Laboratory for Atmospheric and Space Physics
University of Colorado Boulder

System Understanding of Radiation Belt Particle Dynamics through Multi-Spacecraft and Ground-Based Observations and Modeling

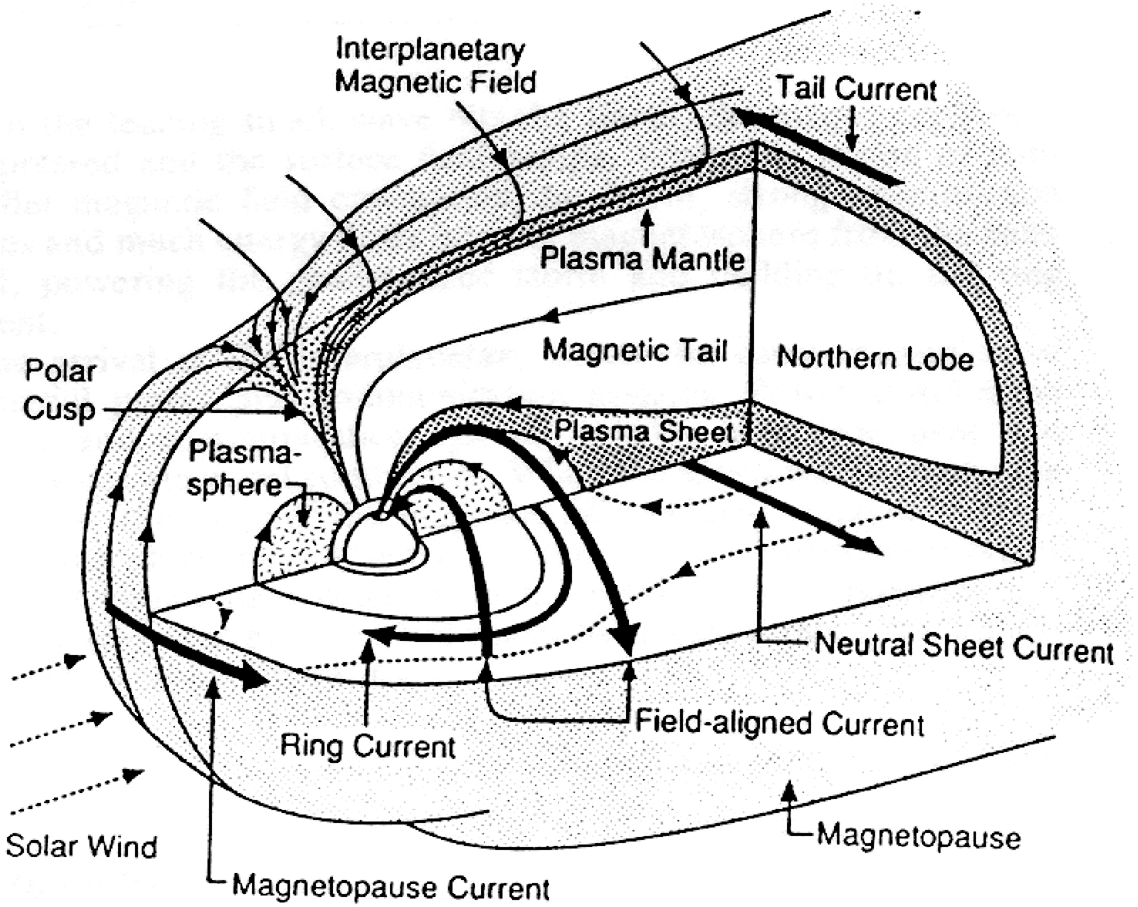
Hong Zhao
LASP, University of Colorado Boulder

Outline

- Introduction of Radiation Belt Particle Dynamics
- Recent Advances in Radiation Belt Studies based on Van Allen Probes observations
- System Understanding of Radiation Belt Particle Dynamics through Multi-Spacecraft and Ground-Based Observations and Modeling
- Summary

Laboratory for Atmospheric and Space Physics
University of Colorado **Boulder**

Earth's Magnetosphere



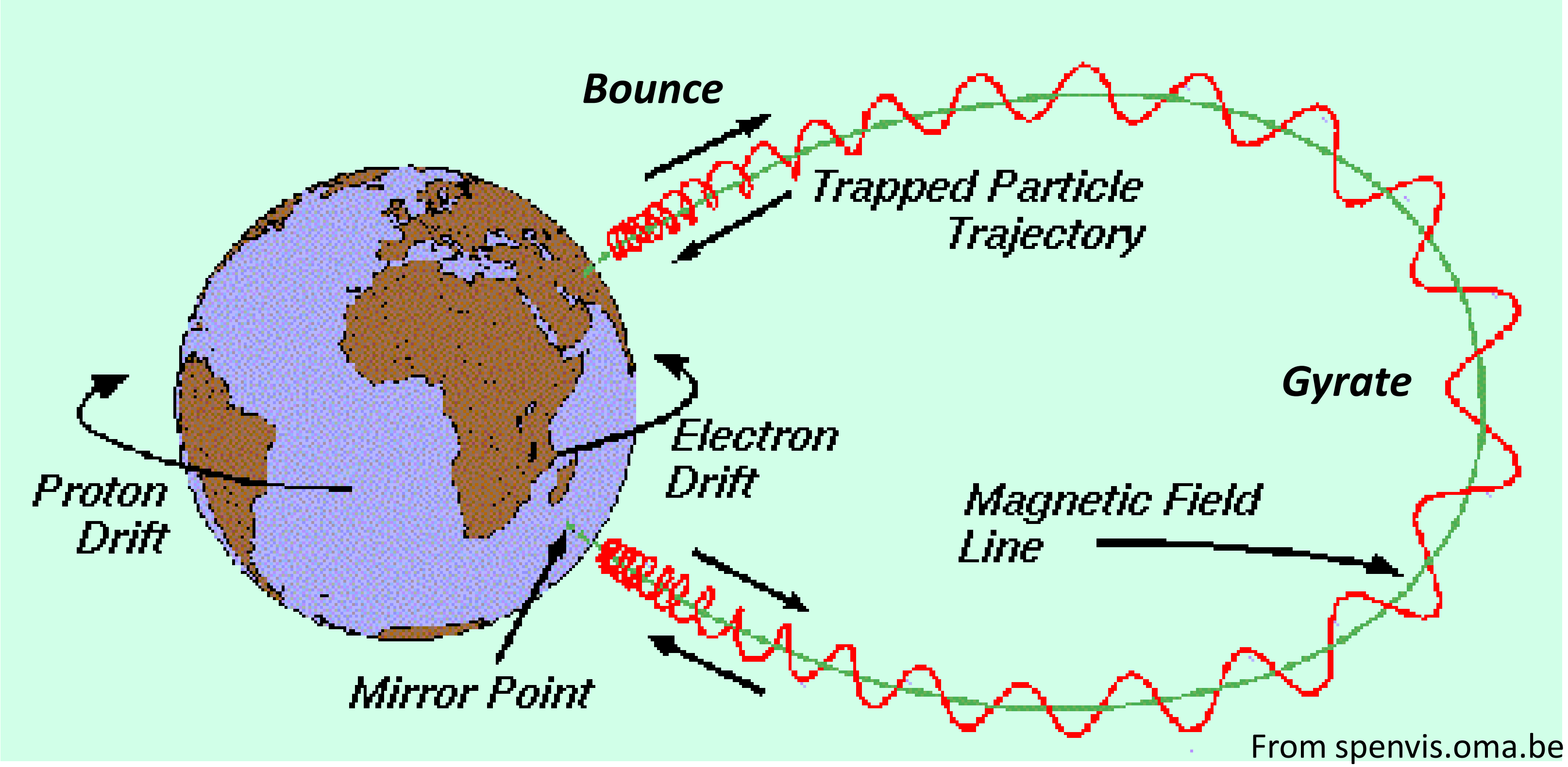
From Kivelson and Russell [1995]

