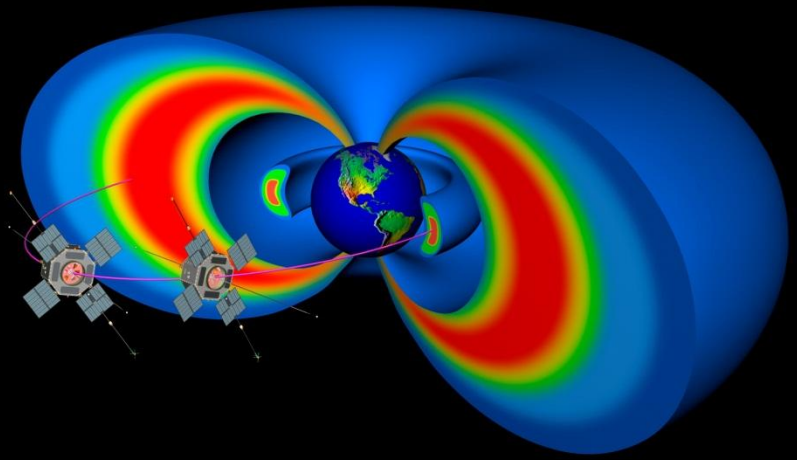
Findings from the Van Allen Probes mission and The path forward to future understanding regarding Earth's radiation belts and inner magnetosphere



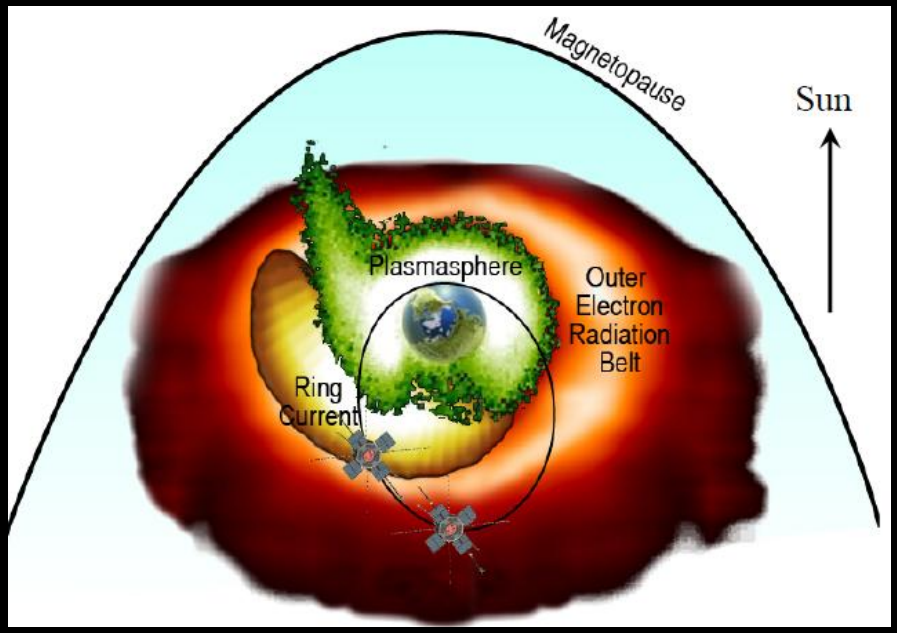
Barry Mauk, Nicola Fox, Ramona Kessel,
David Sibeck, Shri Kanekal,
Van Allen Probes Project Science Team

Outline

- Status of the Van Allen Probes Mission
- Selected findings and accomplishments
- Extended mission trades and proposal

Van Allen Probes Mission Status

- Purpose: Provide understanding, ideally to the point of predictability, of how populations of relativistic and penetrating ions in space form and change in response of variable inputs of energy.
- Two identically-instrumented spacecraft flying in nearly the same 1.1 x 5.8 RE elliptical orbits.
- 1 spacecraft laps the other every ~2.5 months
- Launched: 30 August 2012; Formal Start: 1 November 2012
- Mission Success Criterion achieved 26 March 2014.
- On track for achieving baseline Level-1 requirements on 31 Oct. 2014
- Extended mission proposal under development.

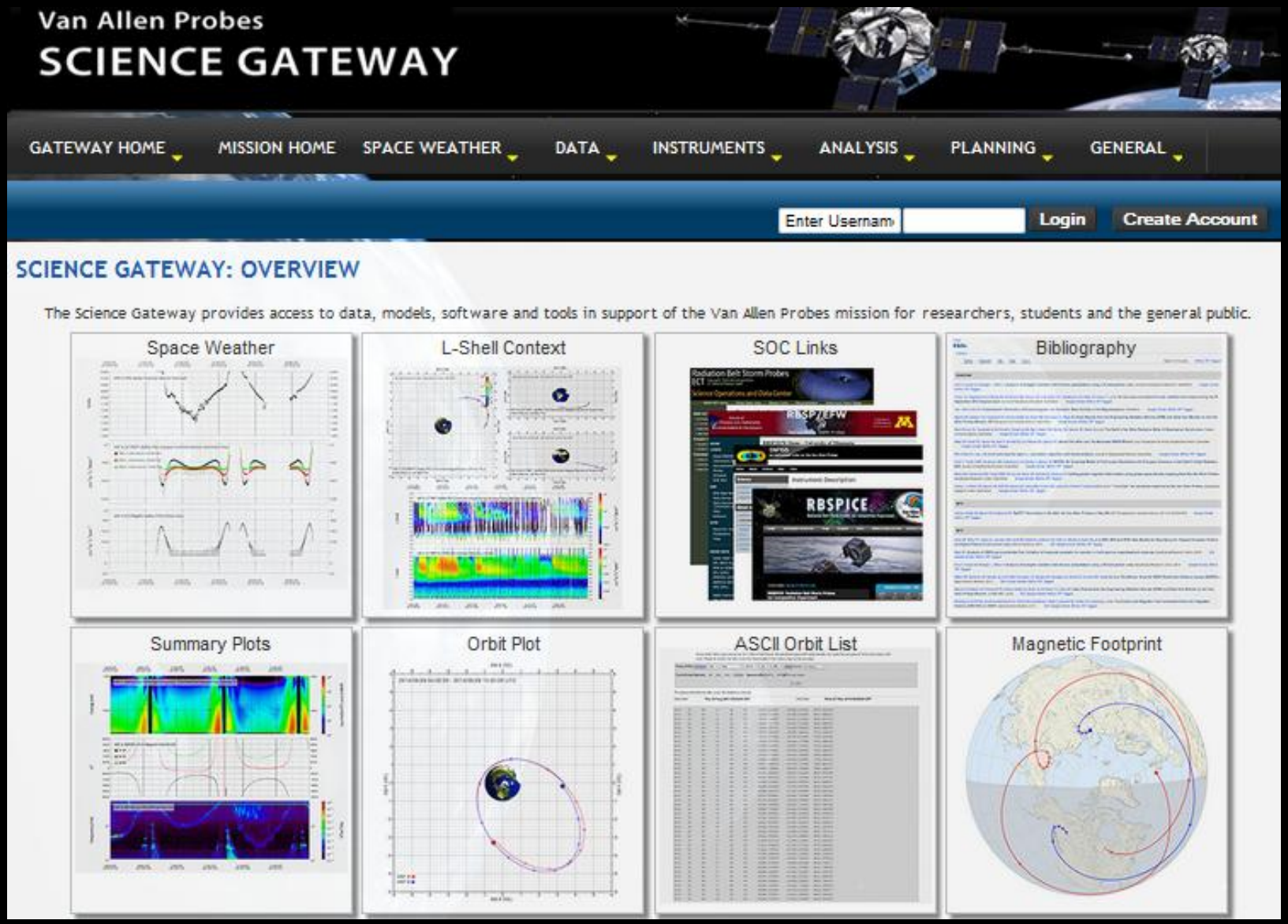


Van Allen Probes Science Status

- All Level 2 and Level 3 data available: see SOC links at http://athena.jhuapl.edu .
- Mission and Instruments documented in a special issue of Space Science Reviews. November 2013, Volume 179, Issue 1-4
- Special issue of Geophysical Research Letters comprising 26 articles published 1 April 2014.
- Special issue of Journal of Geophysical Research ongoing (papers due before 21 November 2014).
- High Profile results include: 2 articles in Science; 2 in Nature and 2 others in Nature Journals; 2 in Physical Review Letters.
- Selected Research Highlights discussed here.

Investigation	PI	Institution
ECT	Spence	UNH
EMFISIS	Kletzing	U. Iowa
EFW	Wygant	U. Minnesota
RBSPICE	Lanzerotti	NJIT
RPS	Mazur	Aerospace
BARREL	Millan	Dartmouth

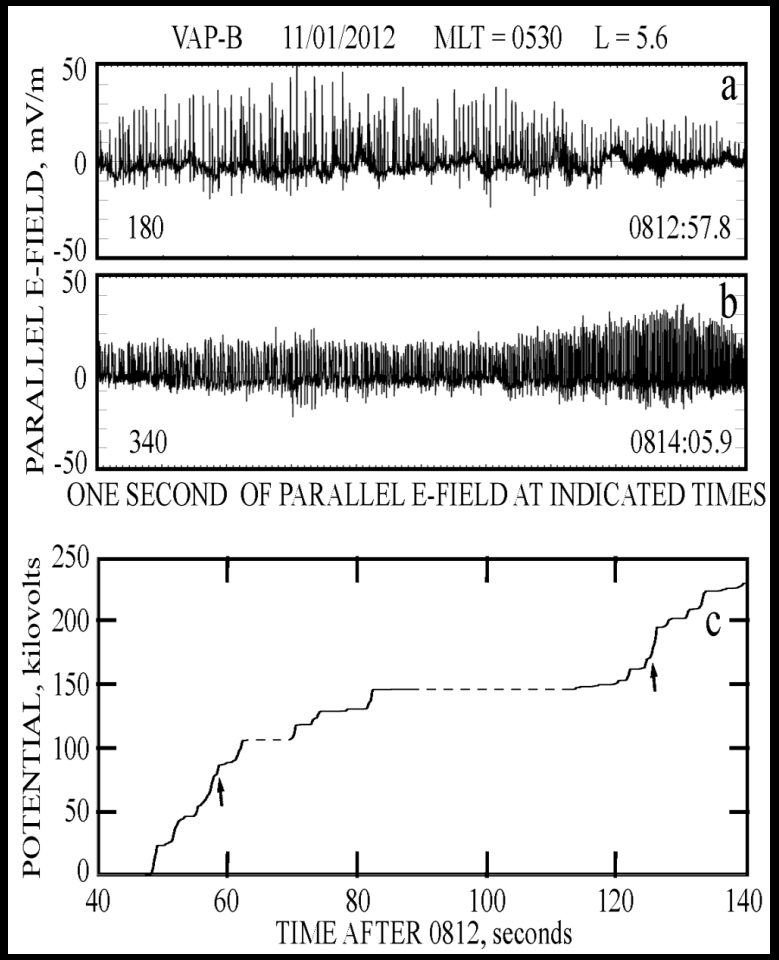
http://athena.jhuapl.edu/



Science Highlights

- With regard to selected findings I will highlight those less mentioned at this conference.
- Specifically I honor here but will pass over in subsequent discussions:
  - 3rd Belt discovery: Baker et al. 2013
  - 3rd Belt analyses: Thorne et al. 2013; Shprits et al. 2013
  - Local in situ acceleration verification: Reeves et al., 2013
  - Quasi-linear acceleration by whistler wave: Thorne et al. 2013
  - ULF generation and drift resonance interactions: Dai et al., 2013; Claudepierre et al., 2013

"Double-Layers" May Provide a Critical Step in the Acceleration of Radiation Belt Electrons.

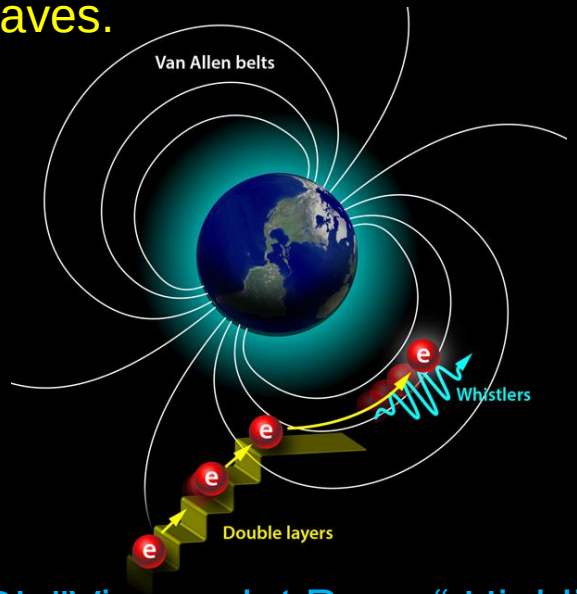


Mozer et al. Physical Review Letters, 2013

The Van Allen Probes EFW instrument has discovered electric spikes called "double-layers" in the heart of the outer radiation belt.

Thousands of ~35 volt double-layers can combine along flux tubes to yield 10's to 100's of kilovolts electron acceleration.

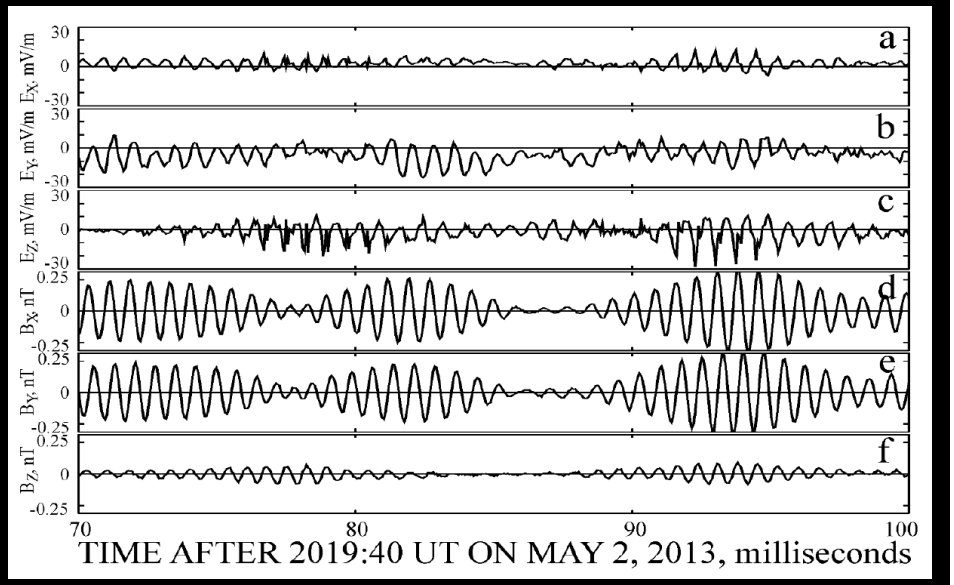
This process may locally generate the seed population for acceleration to MeV energies by whistler waves.



