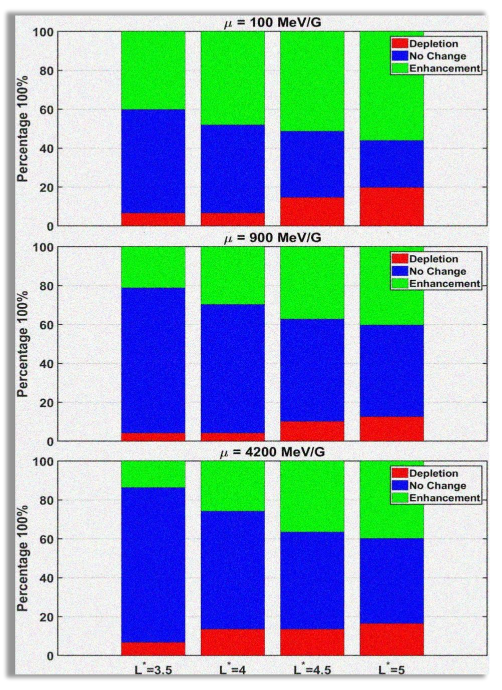


Figure 8. Percentage of event outcome as a function of μ (100, 900 and 4200 MeV/G) and L* (3.5, 4, 4.5 and 5) for near-equatorial mirroring electrons. As shown, the result of each geospace disturbance is μ- and L*-dependent.

- **<u>20 Events</u> with enhancement of the relativistic (μ = 900 MeV/G) electron population at L*≥4.5**
- **<u>8 Events</u> with depletion of the relativistic (μ = 900 MeV/G) electron population at L*≥4.5**

Figure 9 (left). Enhancement vs. depletion group is associated with events characterized by:

- **higher and long-lasting values of solar wind speed**
- **continuously negative values of Bz** up to 1.5 day
- **More intense and prolonged substorm activity** as reflected in the AL index
- **more pronounced and long-lived chorus wave activity**, over a broad L-shell region
- **longer-lived Pc5 wave activity**, especially at L*>4

Figure 10 (right).

- **Enhancement events exhibit clear seed electron PSD increases up to three orders of magnitude,** while **depletion events exhibit intermittent increases and decreases.**

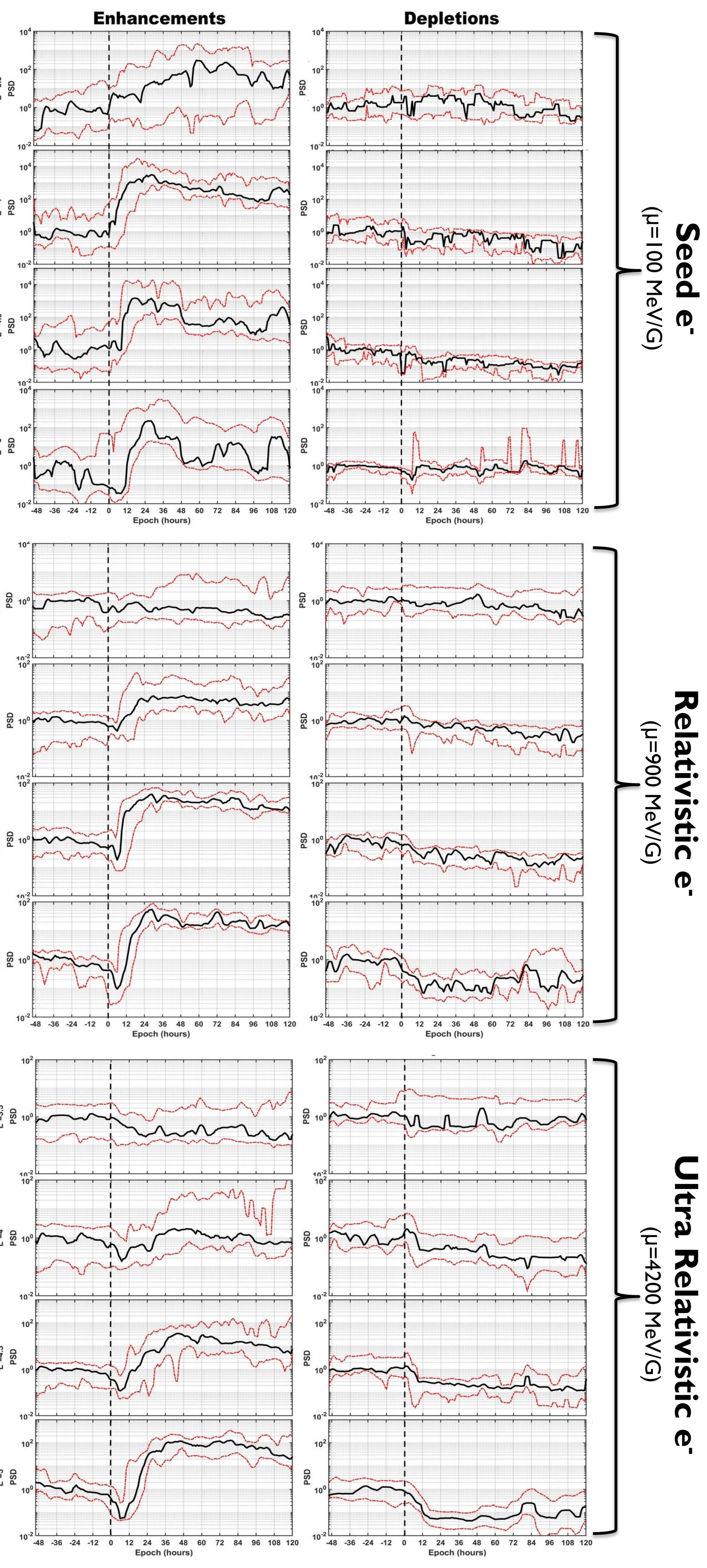
- **<u>Phase 1 (t_0 – t_0+12 hours):</u>**