- Earth's magnetosphere is a tear-shaped region carved out of the solar wind by Earth's magnetic field.

- Close to Earth, the Earth's inner magnetosphere is the region where the geomagnetic field resembles the dipole field. It includes the plasmasphere, radiation belts, and ring current.

- The charged particles and current systems existing in the Earth's inner magnetosphere pose potential threats to the spacecraft and human in the space and technical systems on the ground.

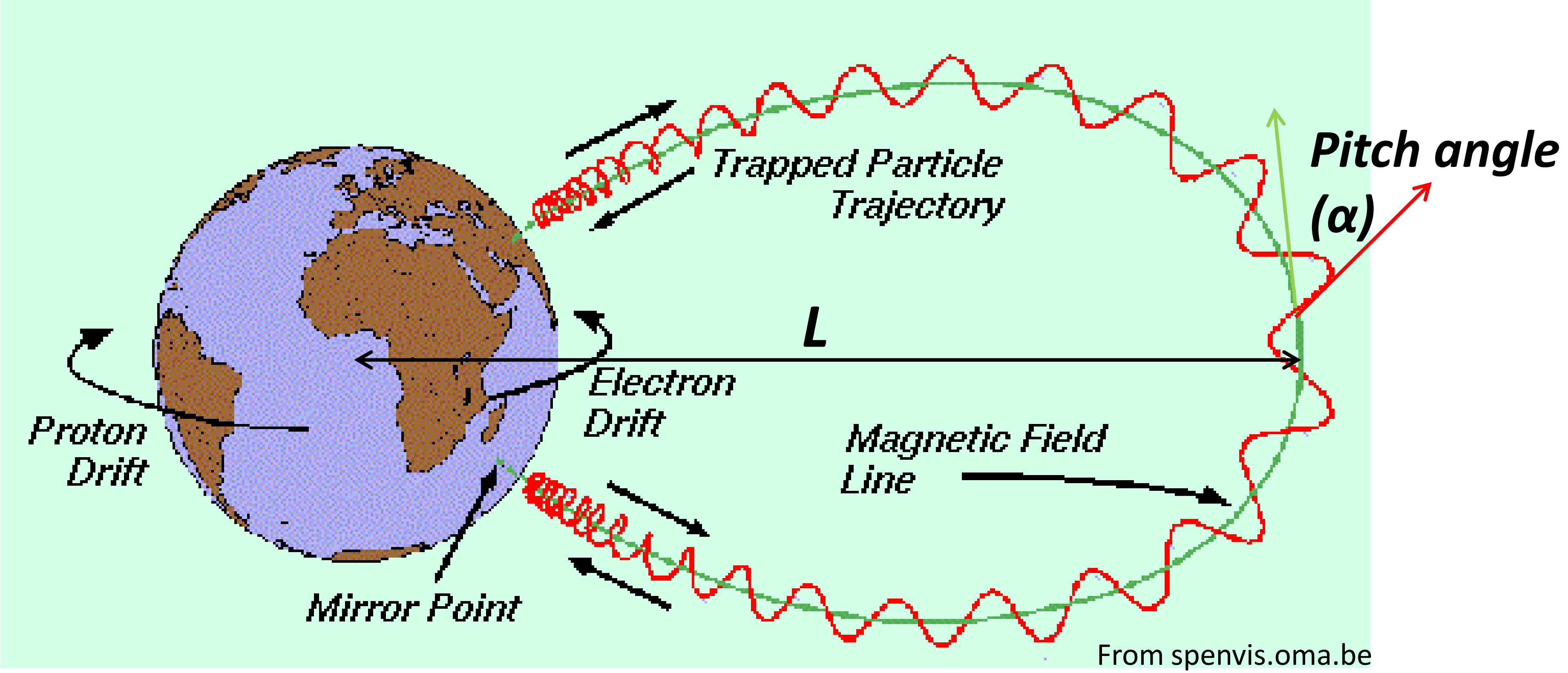
Charged Particle Motions



From spenvis.oma.be

Time scales (GEO, E=1MeV, α=60°)	Gyro	Bounce	Drift
Electrons	1 ms	0.5 s	10 min
Protons	0.6 s	10 s	7 min

Charged Particle Motions



From spenvis.oma.be

Time scales (GEO, E=1MeV, α=60°)	Gyro	Bounce	Drift
Electrons	1 ms	0.5 s	10 min
Protons	0.6 s	10 s	7 min

Adiabatic Invariants

- First adiabatic invariant (corresponding to gyration):

$$\mu = \frac{P_{\perp}^{2}}{2m_0 B} = const.$$

- Second adiabatic invariant (corresponding to bounce motion):

$$J = 2\sqrt{2m_0\mu}\int_{S_m}^{S_m'}\sqrt{B_m - B(s)}ds = const.$$

$$(\text{Or } K = \int_{S_m}^{S_m'}\sqrt{B_m - B(s)}ds = const.)$$

- Third adiabatic invariant (corresponding to drift motion):

$$\Phi = \int_{S}\vec{B}\cdot\overrightarrow{dS} = const.\;;\;\; L^* = \frac{2\pi M}{|\Phi| R_e}$$