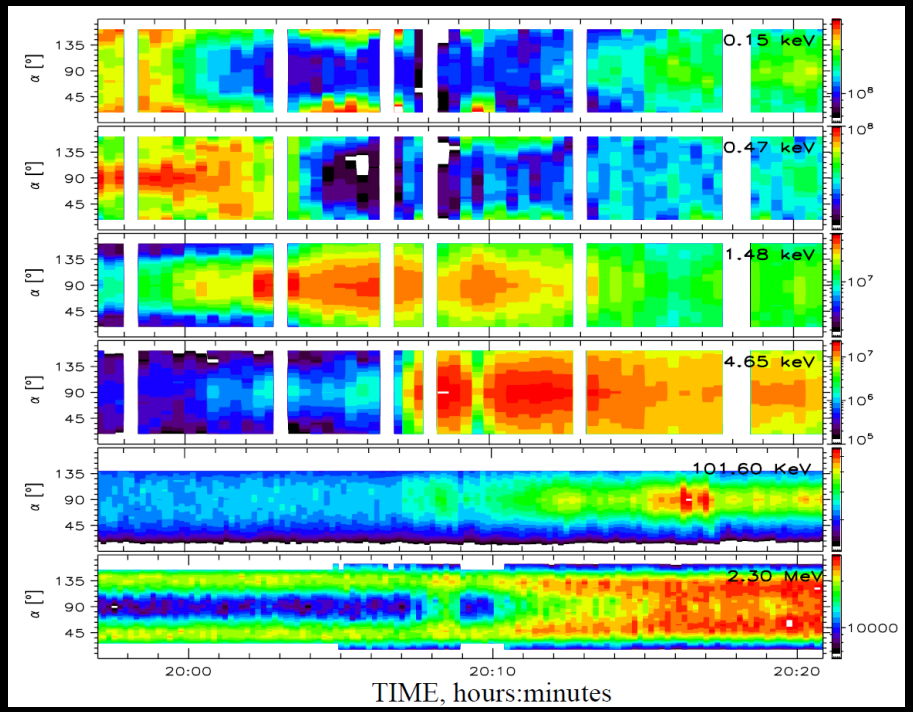
PRL "View-point Paper" Highlight

New Developments on Double Layers
(Mozer et al. PRL, 2014)

Double layers are observed to emerge as non-linear developments (due to trapping) of chorus waves



Double Layers can generate seed populations locally (Lower energy field-aligned component)



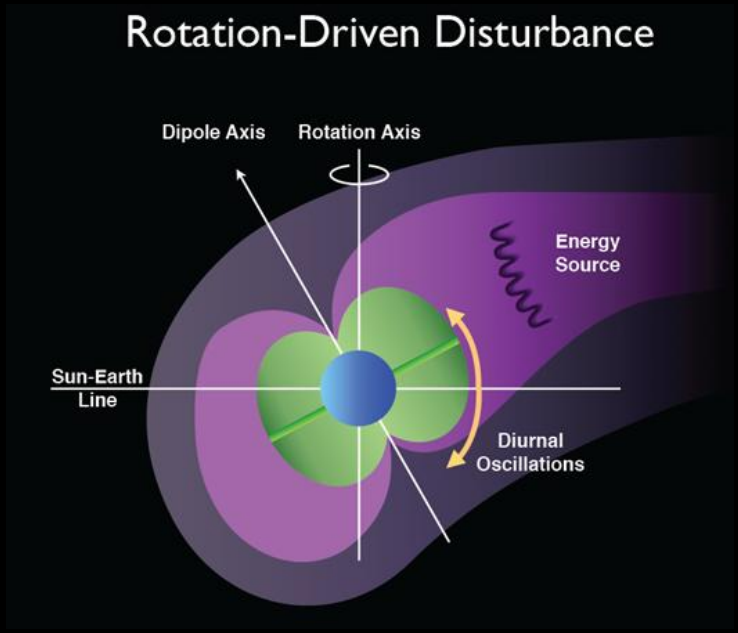
<u>Outstanding question</u>: What is the relative importance of this mechanism relative to direct injection to the generation of seed populations?

Earth's Rotation Unexpectedly Causes "Zebra Stripes" in the Inner Electron Radiation Belt

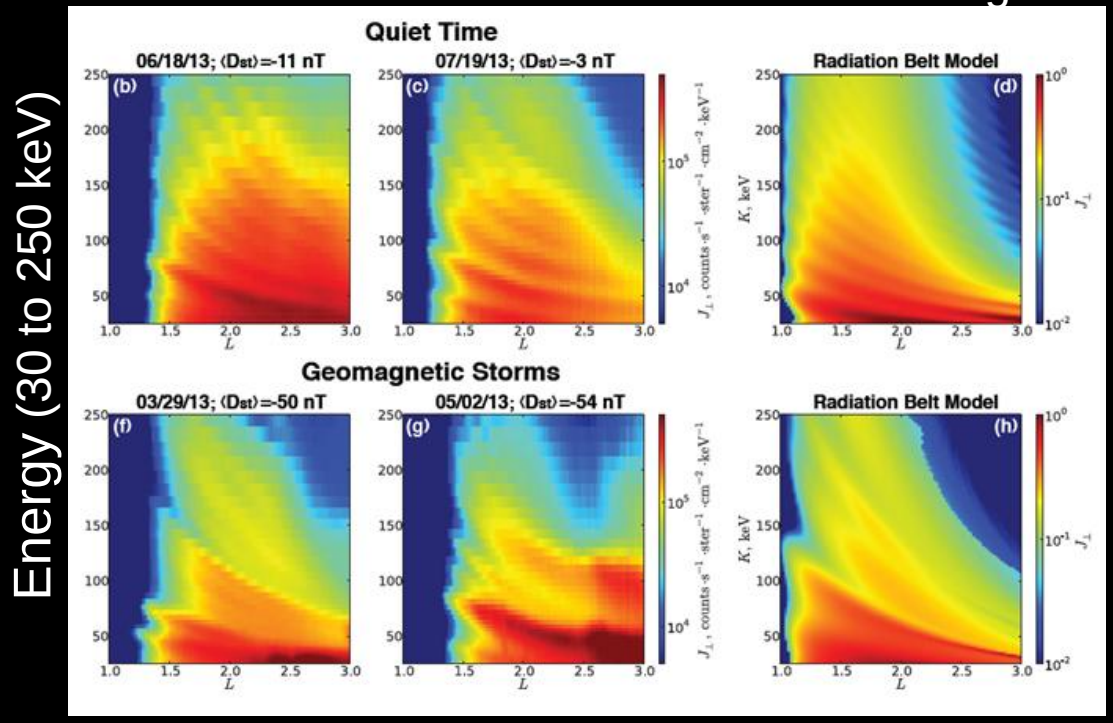
The Van Allen Probes RBSPICE instrument has discovered stripe-like patterns, termed "Zebra Stripes" in the inner portions of Earth's electron radiation belt.

Earth's rotation causes a very weak electric field whose effect builds up strongly over time due to quasi-resonance with drifting electrons.

The stripe pattern is caused by a stretching and folding of electron clouds, much like taffy is stretched and folded in a candy machine.

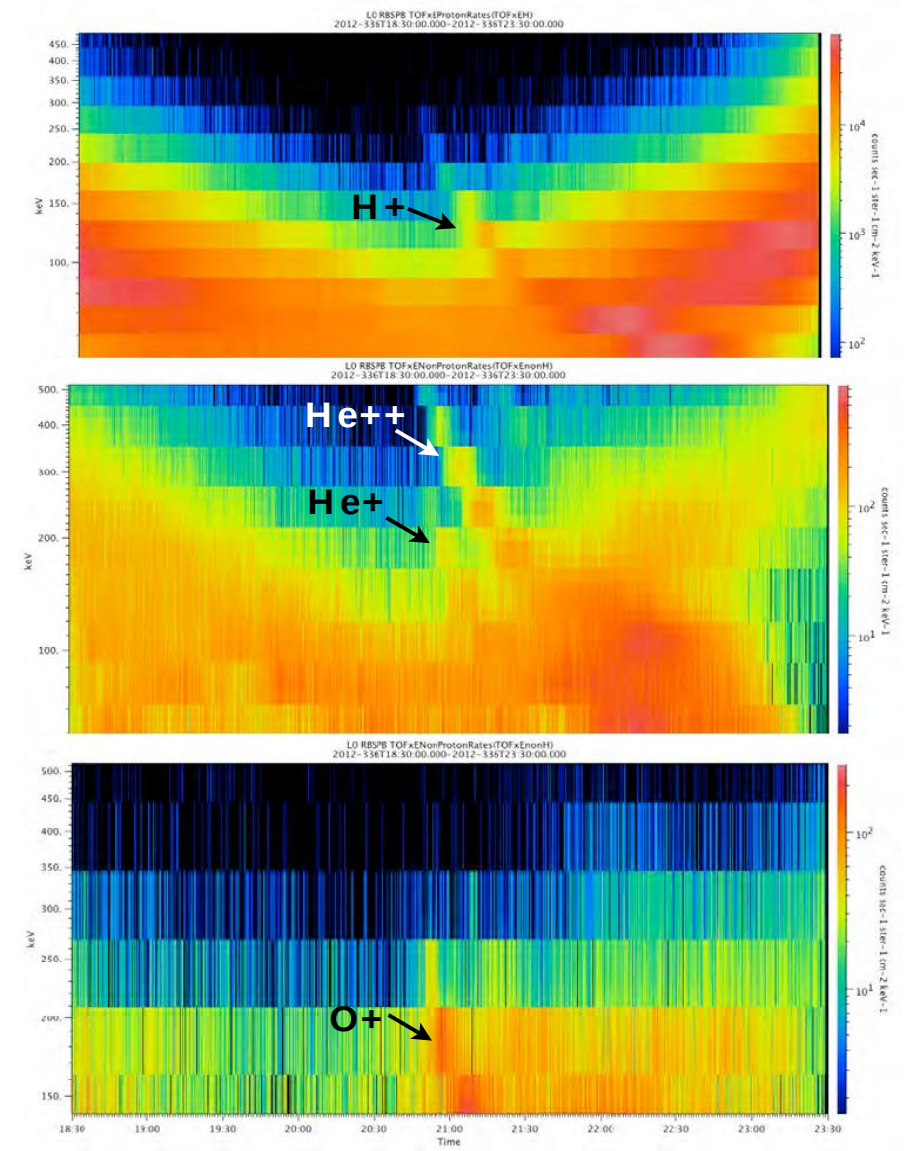


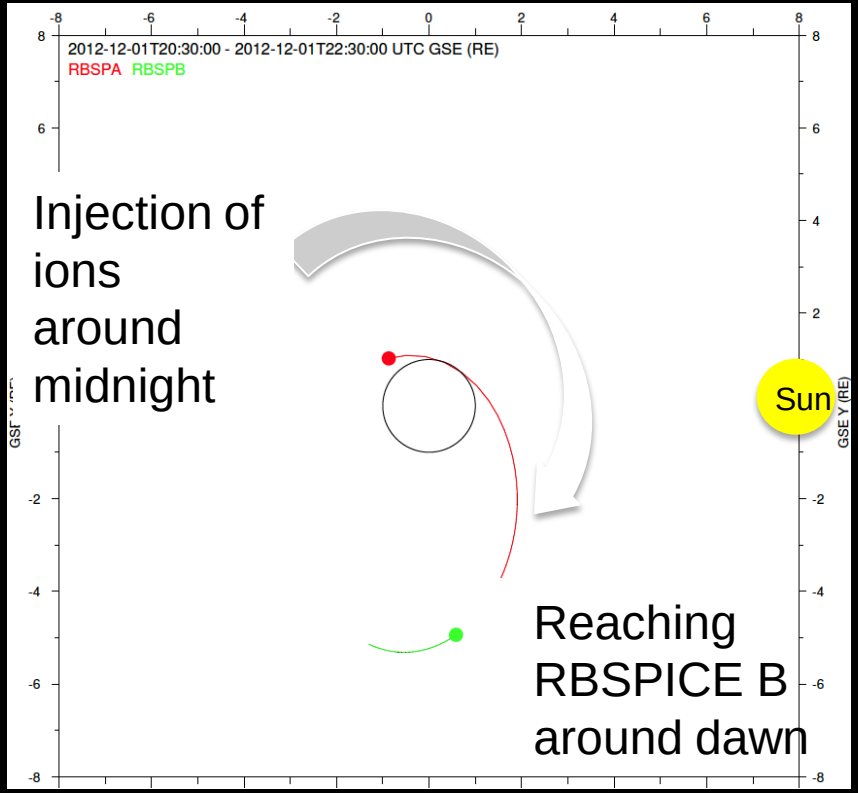
Observations Modeling



Ukhorskiy et al., Nature, 2014

Role of Injections is highlighted in a number of Van Allen Probes results.

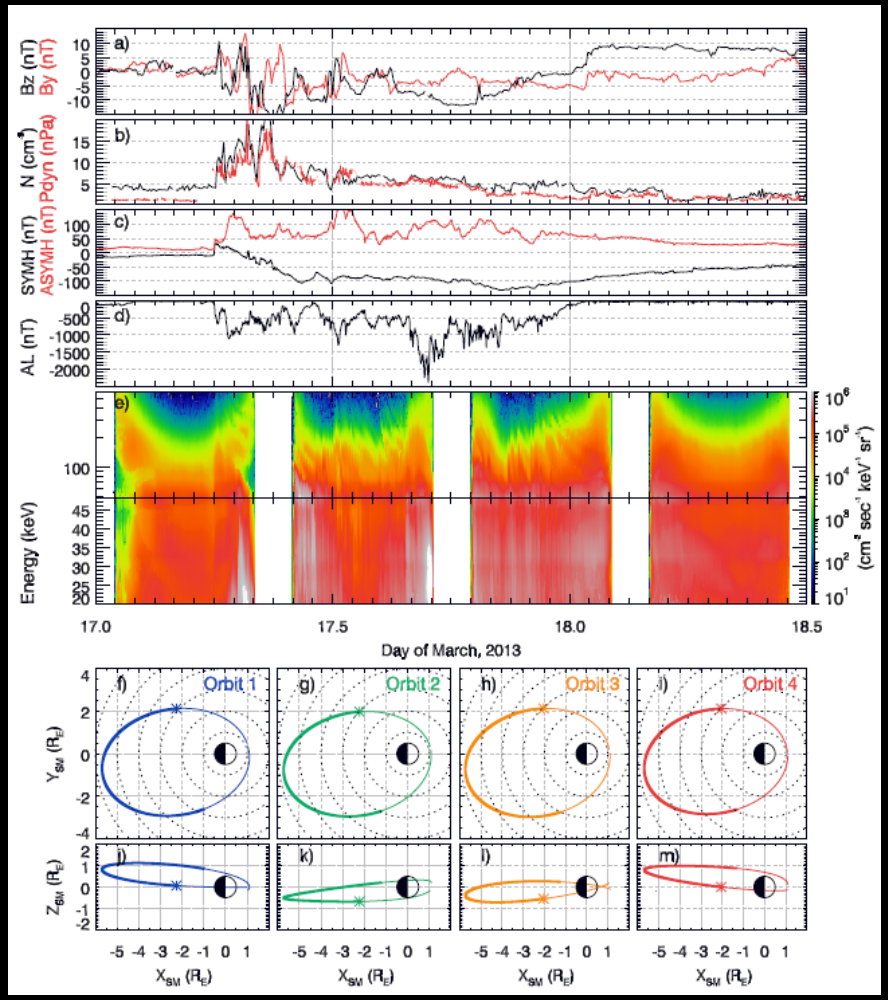


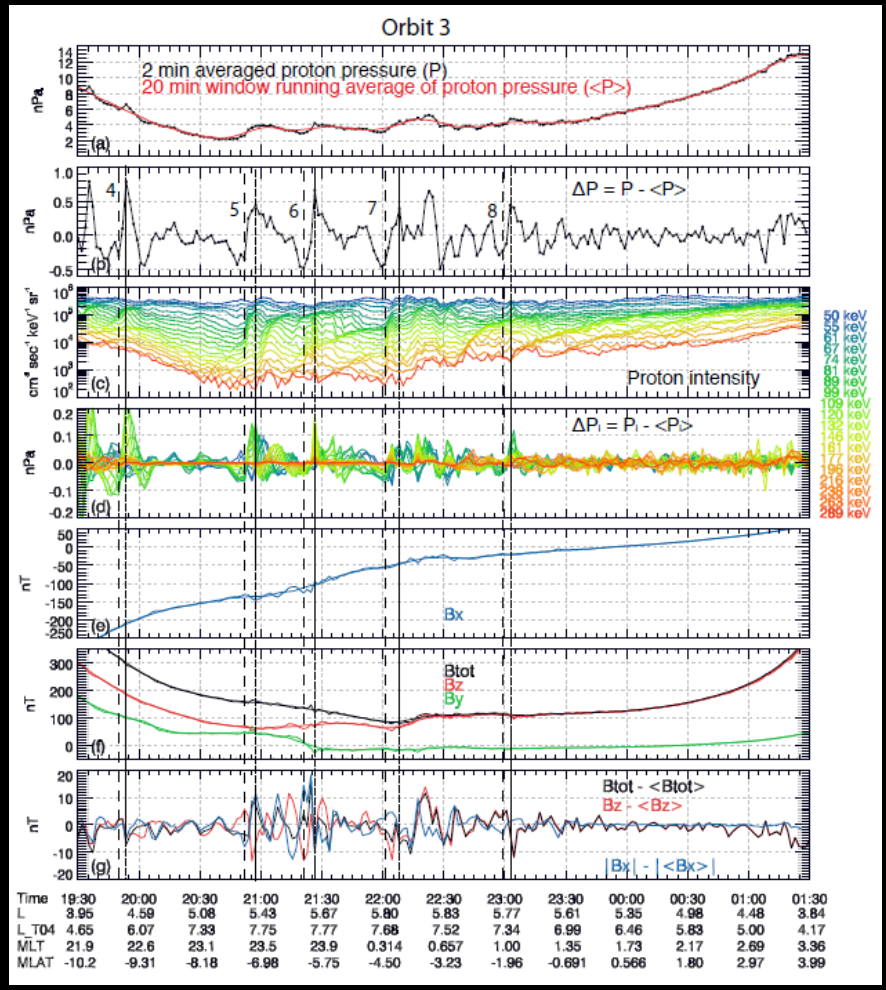


RBSPICE Team (Lanzerotti et al.)