Relativistic PSD dropout which coincides with the minimum Lmp_min and max Pc5 power.

- **<u>Phase 2 (t_0 +12 – t_0+120 hours):</u>**

Enhancement events: relativistic electrons quickly replenished as the **pronounced and long-lived chorus** accelerate the enhanced seed population.

Depletion events: at the absence of significant seed population, **relativistic electrons remain depleted**.



Summary

<u>Statistics</u>

1. **The number of enhancement events is μ- and L* dependent.**
2. **Enhancement vs Depletion events**
   a) **persistently southward Bz**
   b) **large and long–lasting values of solar wind speed**
   c) **stronger and long–lasting decrease of SYM-H index**
   d) **more intense and prolonged substorm activity**
   e) **intense and long–lived chorus activity**
   f) **longer–lived Pc5 activity**

SEA reveals two phases after zero-epoch time.

1. **<u>Phase 1:</u>**

Regardless the net-effect there are significant **losses** of relativistic electrons due to the synergy of **outward diffusion** and **MP shadowing**.

1. **<u>Phase 2:</u>**
   a. During **enhancement events**, the existence of **enhanced seed population and chorus activity** can quickly replenish the losses of relativistic electrons.
   b. During **depletion events,** the absence of enhanced seed population renders **the combination of magnetopause shadowing and outward diffusion as the dominant loss mechanism**.

<u>Acceleration and Loss of relativistic electrons</u>

The combined analysis of PSD radial profiles and radial diffusion simulation of the mid–April to mid–May, 2017 period has shown that:

1. **Intense substorms + chorus activity → enhancement of seed electrons**
2. **Local heating (via chorus waves) → enhancement of relativistic electrons**
3. **Inward diffusion (via Pc5 waves) → enhancement of ultra-relativistic electrons**

Acceleration processes for ultra–relativistic electrons operate below GEO → **need for radiation monitors on–board MEO satellites**

There is a **300 MeV/G threshold** in μ that separates the source of relativistic electrons inside the outer belt even after the arrival of a prominent pressure pulse.

Losses through the magnetopause can occur even for limited compression of the magnetopause due to outward diffusion driven by Pc5 waves. **This is a dominant loss mechanism for equatorially mirroring electron even during periods with northward IMF**.