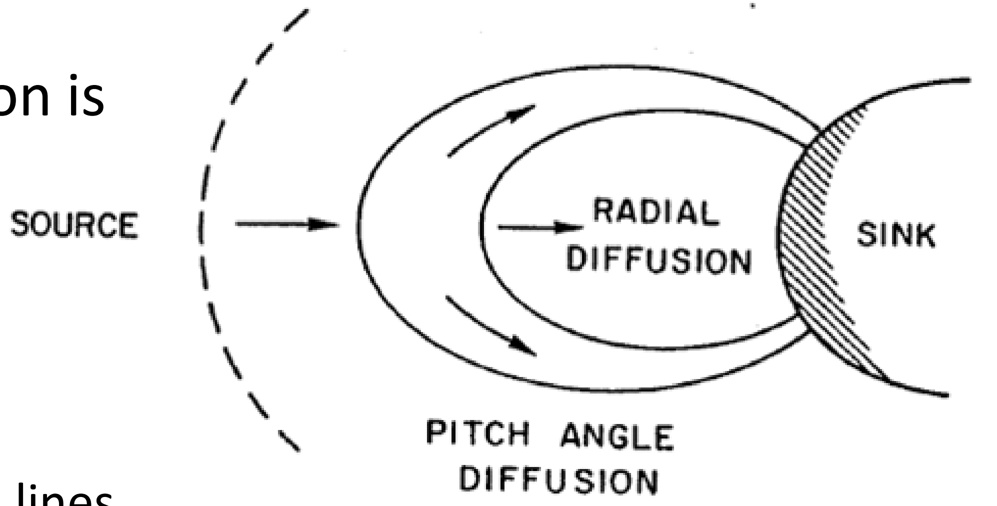
- Phase-averaged phase space coordinates: (μ, K, L^*)
- Phase space density: $f_p = \frac{j}{p^2}$

Violations of the Adiabatic Invariants

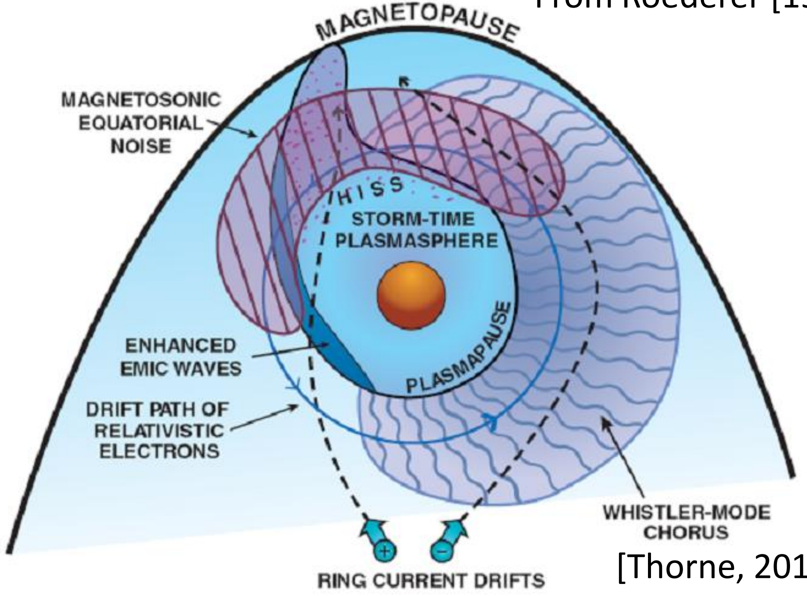
- When the timescale of magnetic/electric field fluctuation is shorter compared to the particle motion, the adiabatic invariant(s) can be violated.

- Violations of the adiabatic invariants -> diffusion
  - Radial diffusion: permits transport of the particles across field lines.
  - Pitch angle diffusion: alters the particle pitch angle.
  - Energy diffusion: changes the particle energy.

- Magnetospheric waves can cause the diffusion processes.
  - ULF waves, chorus waves, hiss waves…

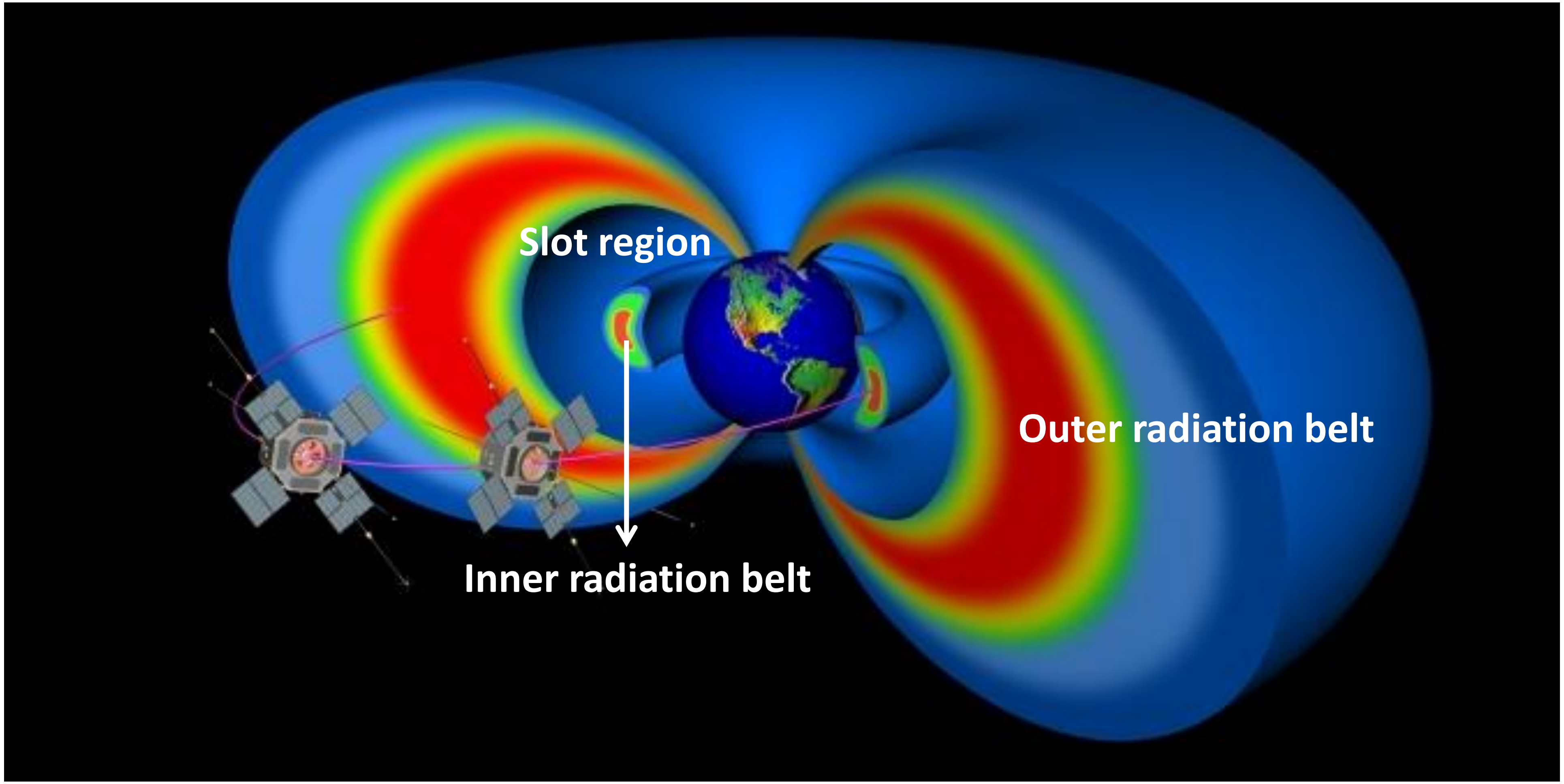


From Roederer [1970]