Substorm injections can contribute substantially to ring current pressure build up during magnetic storms

≥30% of pressure found to come directly from transient injections

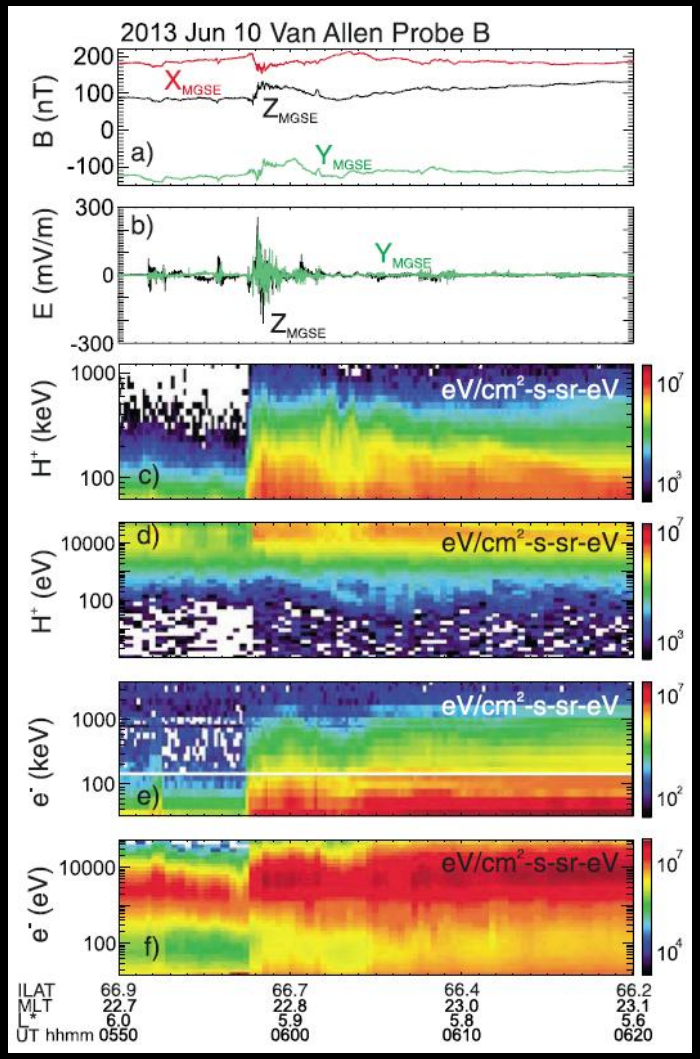




Gkioulidou et al. 2014; See also Yu et al., 2013

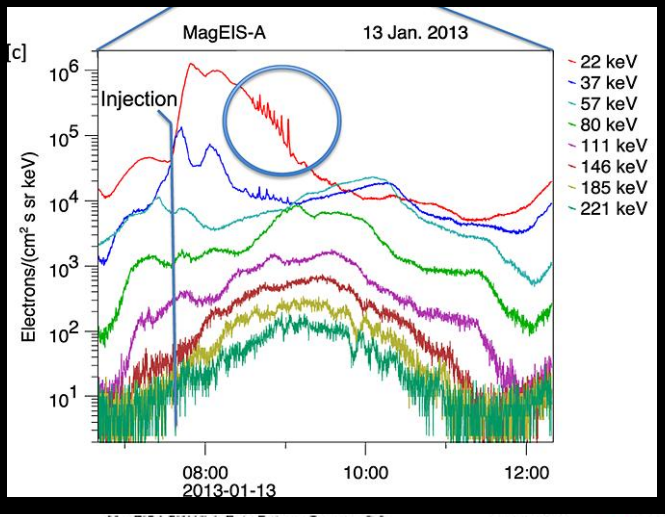
Newly discovered phenomena associated with injections

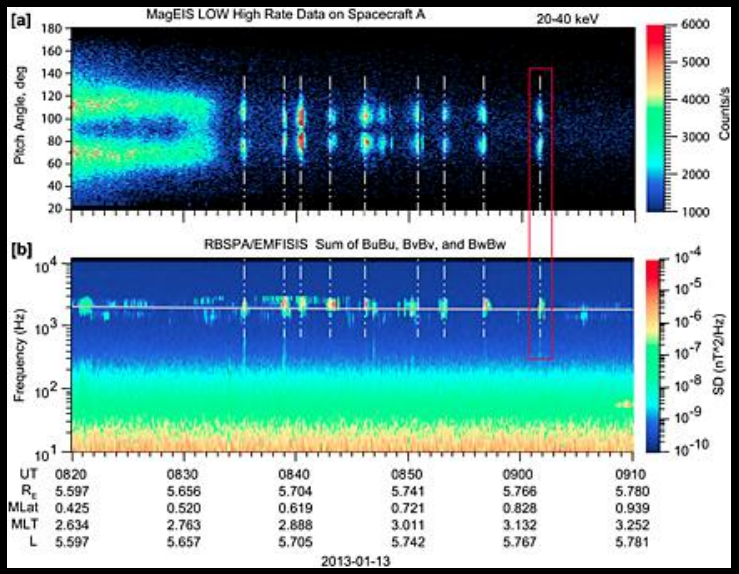
Kinetic-scale Alfvenic field line resonances with feedback amplification



Chaston et al., GRL, 2014

Peculiar particle–whistler interaction features

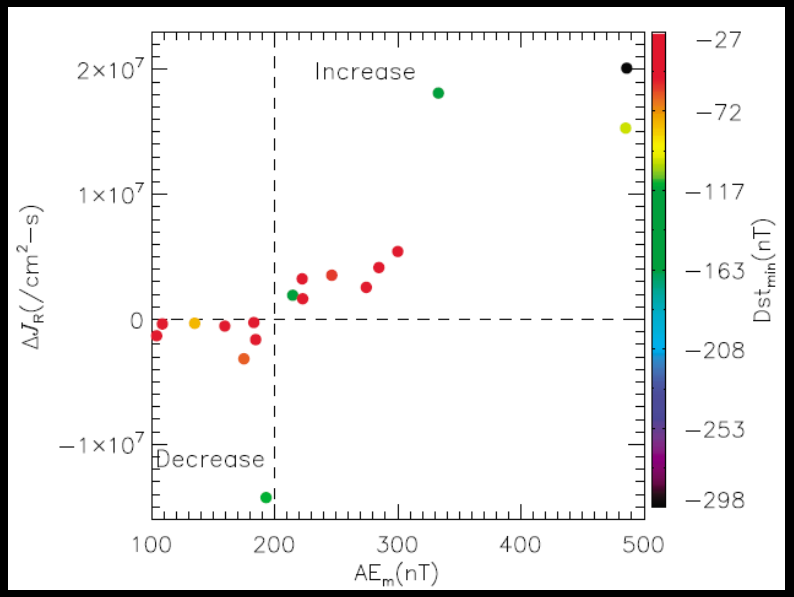


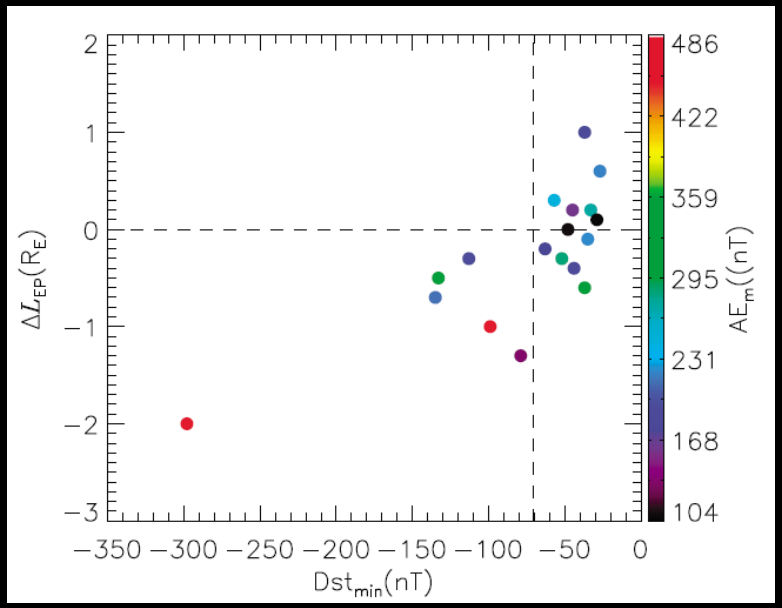


Fennell et al. 2013

An Outstanding Question has been the relative role of storms and substorms in the build up of the outer belt

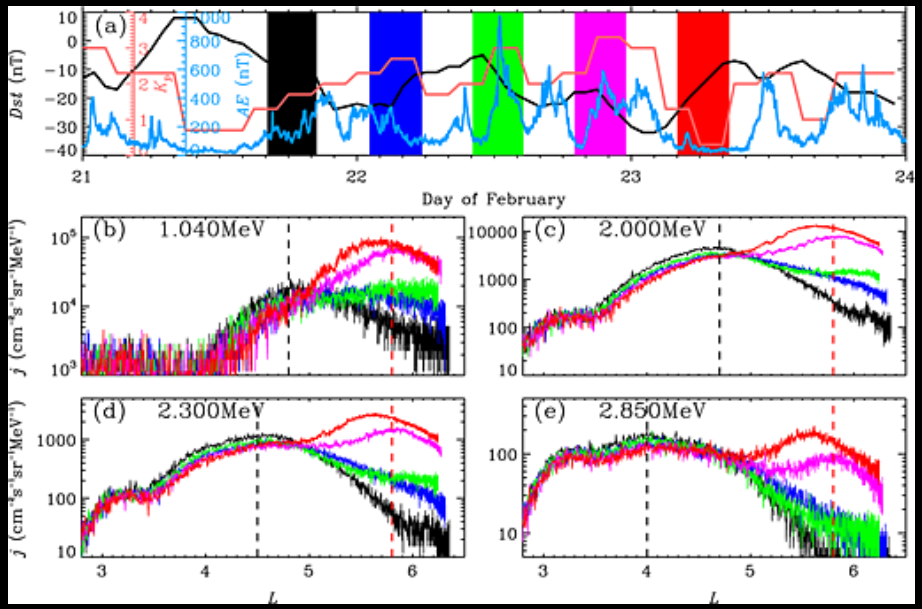
- Li et al. (2009) has suggested that:
  - Primary impact of a storm development is the net loss of relativistic electrons from the entire outer zone via the main-phase losses of relativistic electrons
  - Continuous intense substorm activity (AEm > 200 nT) can cause the net increases of the relativistic electrons in the entire outer zone.
- Similar to Meredith et al. (2002; 2003)
- The proposed agent for acceleration was chorus/whistler mode acceleration

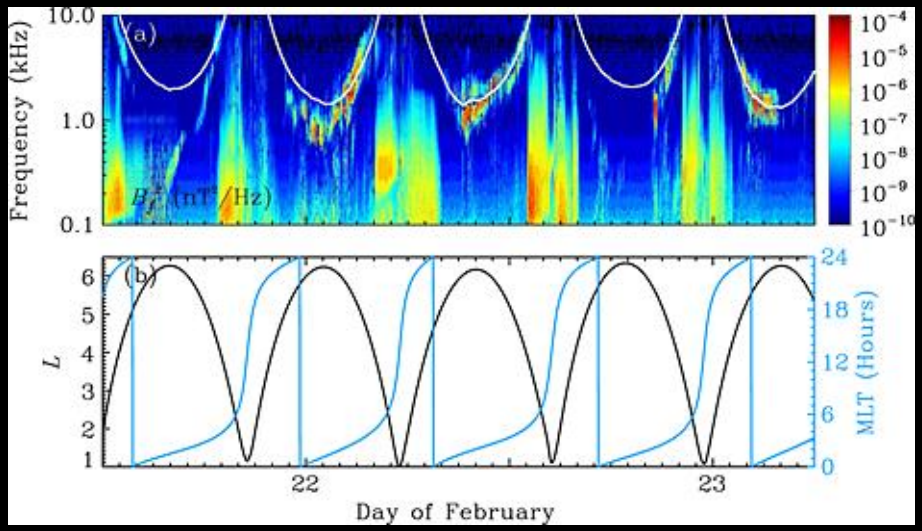




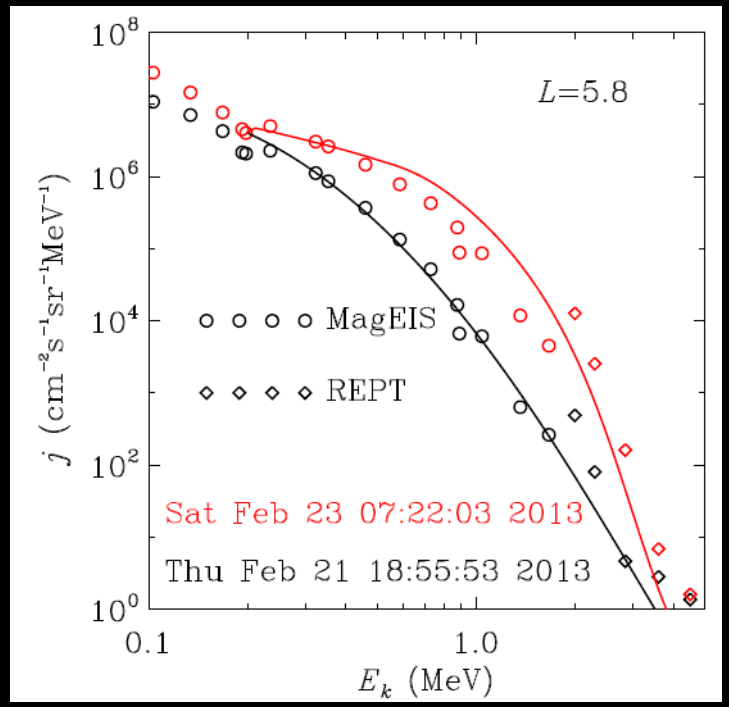
Li, et al. 2009

Role of chorus whistlers in an unusual non-storm electron acceleration now verified for one important event





Solid red line: Modeled whistler acceleration based on observed whistler waves.

