The fascinating dynamics of the high-energy Van Allen radiation belts

D.M. Malaspina, A.A. Chan, S.R. Elkington, M. Bruff, H. Zhao, D.N. Baker, X. Li, S.G. Kanekal
The Van Allen Probes mission has filled in some missing pieces

- Dynamics during both active and quiet times
- Ideal case studies of every kind
- Incredible collaborative science
  - HSO missions
  - Missions of Opportunity
  - ground-based assets

What accelerates electrons up to the very highest energies in Earth’s radiation belts?

What are the missing pieces yet to fill in?
Almost six years of data show amazing variability of high-energy electrons

- So quiet through 2013-2014
- Remnant belts appear regularly (double outer belt)
- Quiet periods of slow decay make great tests of diffusion rates
- HSS activity picked up in declining phase, with noticeable repeat enhancements from coronal holes
Up at 7.7 MeV, the activity is diminished but highlights the most energetic events.

What is the dominant mechanism behind this acceleration?
With every answer comes another question…

No final answers: just a change in perspective

- Two competing mechanisms for energization of the radiation belts
- Same geomagnetic storm event, same data available two different conclusions: one mechanism vs. the other
- New question: When and under what conditions is one mechanism or the other the dominant factor?

Mann+ 2016

Reeves+ 2013
The case for local acceleration

September 2014 storm event (Dst = -100 nT) with no enhancement of relativistic electron populations

Forecast model fails!
The role of source and seed electrons

In September, 2014 a storm period failed to produce high-energy electrons in the radiation belts. Why?

Source: several to 10’s of keV
Seed: 100’s of keV

Do you absolutely need local acceleration to see strong enhancements at ultra-relativistic energies in the heart of the outer belt?
Inward radial diffusion that results in multi-MeV electrons at $L\sim4$ is apparent in both flux and PSD data.

Almost no chorus waves by the time ultra-relativistic energies start to appear in the outer belt.


Acceleration occurs after the storm, well into the recovery phase.
Fast radial diffusion

- Flux peak rises and shifts to lower L, phase space density increases by 2 orders of magnitude
- Acceleration from external source is clear in PSD data (right panel)

ULF-driven acceleration alone can account for intense ultra-relativistic particle enhancements observed in the inner magnetosphere
Back to VLF chorus waves…

Tasked an REU undergraduate summer student with sorting through and aggregating all wave power over 3+ years of the Van Allen Probes mission.

Mean electric and magnetic field spectra covering 3 years for the dawn MLT sector.

Waves are highly organized with respect to the plasmapause! (right panels)

VLF chorus exhibits a ~1 L-shell stand-off distance outside the plasmasphere boundary.
Connection to ultra-relativistic enhancements

Next year, a different REU undergraduate summer student found the locations of peak flux following enhancement events – and their distance from the local plasmapause. Distribution is very similar to VLF chorus wave distribution: stand-off of ~1 L-shell from the plasmapause.

Makes the argument that local acceleration by VLF chorus is usually the dominant mechanism.
Missing piece: the role of our Sun

Sun-Earth coupling is the foundation of radiation belt dynamics

- Large scale solar wind drivers and solar wind structures
- Not just how fast or how dense, but what type of substructures: stream interface regions, CME ejecta regions, shocks, combinations

- For example, shocks embedded in CMEs have proven to be extremely geoeffective (Lugaz+ 2015)
- Parker Solar Probe mission will bring more understanding to this problem
Missing piece: loss to the atmosphere

- Loss can occur at the outer boundary of the magnetosphere system very suddenly (Ukhorskiy+ 2015, Turner+ 2012)
- At the inner boundary is Earth’s atmosphere
- Coupling between radiation belts and middle atmosphere has long been suggested (e.g. Baker+ 1987)
- Radiation belt particles can end up deep in the lower atmosphere and influence the atmospheric chemistry that ultimately controls ozone variability (Randall+ 2003)

We don’t yet know the rates and locations of radiation belt particles entering Earth’s atmosphere, how they relate to changes in solar wind, and how they ultimately couple to the atmosphere

modified from Randall+ 2015
Particle acceleration in our backyard

- Acceleration events can be primarily caused by different mechanisms: there is no ONE way
- We can use the natural laboratory in our own magnetosphere to study fundamental physics of the universe
- Fully understanding the difference between subsequent years of radiation belt dynamics is crucial to the prediction of space weather and our human future in space
Solar wind driving

September 2014 storm event with little/no enhancement of relativistic electron populations
ULF wave power

- EFW axial E field derived from $E \cdot B = 0$
  - If $B$ is greater than $\sim 6^\circ$ from spacecraft spin axis
  - Components of $E$ and $B$ used to obtain $B_{||}$ and $E_\phi$

- Diffusion coefficients from Fei+ 2006 formulation

$$D_{LL}^B = \frac{M^2}{8q^2\gamma^2B_E^2R_E^4} L^4 \sum_m m^2 P_m^B(m\omega_d)$$

$$D_{LL}^E = \frac{1}{8B_E^2R_E^2} L^6 \sum_m P_m^E(m\omega_d)$$

March 17, 2015 storm ULF wave power

![Power Spectral Density](image)
Radial diffusion rates are event-specific (and magnitudes change throughout).

ULF-driven acceleration alone can account for intense ultra-relativistic particle enhancements observed in the inner magnetosphere.
Response to storm

- Acceleration of lower relativistic energies (~800 keV) started within <1 day.

- Higher energies showed up later and later, with the 7.7 MeV electrons appearing on March 20 (3 days after storm commencement).

- Lower energies are accelerated in the heart of the outer belt; higher energies are driven inward from higher L-shells.

- Chorus waves have subsided by the time ultra-relativistic energies appear in the outer belt.