[Thorne, 2010]

The Earth's Radiation Belts



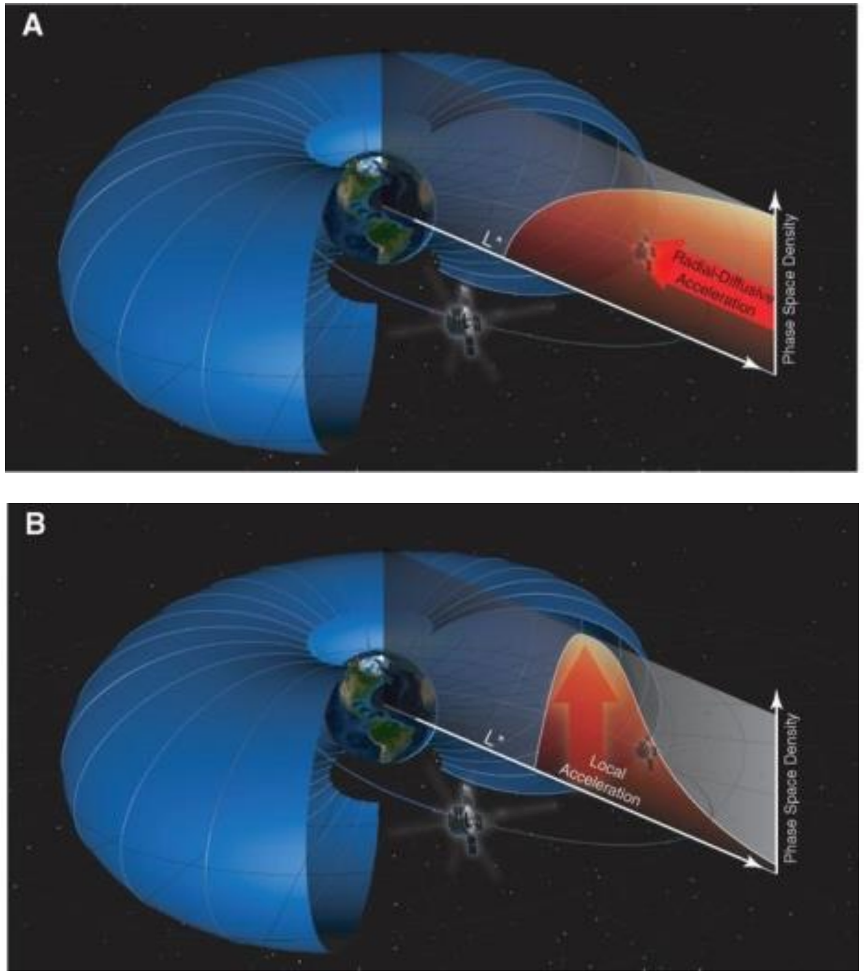
[From nasa.gov]

Source and Loss Processes for Radiation Belt Electrons

- Source processes
    - Inward radial diffusion
    - Local acceleration
- Loss processes
    - Magnetopause shadowing
    - Precipitation into the atmosphere
    - Outward radial diffusion

Inward radial diffusion

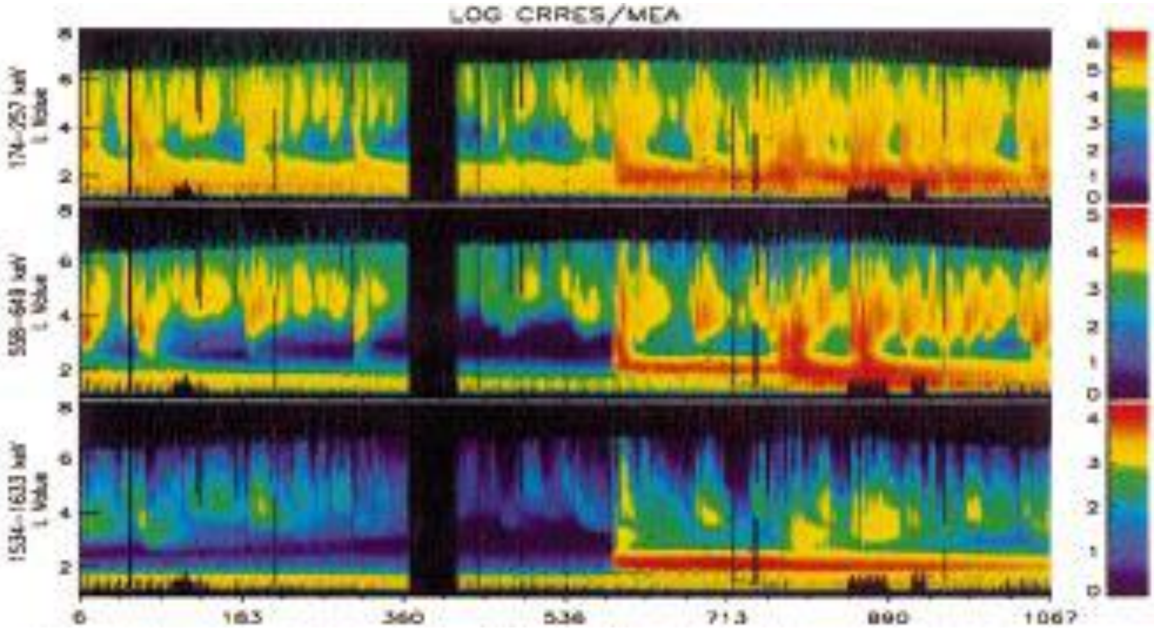
Local acceleration



(Reeves et al., 2013)