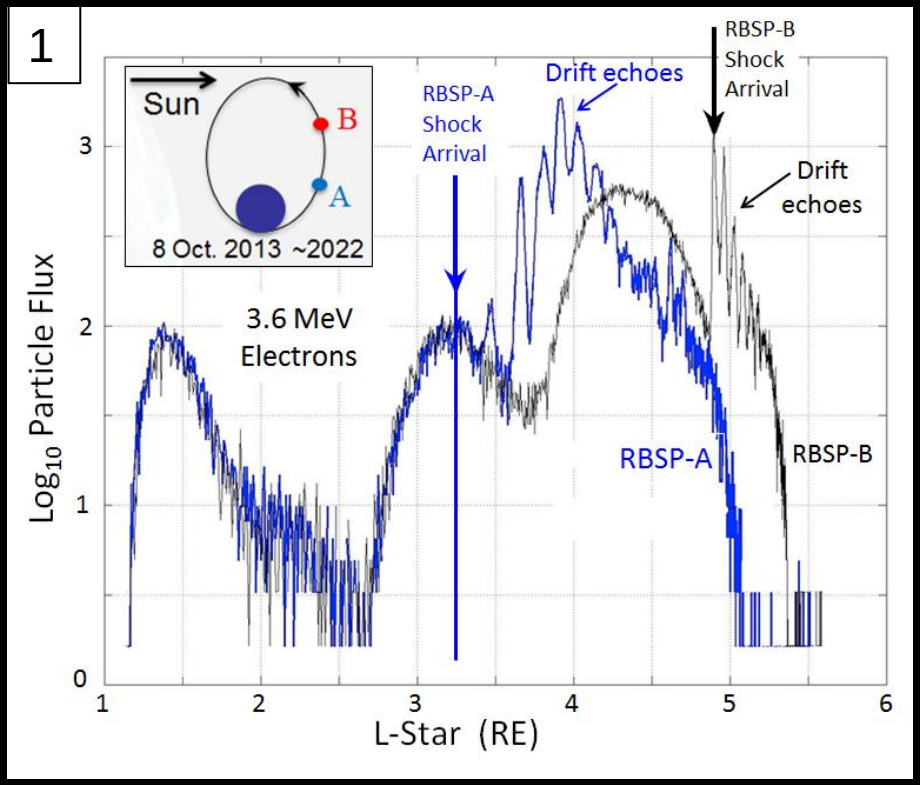


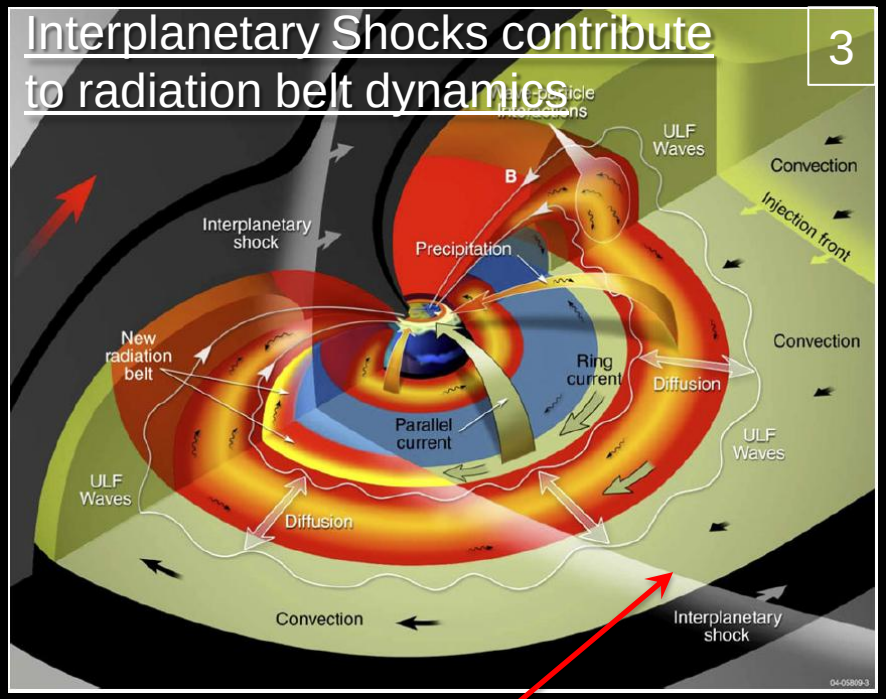
Su et al.

See also: Schiller et al. 2013

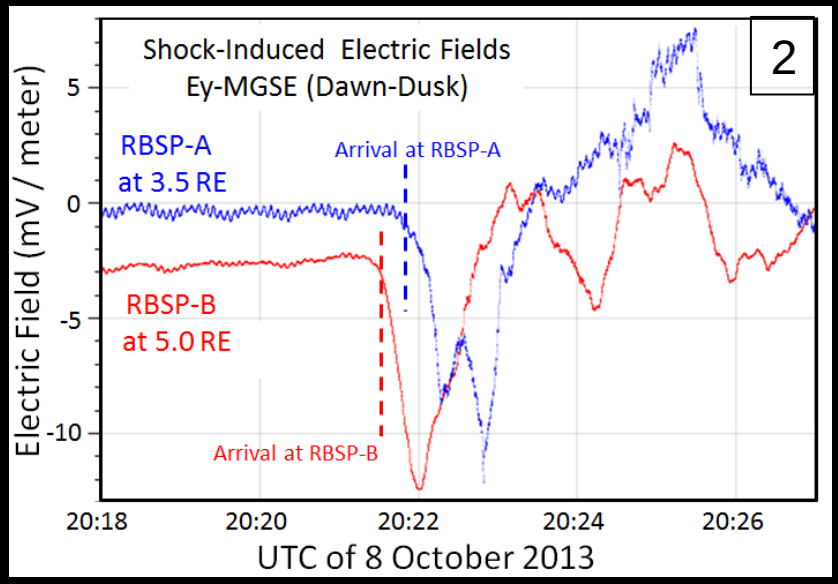
Interplanetary Shock Wreaks Havoc on Earth's Electron Radiation Belt

- Van Allen Probes track an interplanetary shock through the inner magnetosphere (1).
- Induced electric fields (2) cause drift echoes and acceleration of MeV-class electrons throughout the outer radiation belt (1)
- Local shock effects and wave drift-resonance diffusion contribute to the acceleration (3)





Interplanetary Shock



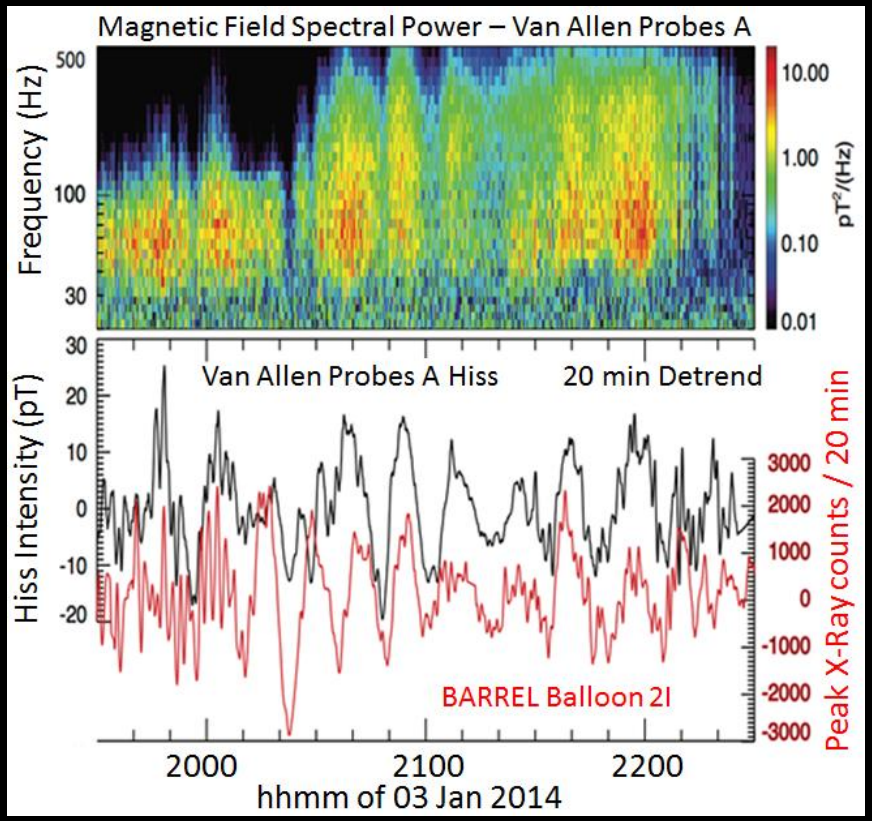
Foster et al., 2014, In Preparation

Modulated Magnetospheric Whistler-Wave "Hiss" emissions cause high energy electron precipitation into atmosphere

1. Van Allen Probes A, deep within the magnetosphere, observed intense and modulated broadband "Hiss' radio waves with frequencies from 30 – 500 Hz.
2. BARREL Antarctic Balloon 2I, instrumented to measure Bremsstrahlung X-rays from precipitating energetic electrons, crossed the magnetic footpoint of the Probes.
3. Strong correlation between the precipitating electrons (10's of keV) and integrated Hiss demonstrates that whistler mode Hiss contributes greatly to radiation belt losses.

1.

3.



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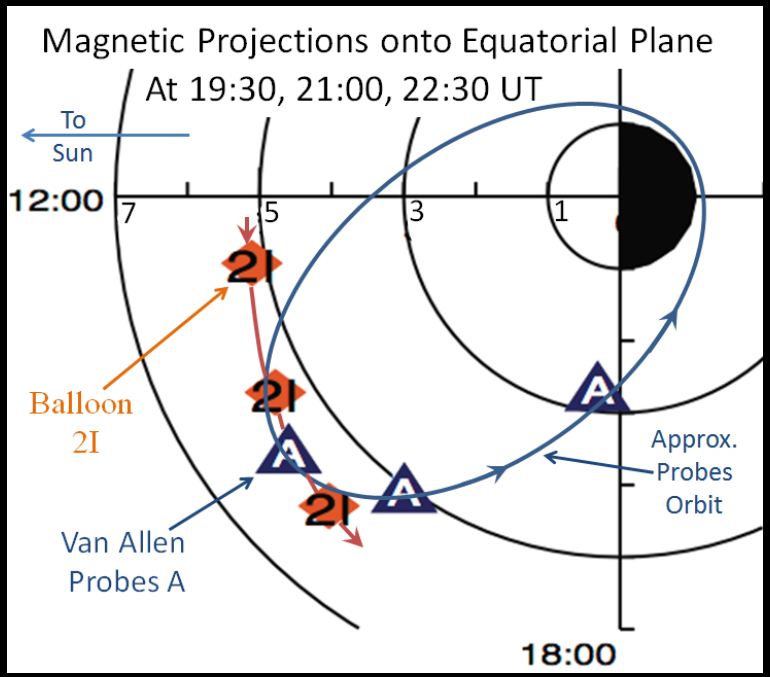


Breneman, Halford, Millan, Wygant et al., in prep

Outstanding Question:

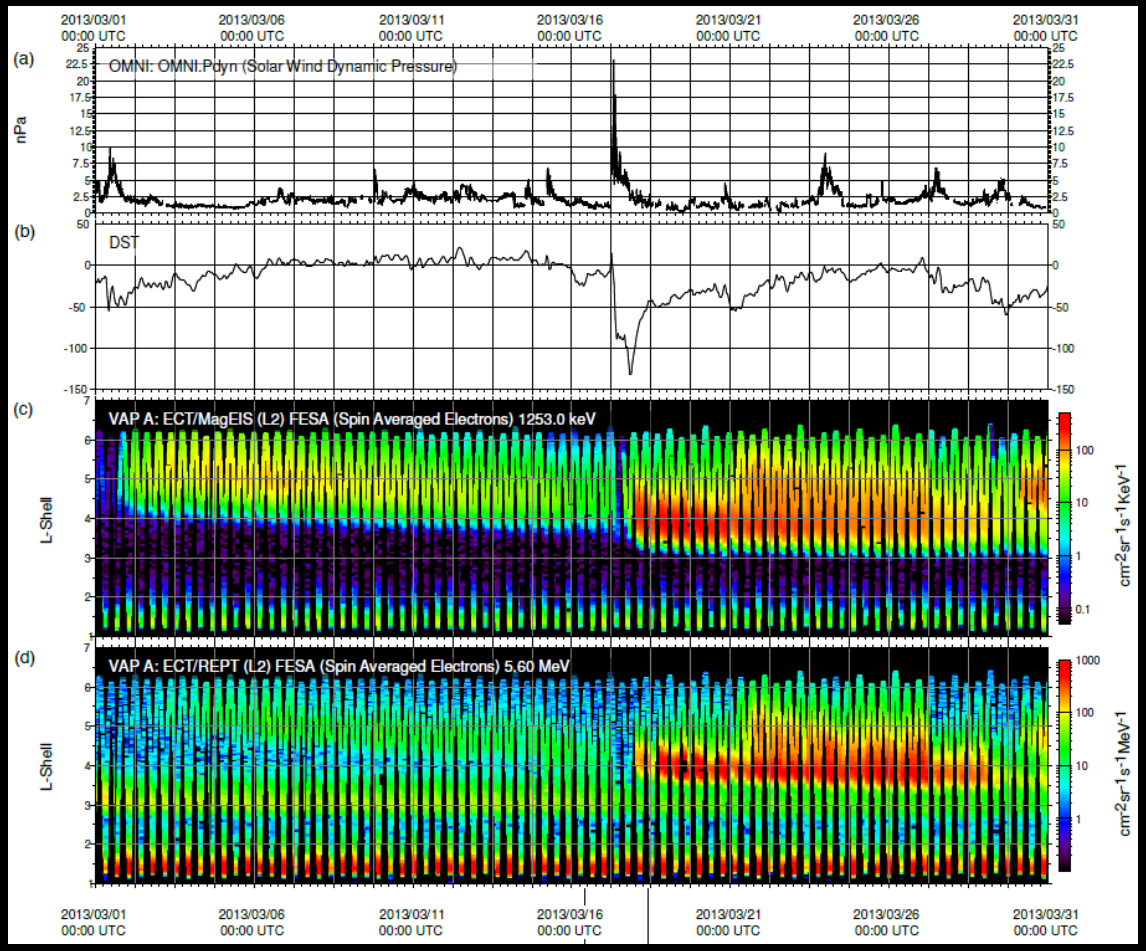
What causes sudden belt dropouts associated with storms?

SW Ram Pressure

DST

Electrons 1.2 MeV

5.6 MeV



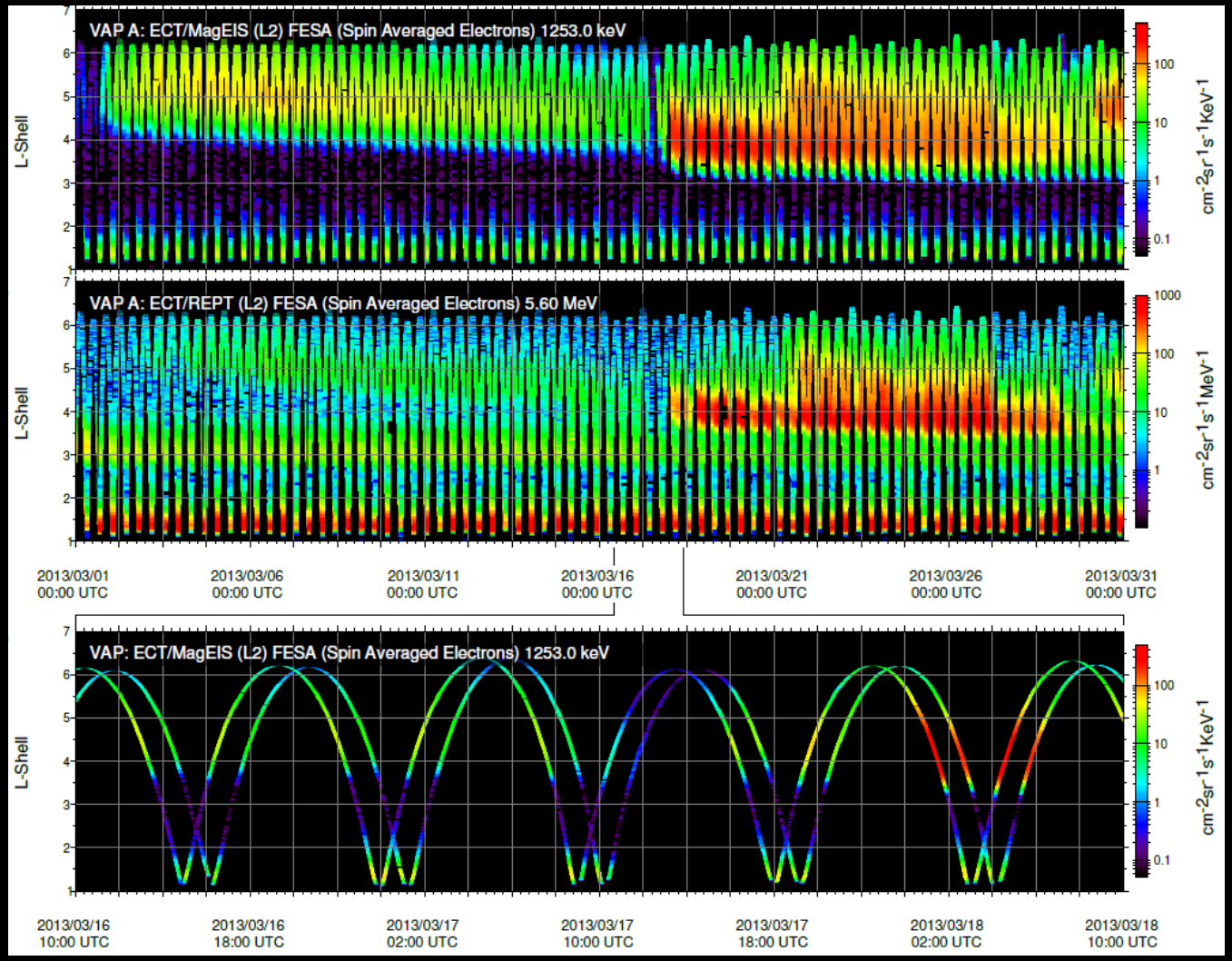
1 month

Ukhorskiy et al., 2014, submitted

The 17 March Storm period highlighted by several authors e. g. Baker et al., 2014; Gkioulidou et al., 2014, etc.