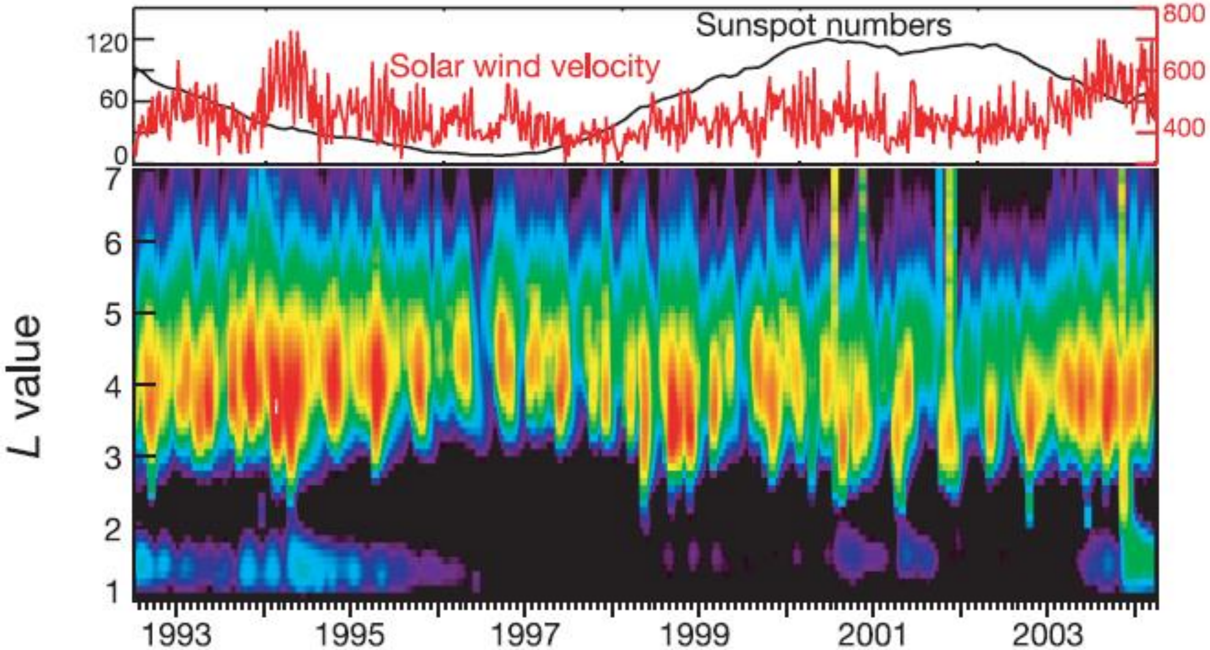
Long-Term Variations of Radiation Belt Electrons: Measurements Prior to the Van Allen Probes Era

CRRES



(Li and Temerin, 2001)

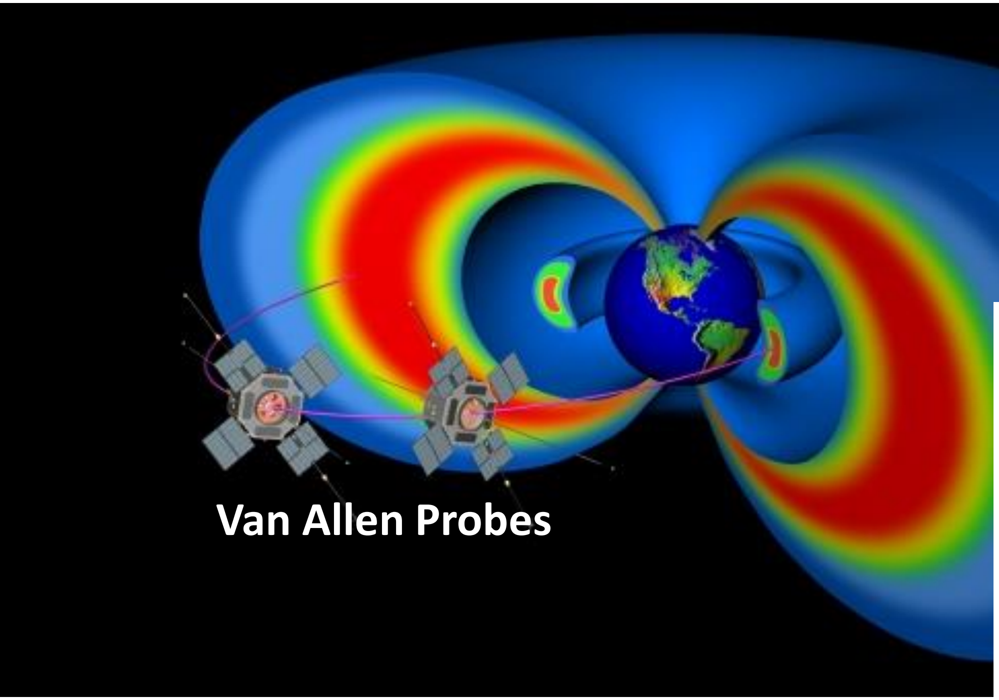
SAMPEX



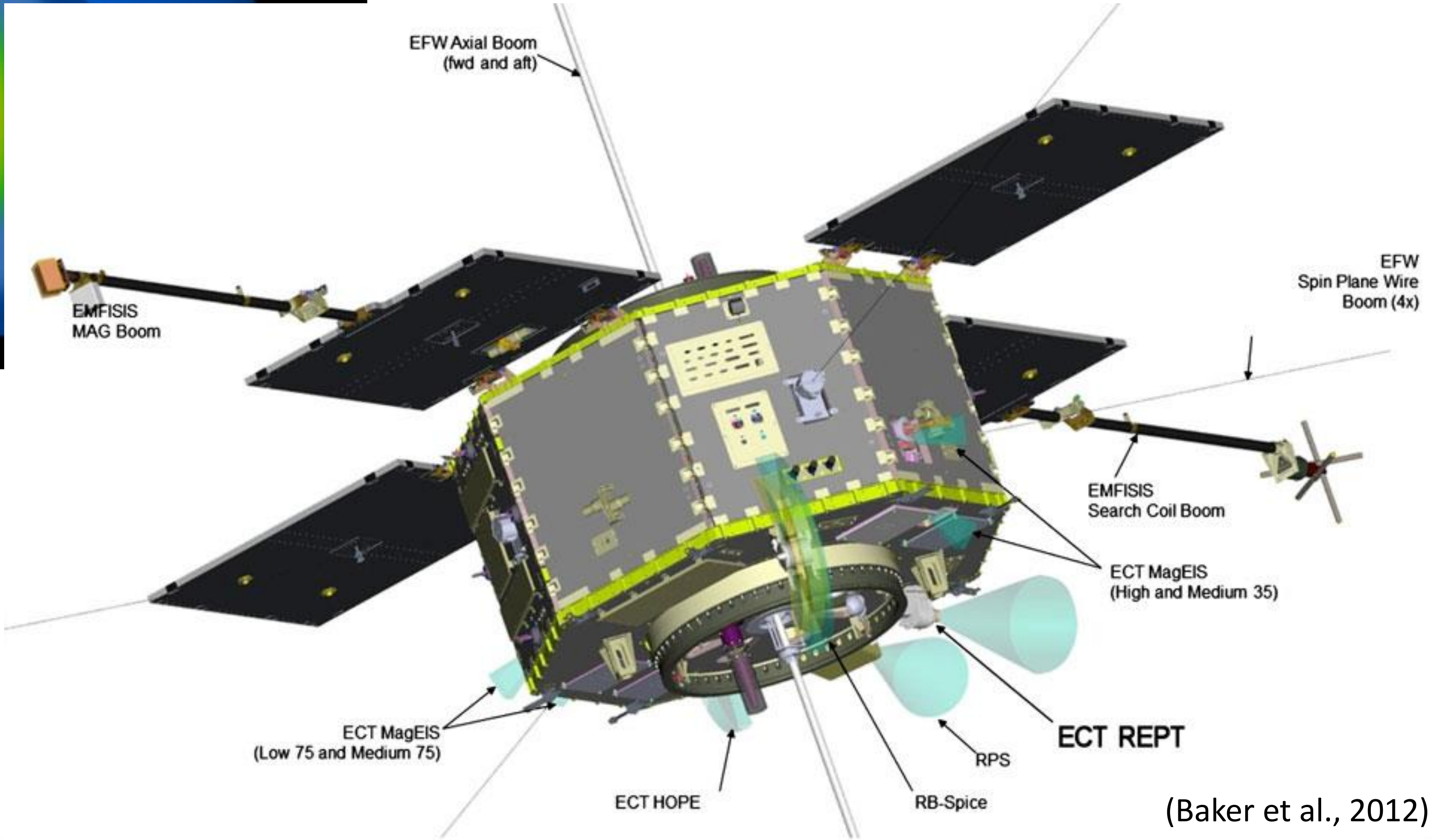
(Baker et al., 2004)