The dropout is complete and comprehensive

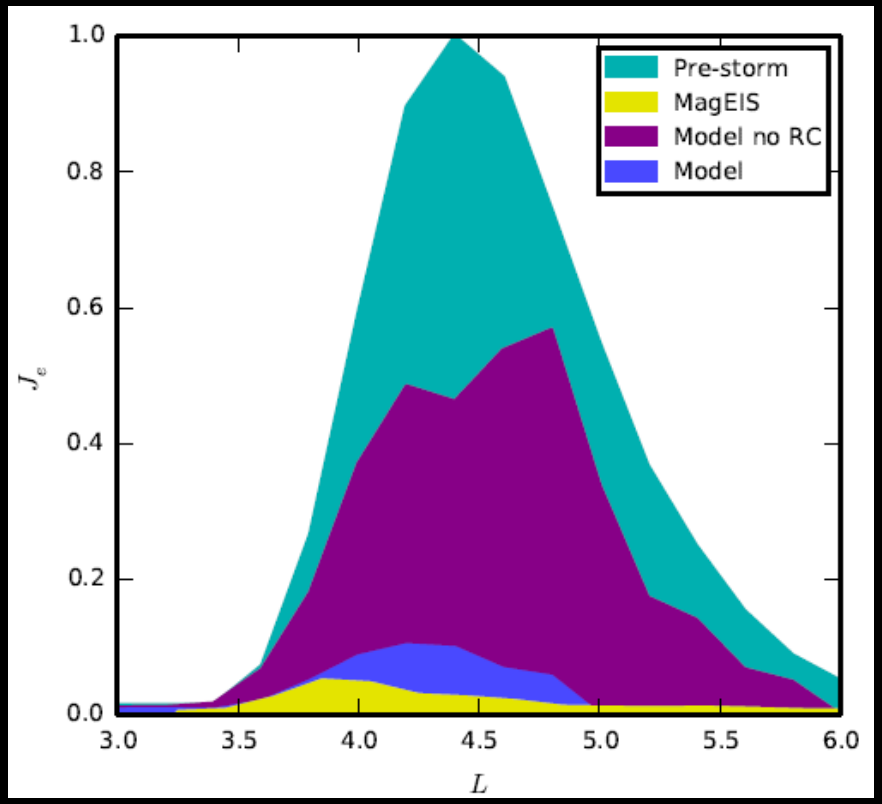
Developing consensus that Magnetopause shadowing is a key contributor, but how does it work?

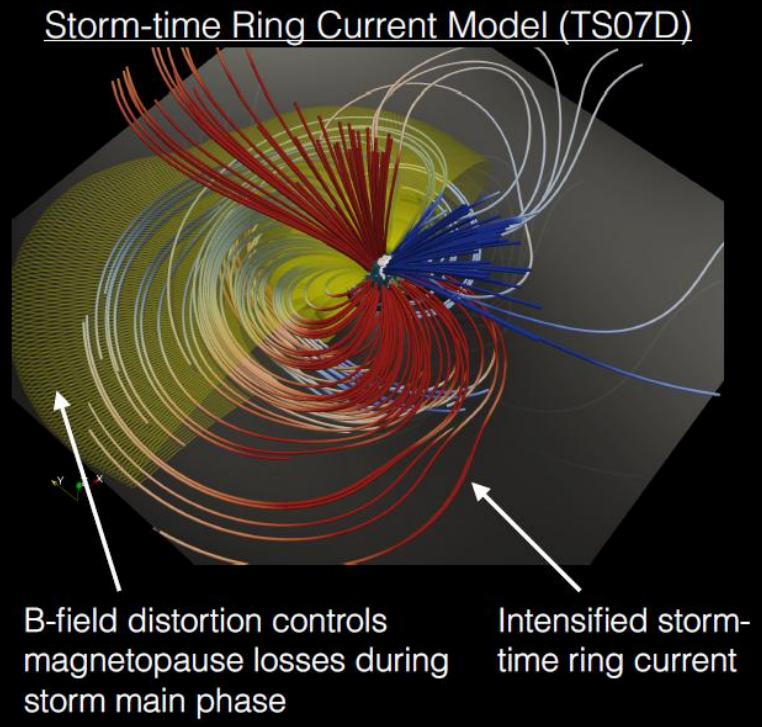


Ukhorskiy et al., 2014, submitted

Model versus observations

- Non-adiabatic motion is key
  - Violation of 3rd invariant due to inductive electric fields associated with magnetic field time dynamics.
  - Violation of 2nd invariant by drift orbit bifurcations,
- Deep depletion is enabled by storm-time ring current.





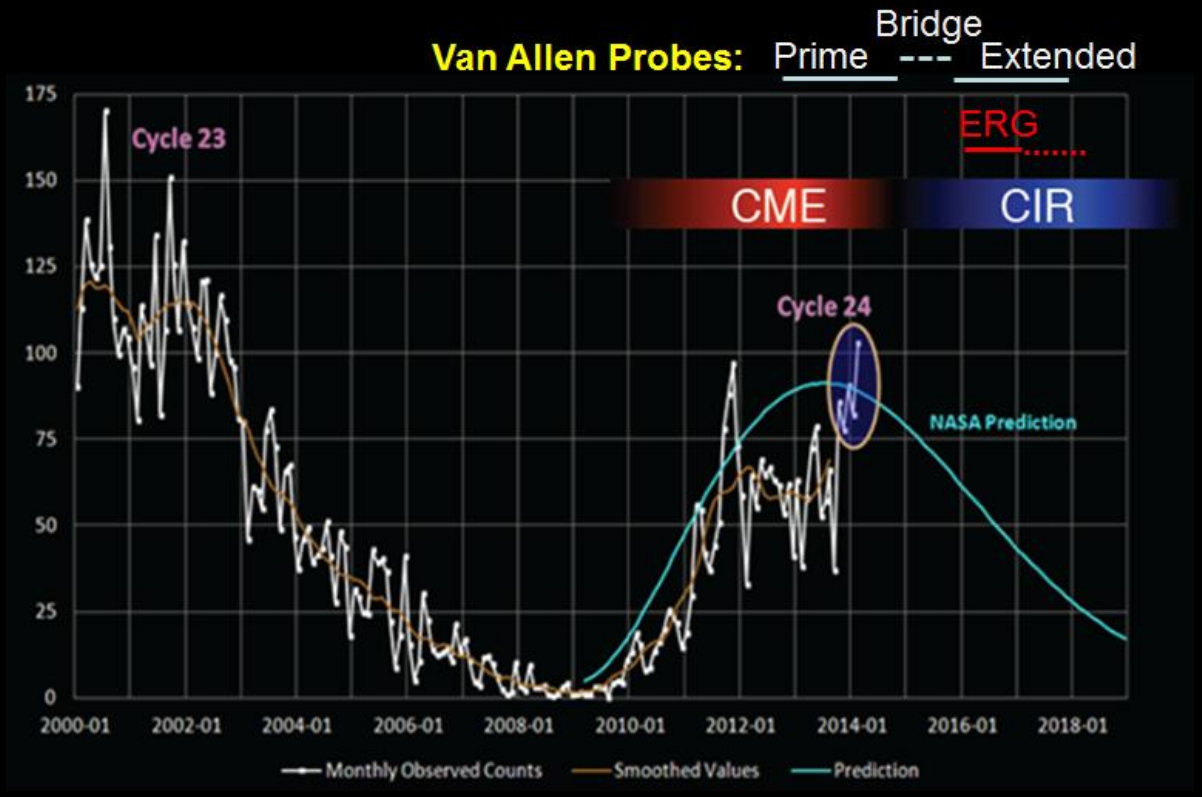
Ukhorskiy et al., 2014, submitted

What will the Van Allen Probes do in an Extended Mission?

- Formal prime mission ends 31 October 2014
- A “Bridge Phase” will take the mission through about Sept. 2015
- The Project will request an extended mission beyond the Bridge Phase through the NASA “Senior Review” process
- The Proposal to the NASA must convince NASA and the review panel that:
  - New and different kinds of information will be obtained during the extended mission that are unavailable from prime mission operations
  - Progress in our understanding of the radiation belts and the inner magnetosphere require that we acquire the new kinds of information
  - Specific scientific findings will be achieved by making us of the new kinds of information
- The Project would appreciate any ideas from the scientific community regarding the plans forward for the mission.

Some new opportunities for the Van Allen Probes mission

- A new phase of the solar cycle, the declining phase, transitioning from a CME-dominated period to a CIR dominated period
- Coordinate with such new assets, as MMS, ERG, several planned CubeSats, etc.
- Possibly perform modest modifications to the orbital configuration and/or orbital phasing to sample differently the radial-azimuthal space
- Operating the instruments in different modes to target specific phenomena.



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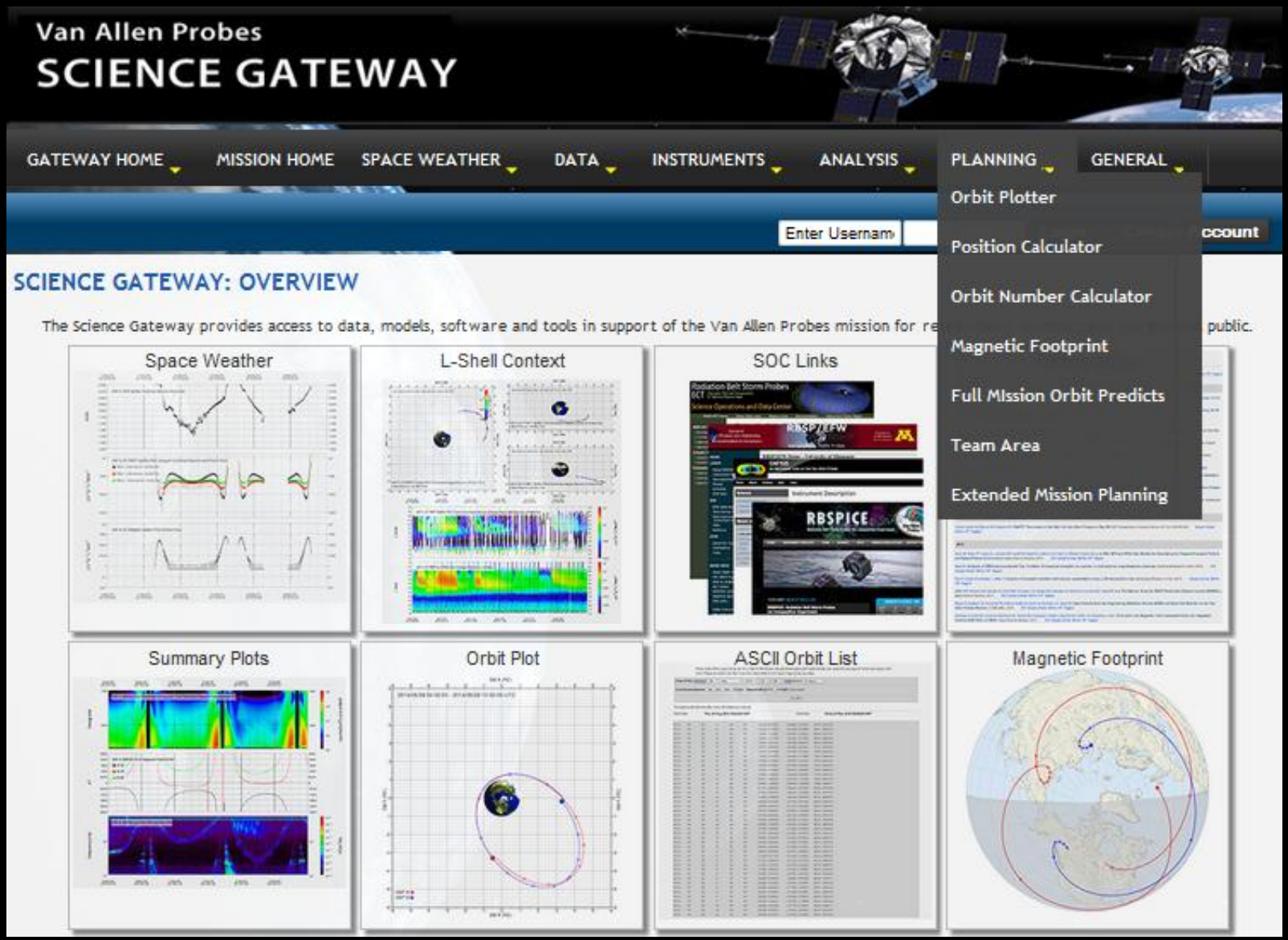
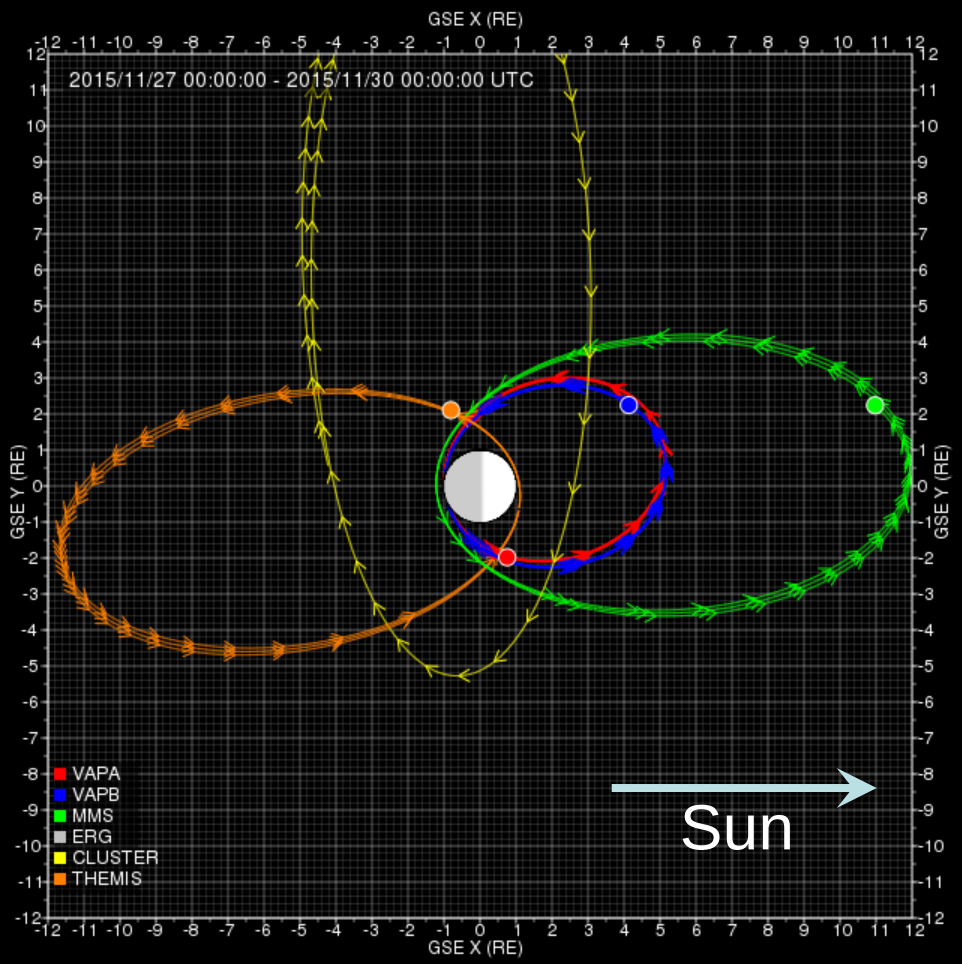
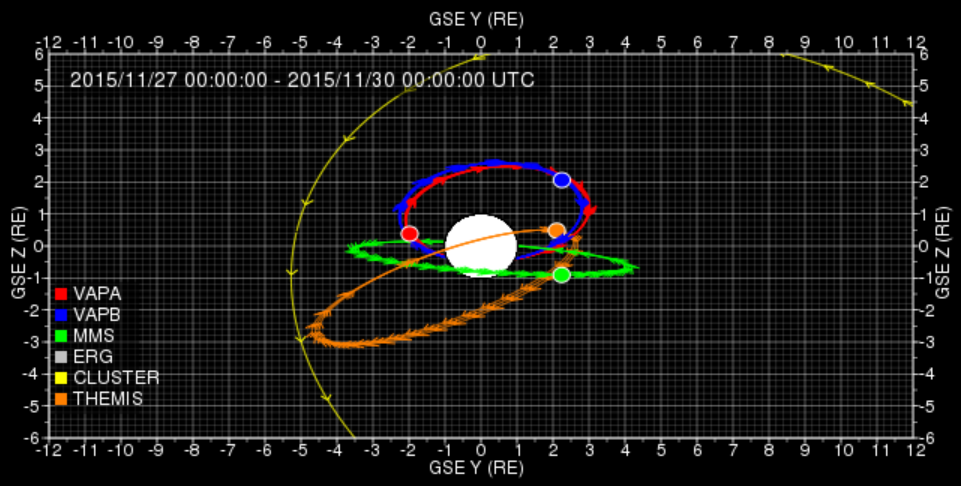
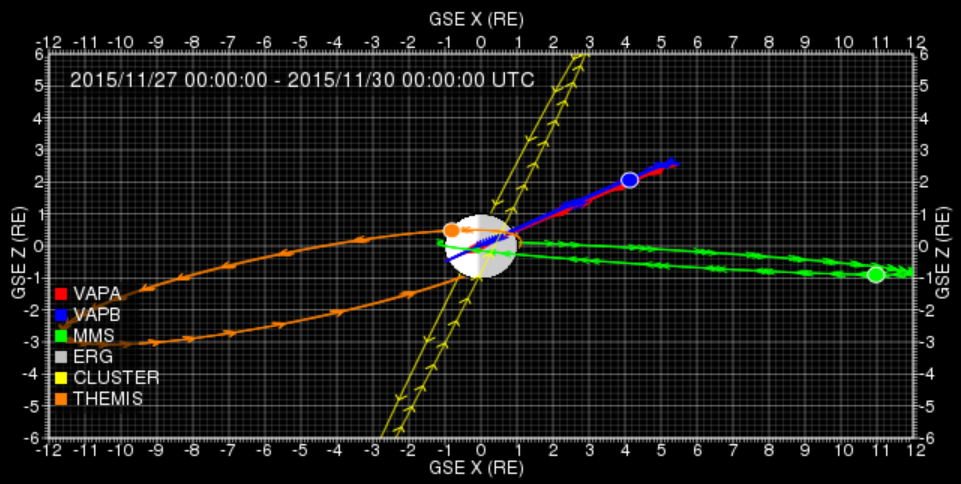


November 2015

Coordinate with MMS on magnetopause coupling (2 of 2)



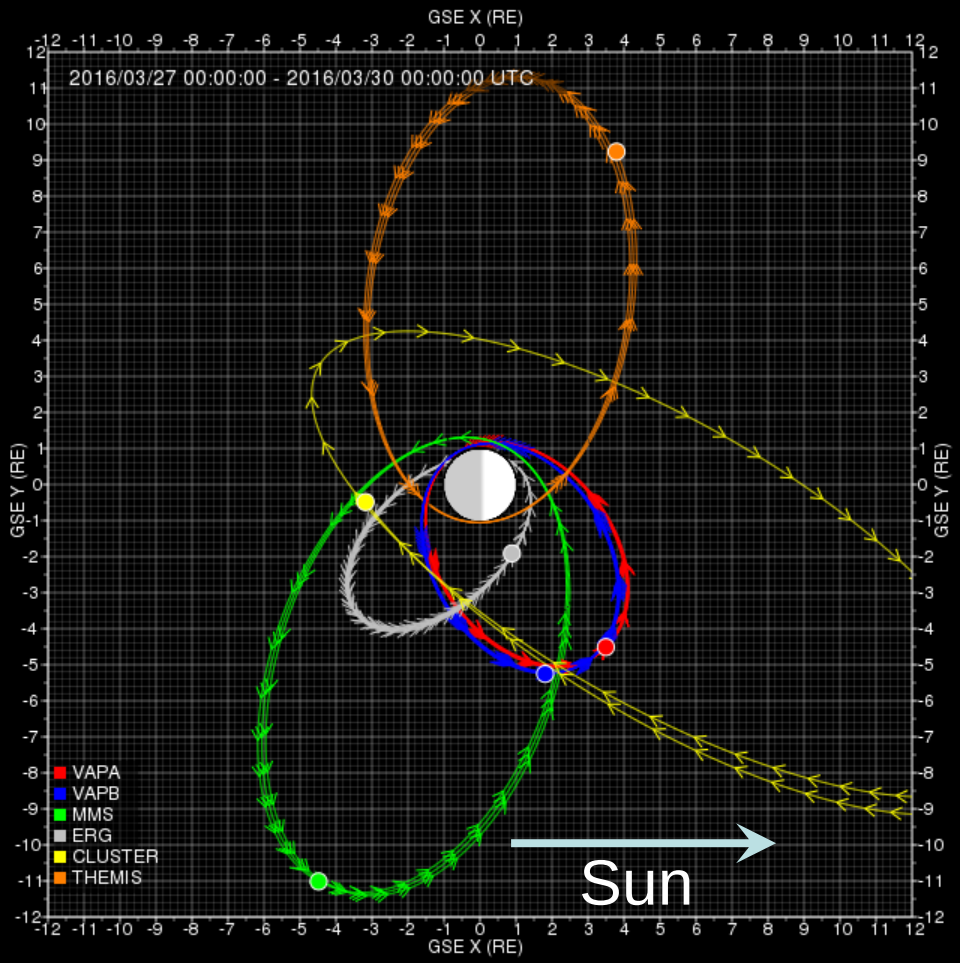


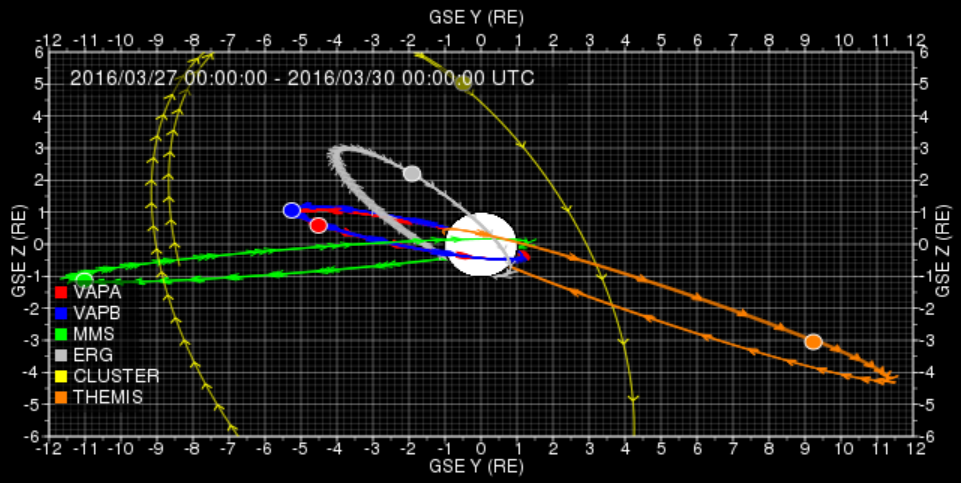


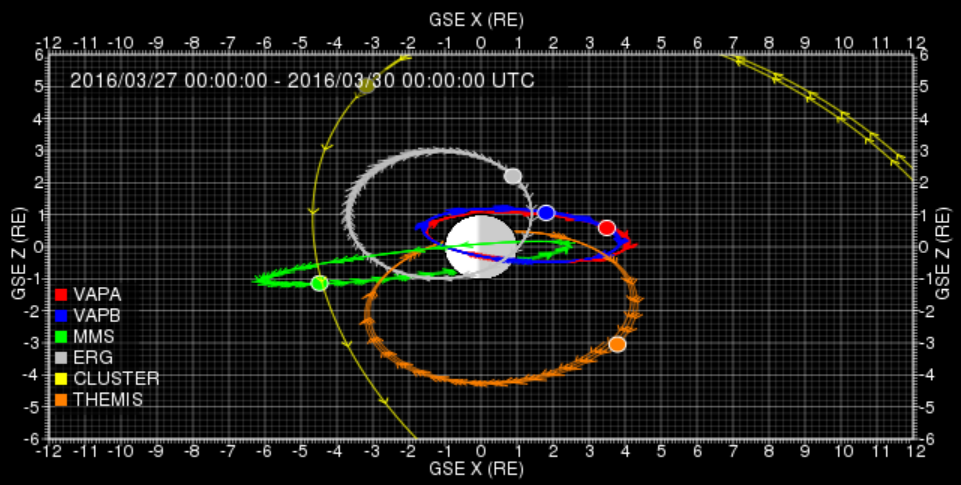
http://athena.jhuapl.edu/ExtendedMissionOrbit

March 2016

Unique 3-spacecraft configuation with MMS, ERG, and the Van Allen Probes (1 of 3)

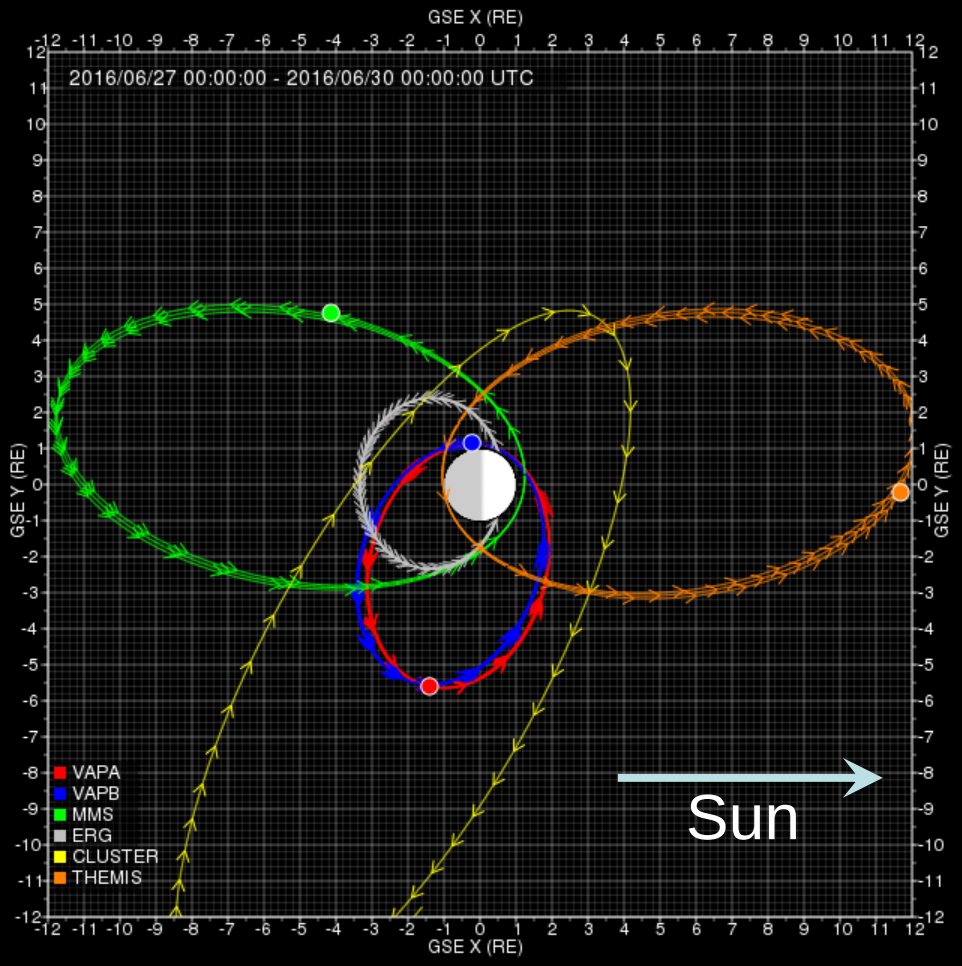


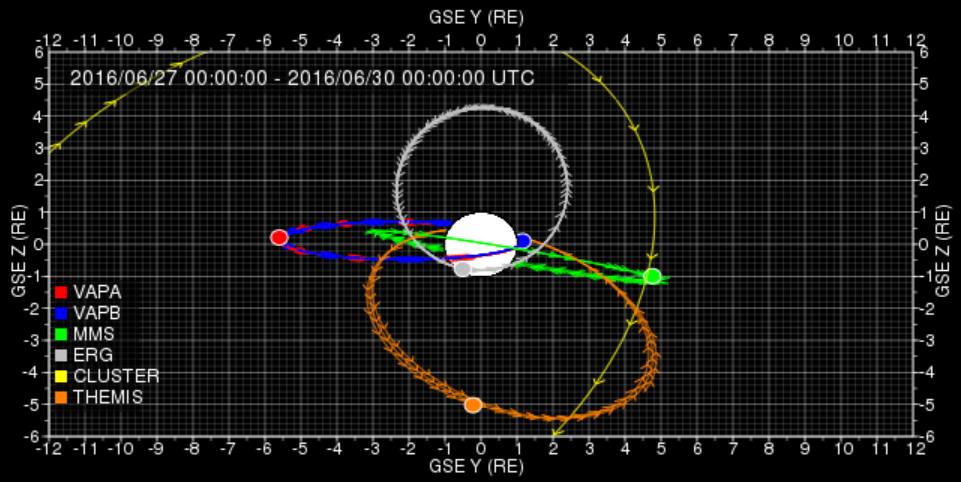


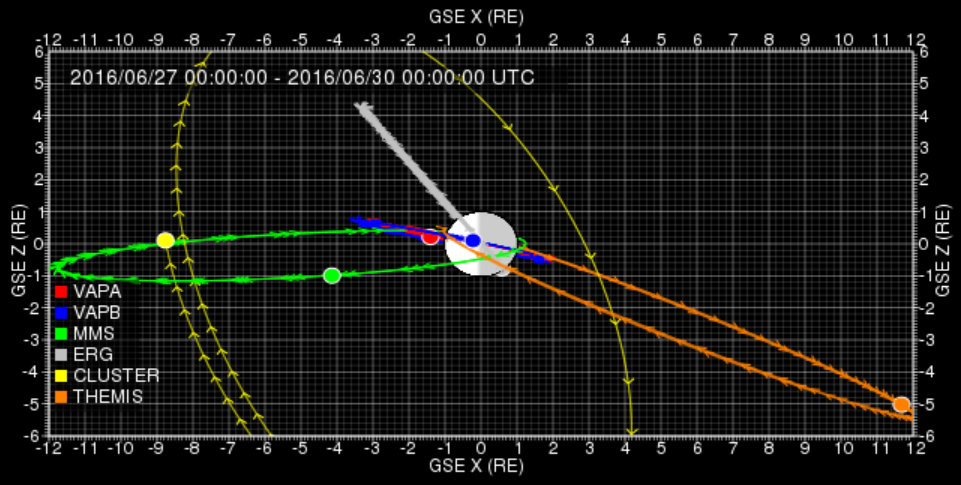


http://athena.jhuapl.edu/ExtendedMissionOrbit

June 2016
Unique 3-spacecraft configuation with MMS, ERG, and the Van Allen Probes (2 of 3)