- The outer radiation belt is very dynamic and radiation belt particles are subject to significant influence from the solar wind.

The Van Allen Probes

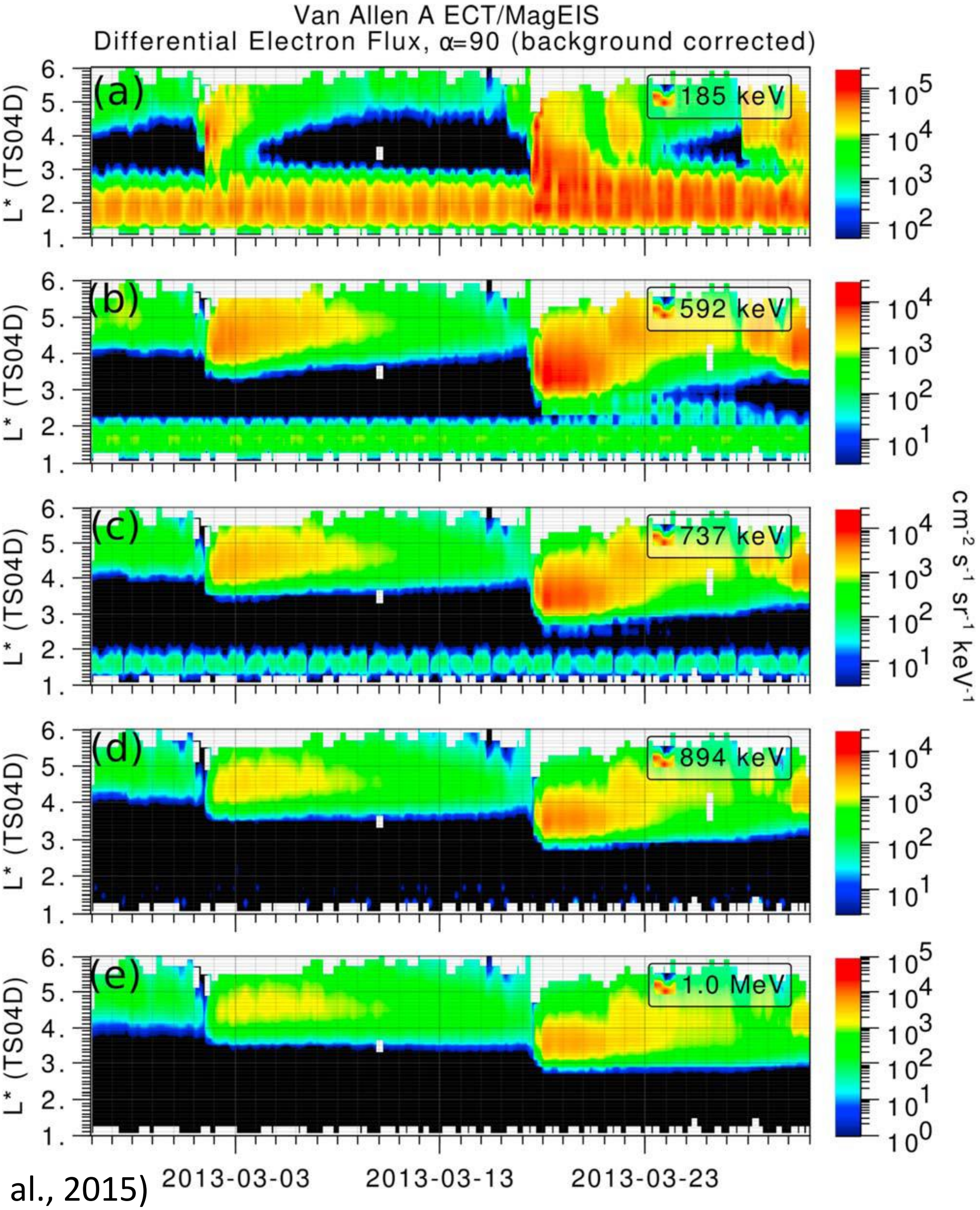


[From nasa.gov]