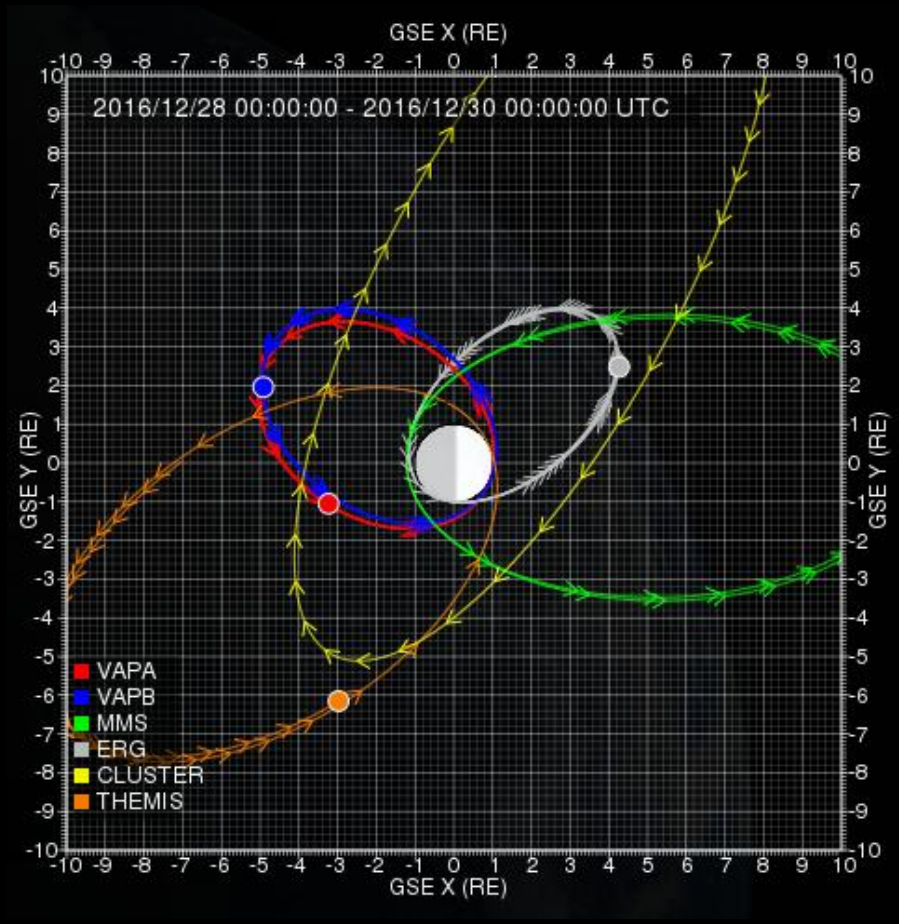


http://athena.jhuapl.edu/ExtendedMissionOrbit

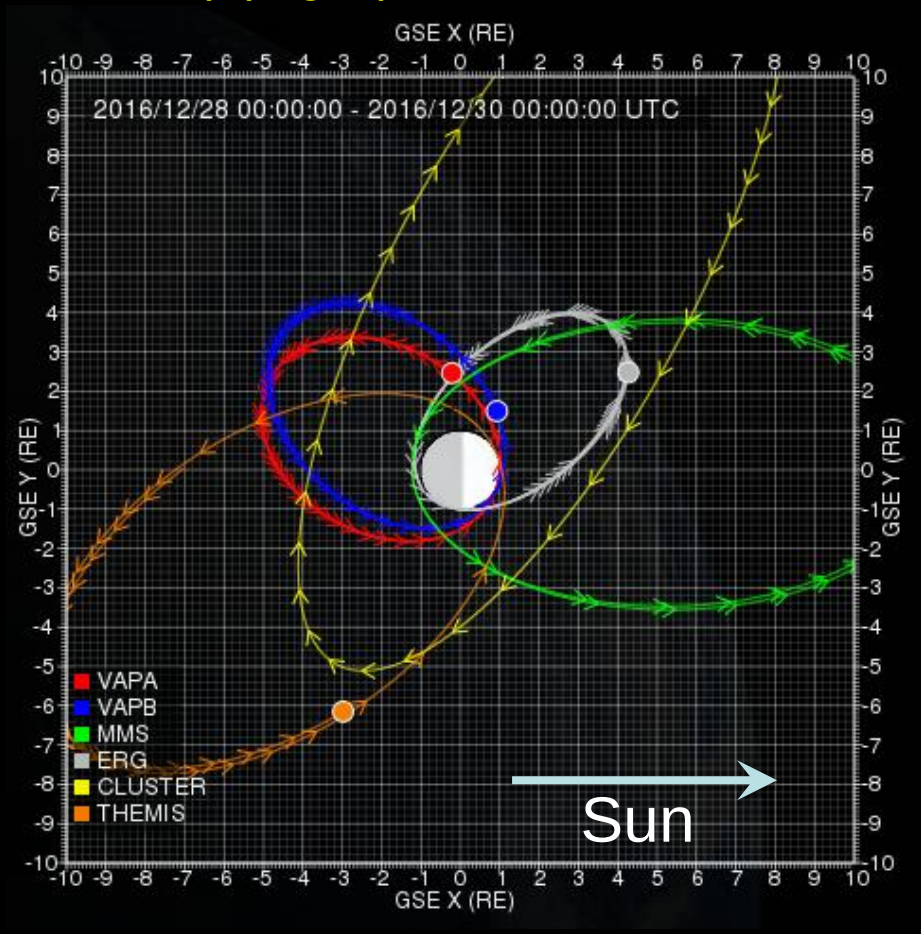
December 2016

Contemplated possible modifications of orbit configurations to alter radial-azimuthal sampling.

Nominal Mission



Δ(Apogee) = 300% of nominal



http://athena.jhuapl.edu/ExtendedMissionOrbit

Van Allen Probes Extended Mission Science Themes (1 of 3)

1. Spatial and temporal structures of injections and other transient phenomena and their effects on the radiation belts and ring current

   New Opportunities:

   - Modified orbit configurations
   - Different modes of operation for the instruments
   - Additional Assets: MMS and ERG

2. Three-dimensional structures and distributions of VLF and ULF waves and their effects on the radiation belt and ring current populations

   New Opportunities:

   - Tweak the orbit phases to align spacecraft along field lines
   - Modify orbits for longitude sampling of ULF wave structures
   - Operating the instruments in different modes,
   - ERG measurements at mid-latitudes within Probe Quadrants

Van Allen Probes Extended Mission Science Themes (2 of 3)

3. What are the detailed physical mechanisms responsible for energetic electron precipitation.

   New Opportunities:

   - Magnetic latitude orbit separations.
   - New CubeSats: e. g. a) CeREs (mid-2015), and b) ELFIN (late 2016)
   - ERG flying at mid-latitudes.
   - Extended mission BARREL Campaign (beyond bridge phase).

4. Responses of Earth's radiation belt regions, as the interplanetary drivers evolve from CME dominated to CIR dominated conditions?

   New Opportunities:

   - Operating during a critical new phase of the solar cycle,
   - May result in stronger / more energetic electron belt enhancements

Van Allen Probes Extended Mission Science Themes (3 of 3)

5. Detailed structures and characters of the microphysical processes that act to energize radiation belt particles in the inner magnetosphere?

   New Opportunities:

   – Operate the instrument differently in target regions
   – Adjust the phases of the two probes to minimize close approach
   – Adjust orbit phases to align spacecraft along field lines
   – Adjust relative apogees to increase lapping rate and close approaches.

6. Coupling between the magnetopause and the inner magnetosphere? Role and mechanisms of the magnetopause act as a sink of belt particles?

   New Opportunities:

   – MMS measurement of reconnection as it skims the magnetopause
   – MMS measurements of energetic particle escape through the magnetopause.

Summary / Conclusions

- Significant new discoveries by the Van Allen Probes about Earth's radiation belts and inner magnetosphere.
- Significant new science has been identified to be achieved using new kinds of data that will be sampled during an Extended Mission
- Ideas about the Extended Mission from the broad scientific community would be well received.

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Backup

The episodic 3 belts discovered by the Van Allen Probes result from coherent and now understood magnetospheric processes

- The"3rd Belt" (Baker et al., 2013) is a now predictable consequence of the protection from losses that the plasmasphere provides to a part of the outer radiation belt.
  - Thorne et al., GRL, 2013
  - Shprits et al., Nature Physics, 2013

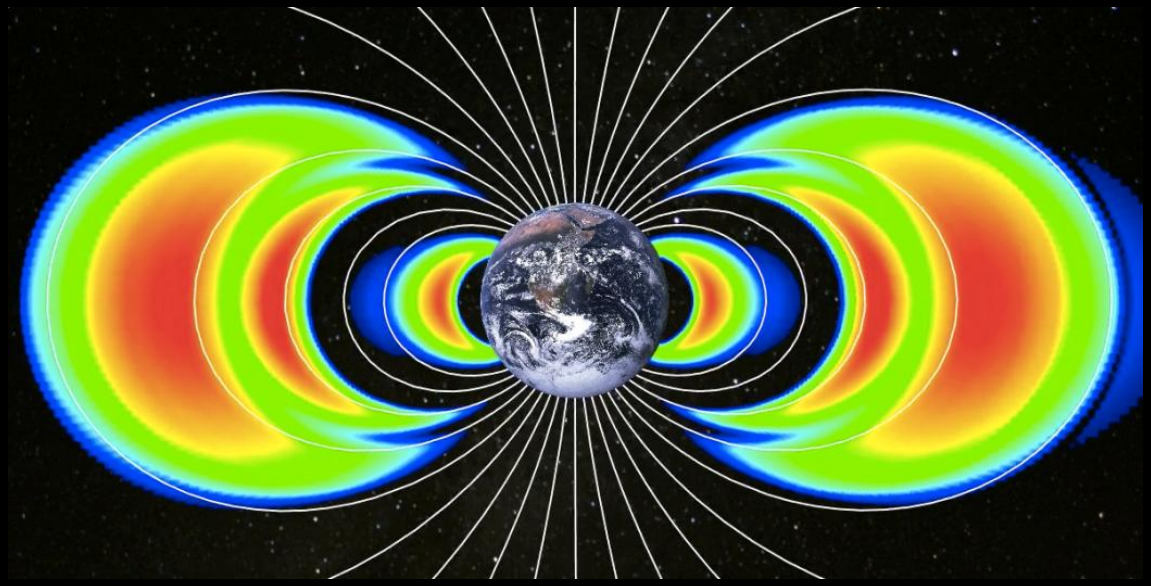
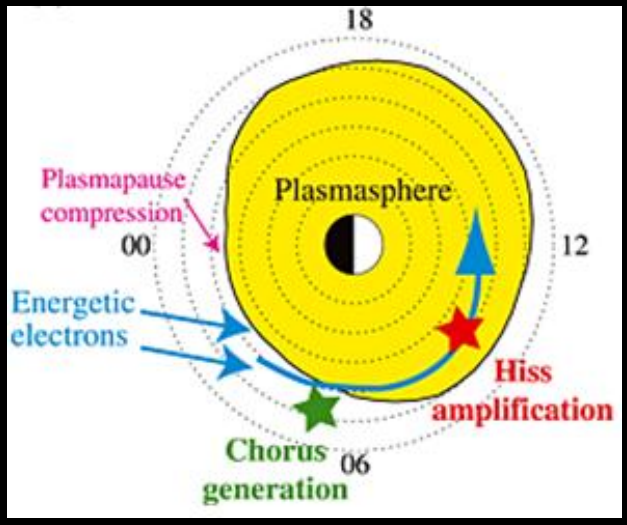
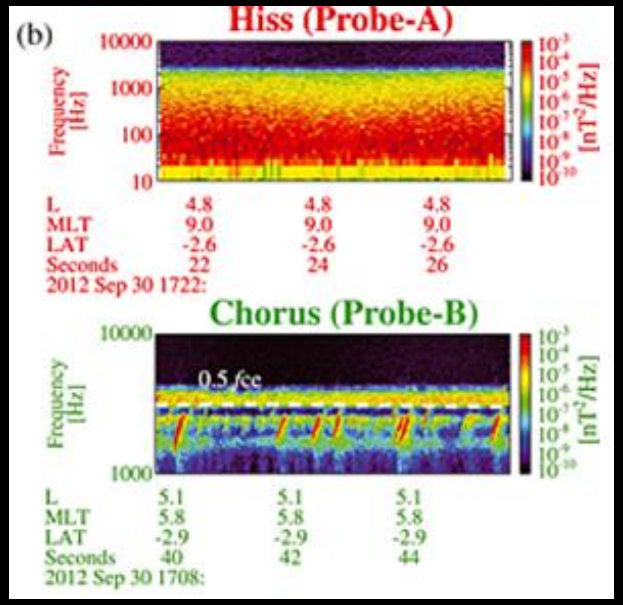


Image from: Ukhorskiy, Stephens, Barnes

Li et al., 2013

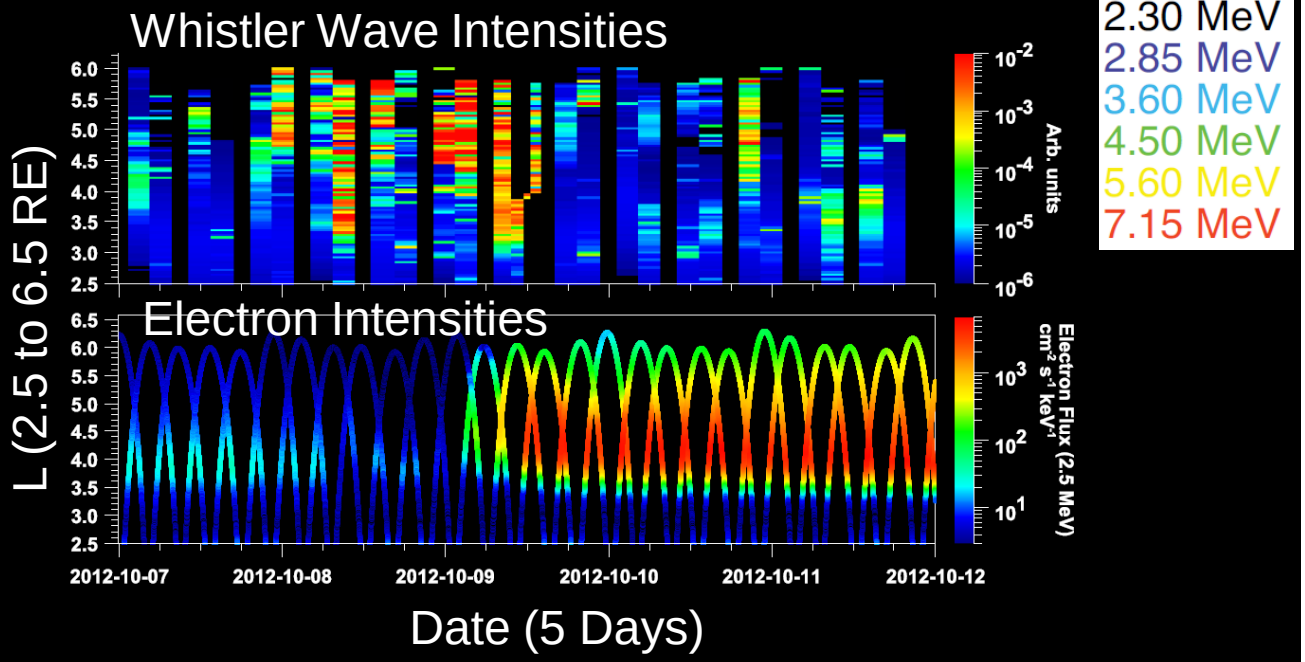




Radiation Belt Electrons are Accelerated Locally by Whistler Waves

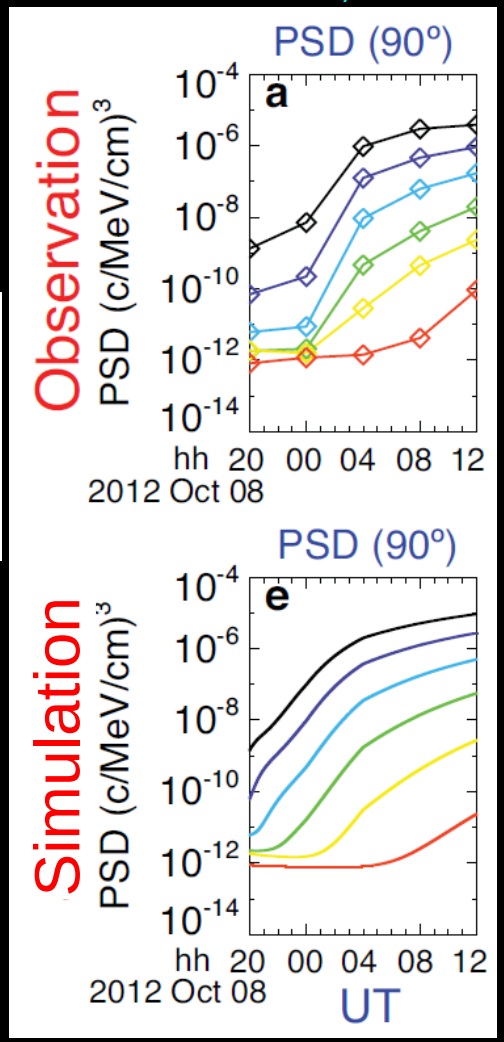
Van Allen Probes observations and modeling show that local, "quasi-linear" wave-particle interactions may suffice in energizing multi-MeV electrons