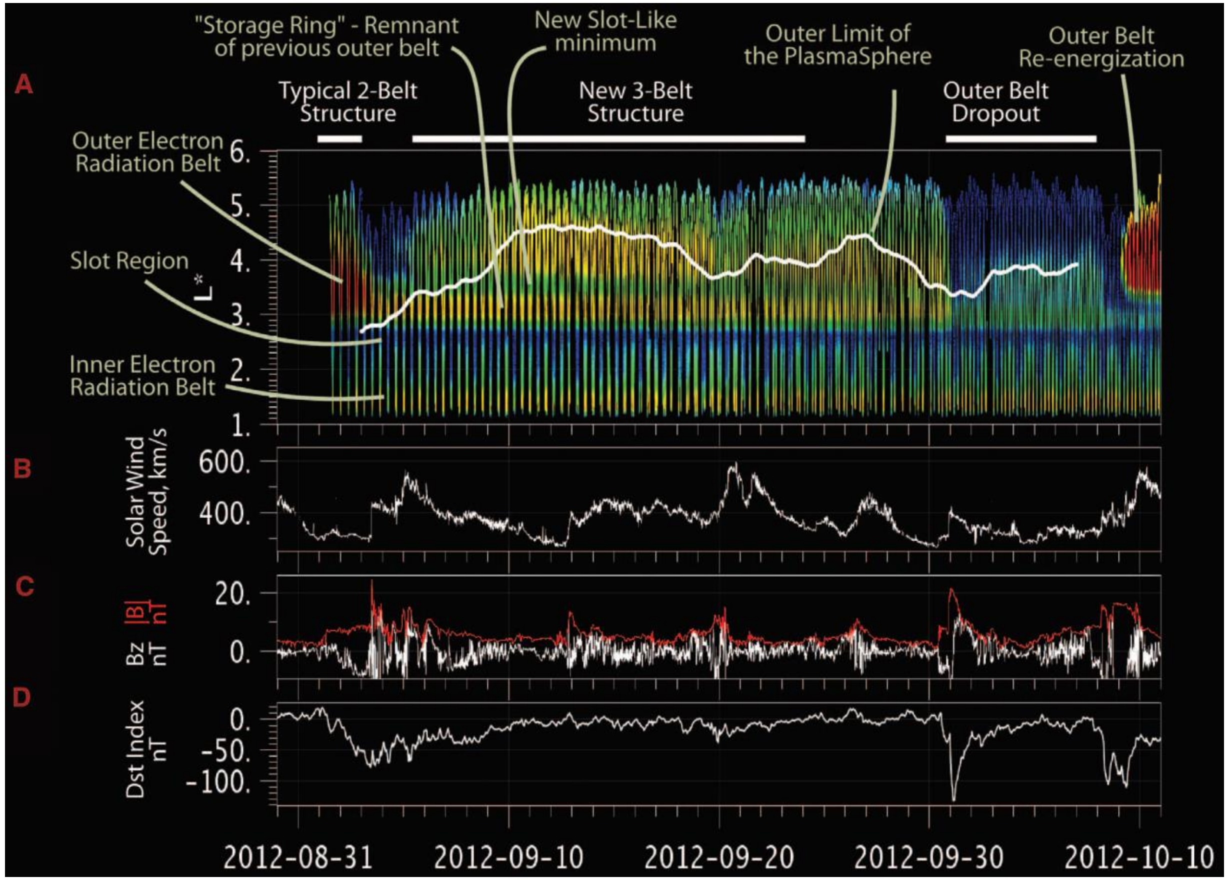


(Baker et al., 2012)

Radiation Belt Electron Measurements of the Van Allen Probes



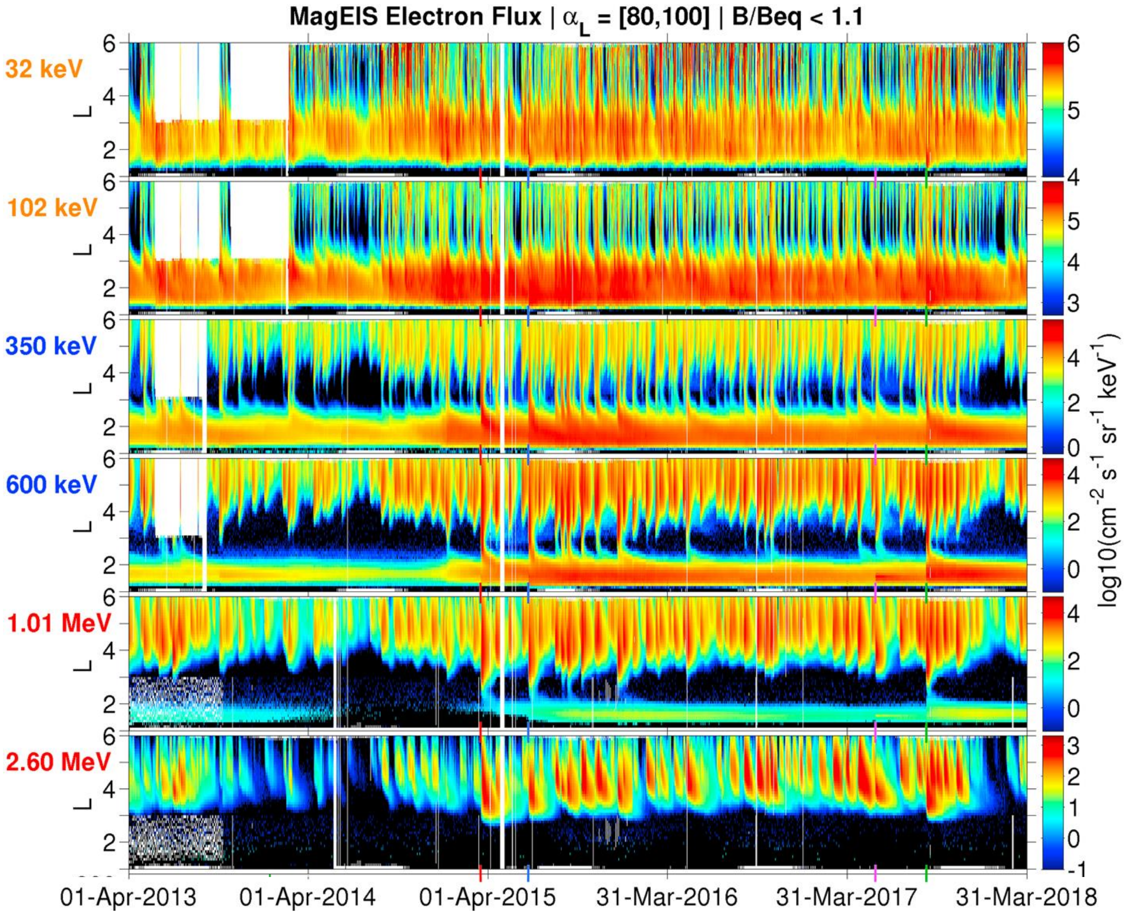
(Fennell et al., 2015)