- Here, the sudden (12 hours) energization of multi-MeV electrons as observed by the REPT instrument correlate well with whistler waves observed by EMFISIS
- Detailed simulations using observed particle and wave inputs show outstanding concurrence with observations



Reeves et al. 2013, Science

Thorne et al. 2013; Nature



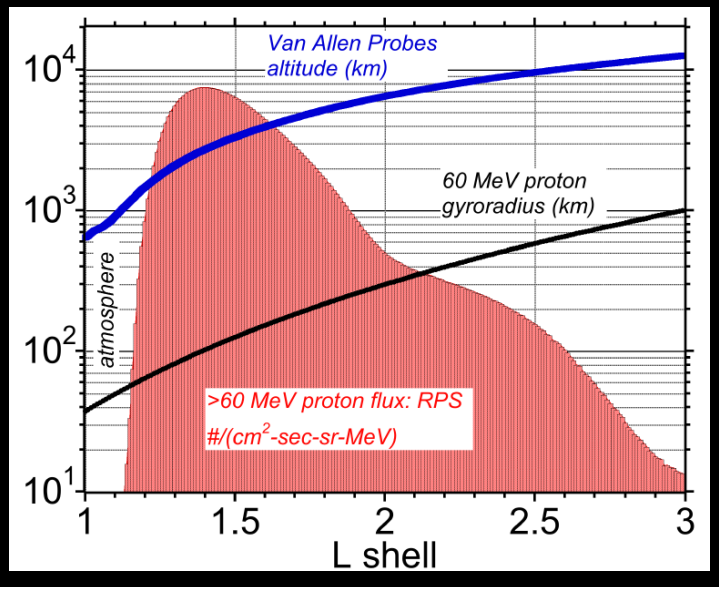
Van Allen Probes Extended Mission Science Theme Suggestions (1 of 3)

1. What are the spatial and temporal structures of injections and other transient phenomena such as shock-driven fronts, and how do they evolve, within Earth's inner magnetosphere; what are the effects of those structures on the radiation belt and ring current populations?
   - New Opportunities:
     - Enhanced orbit evolutions of the 2 Van Allen Probes to achieve different kinds of radial and local time separations, to better sample the evolving structures.
     - Possible different modes of operation for the instruments
     - The addition of other assets to the Van Allen Probes and THEMIS: specifically MMS and ERG.
2. What are the 3-dimensions structures and distributions of VLF and ULF waves within Earth's inner magnetosphere, and what are the effects those structures on the radiation belt and ring current populations? (**dE**, **dB**, **k** spatial coherence, spatial distributions, ULF structures)?
   - New Opportunities:
     - Modifications of the phasing of RBSP-A and RBSP-B close encounters such that they are aligned along the same magnetic flux tubes
     - Modifications of orbit evolutions to achieve different longitude sampling of ULF wave structures
     - Operating the instruments in different modes, with higher available rates, to capture details of the VLF interactions.
     - ERG measurements at mid-latitudes along flux tubes that connect roughly to the Van Allen Probes A and B.

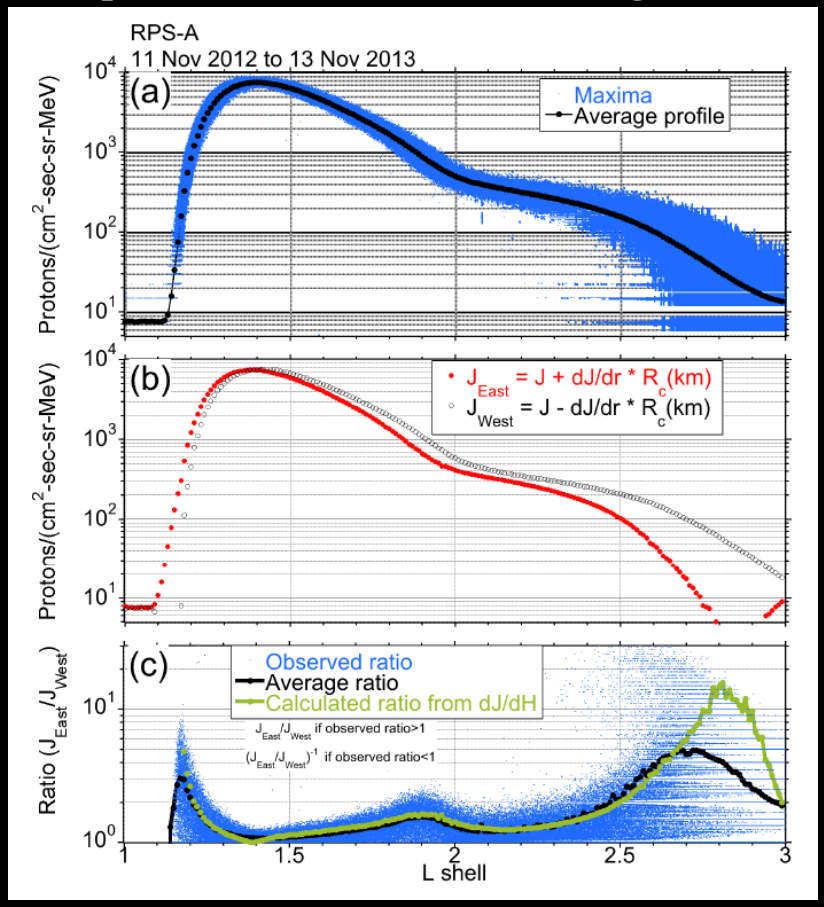
Van Allen Probes Extended Mission Science Theme Suggestions (2 of 3)

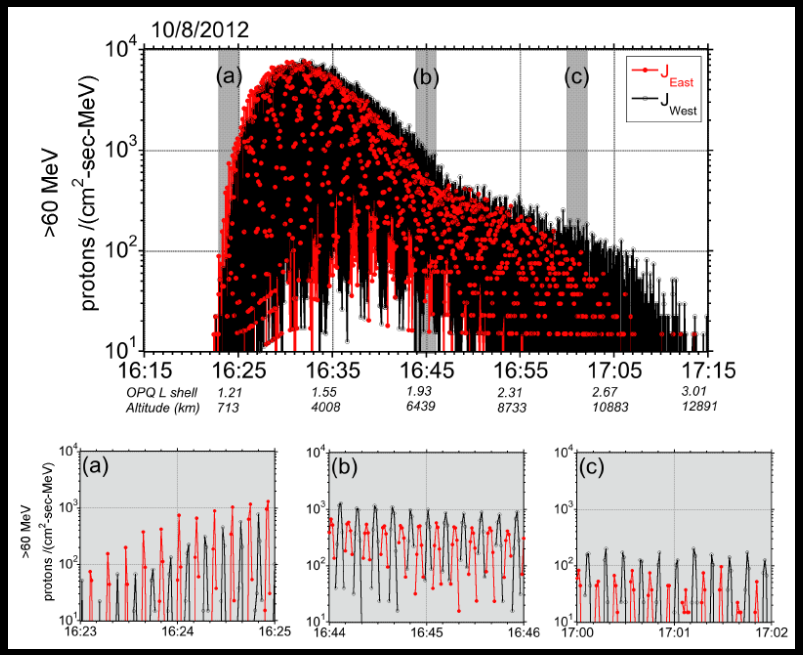
3. What are the detailed physical mechanisms responsible for energetic electron precipitation.
   - New Opportunities:
     - Magnetic latitude orbit separations.
     - Two new CubeSats: a) CeREs expected to launch in mid-2015 with the ability to resolve microbursts, and b) ELFIN, scheduled for launch in late 2016 to early 2017.
     - ERG flying at mid-latitudes better able to resolve particle loss cones at the same time that the Probes are measuring equatorial waves and source distributions.
     - Extended mission BARREL Campaign (beyond bridge phase).
4. How do the physics and the dynamical responses of Earth's radiation belt regions, including the ring current, change as the interplanetary drivers evolve from CME dominated to CIR dominated conditions?
   - New Opportunities:
     - Van Allen Probes will be operating during a critical new phase of the solar cycle, the declining phase, following its operation during solar maximum.
     - CIR's may provide stronger and more energetic radiation belt electron enhancements than have been seen during the mission to date.

Unprecedented quality of inner belt measurements: Gradient anisotropies offer a new diagnostic.



Clean angular distributions allow detailed diagnosis of atmosphere loss interactions along drift shells.





Mazur et al., 2014

See also: Selesnick et al., 2014 for more on inner belt findings

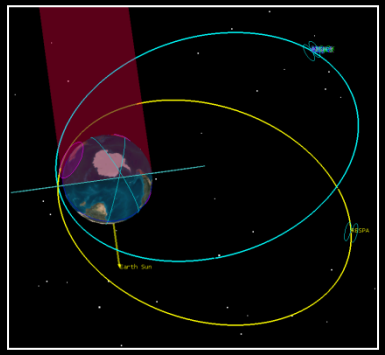
Orbit Options Being Assessed

Option	ΔV RBSPA (m/sec)	Fuel Used RBSPA (kg)	Mission EOL Estimate** RBSPA	ΔV RBSPB (m/sec)	Fuel Used RBSPB (kg)	Mission EOL Estimate** RBSPB	Angle Between Apse Lines in May 2016 (deg)
Do nothing	0	0	5/1/2019	0	0	4/1/2019	5.5
Swap Apogee and Perigee Altitudes	4.5	1.4	2/1/2019	4.5	1.4	1/1/2019	0.0
Increase Delta Apogee by 100%*	3.2	1.0	3/1/2019	3.2	1.0	3/1/2019	9.2
Increase Delta Apogee by 200%*	6.4	2.0	1/1/2019	6.4	2.0	1/1/2019	12.9
Increase Delta Apogee by 300%*	9.6	3.0	11/1/2018	9.6	3.0	11/1/2018	16.6
Increase Delta Apogee by 400%*	12.9	4.0	09/1/2018	12.9	4.0	09/1/2018	20.4
Decrease RBSPA Perigee to 550 km	12.9	4.0	09/1/2018	12.9	4.0	09/1/2018	27.7

*Current delta between apogee altitudes is ~140 km

**Based on continuing current propellant usage. Predicted EOL due to environmental radiation 12/1/2019.

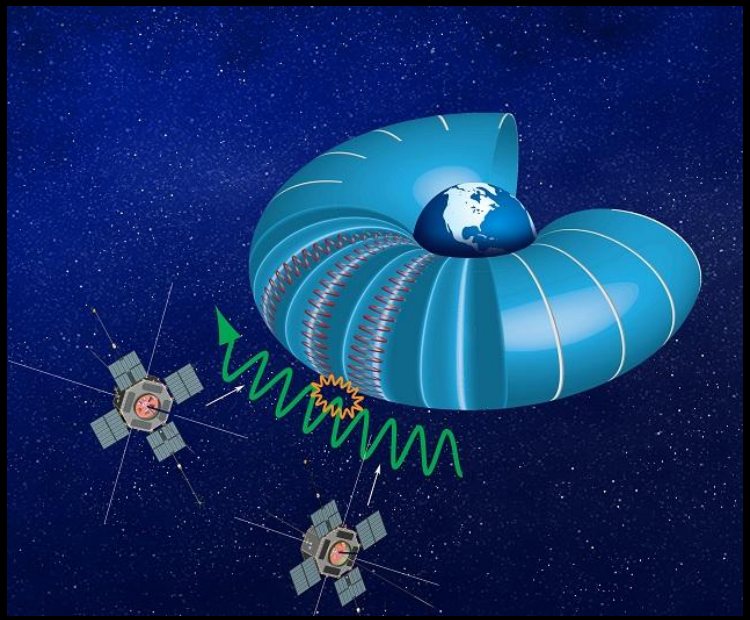
Predicted angle between apse lines at end of prime mission is 2.25 deg



Wave-Particle Drift Resonance Interactions are Critical for Radiation Belt Transport and Energization

Van Allen Probes instruments (EMFISIS, EFW, and MagEIS) have resolved critical questions about resonant interactions between Ultra Low Frequncy (ULF) Waves and drifting electrons

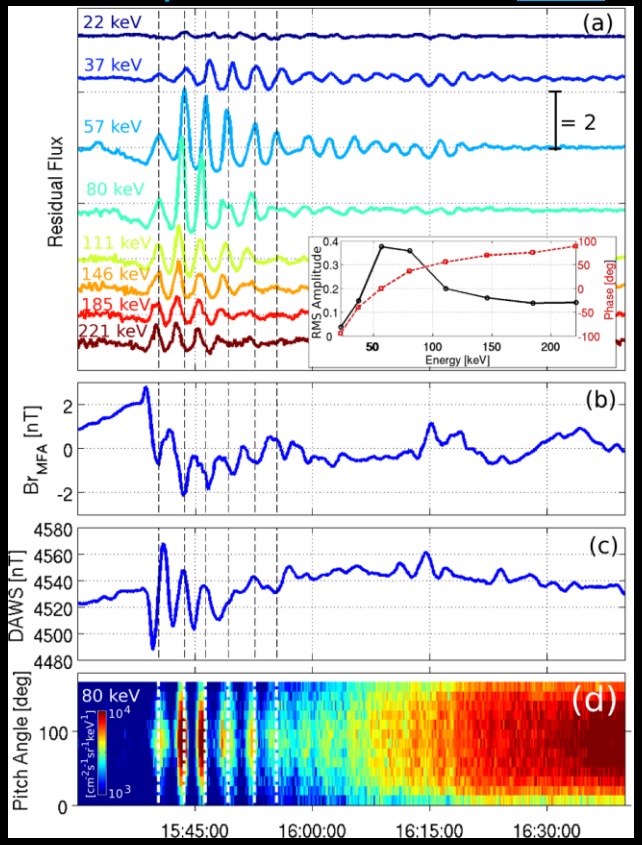
Dai et al., 2013 GRL



GRL Research Highlight and Cover

The first definitive identification of radial particle gradients as the source of free energy for the growth of the ULF waves using unique multi-satellite measurements

Claudepierre et al., 2013, GRL



Electrons

Magnetic Fields

Electrons

The first direct observations of the drift resonance exchange of energy between ULF Waves and drifting electrons