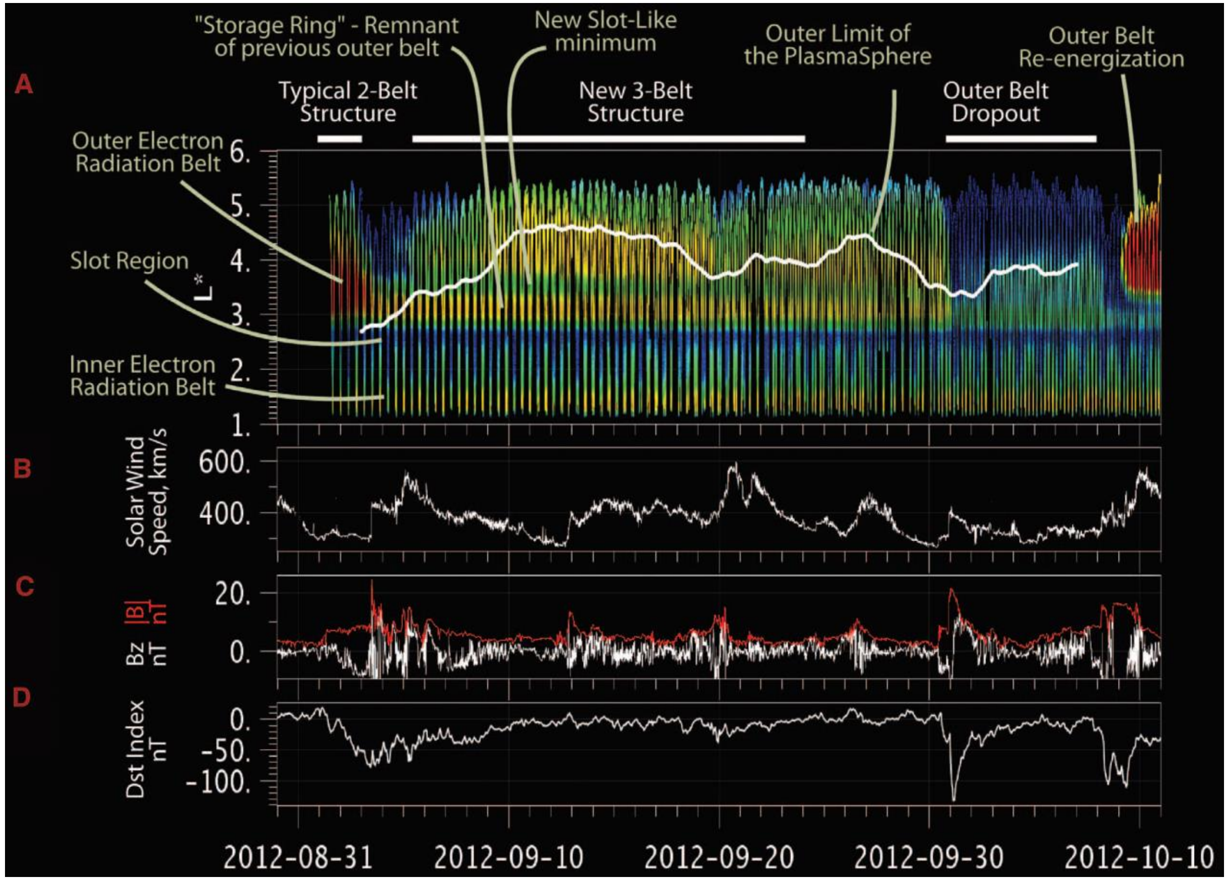
(Baker et al., 2013)

- Abundant 100s of keV electrons but limited >MeV electrons exist in the inner radiation belt;
- Three-belt structure of radiation belts is found.

Radiation Belt Electron Measurements of the Van Allen Probes



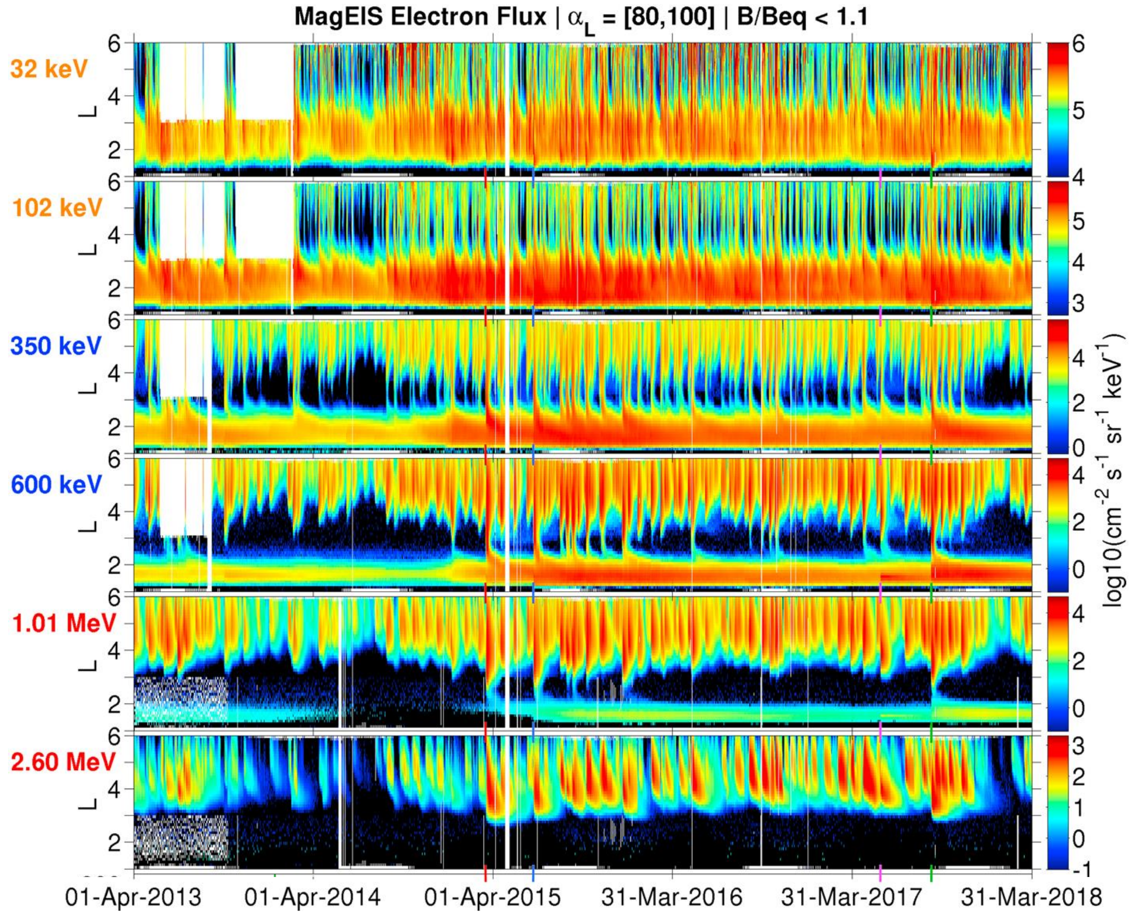
(Claudepierre et al., 2019)



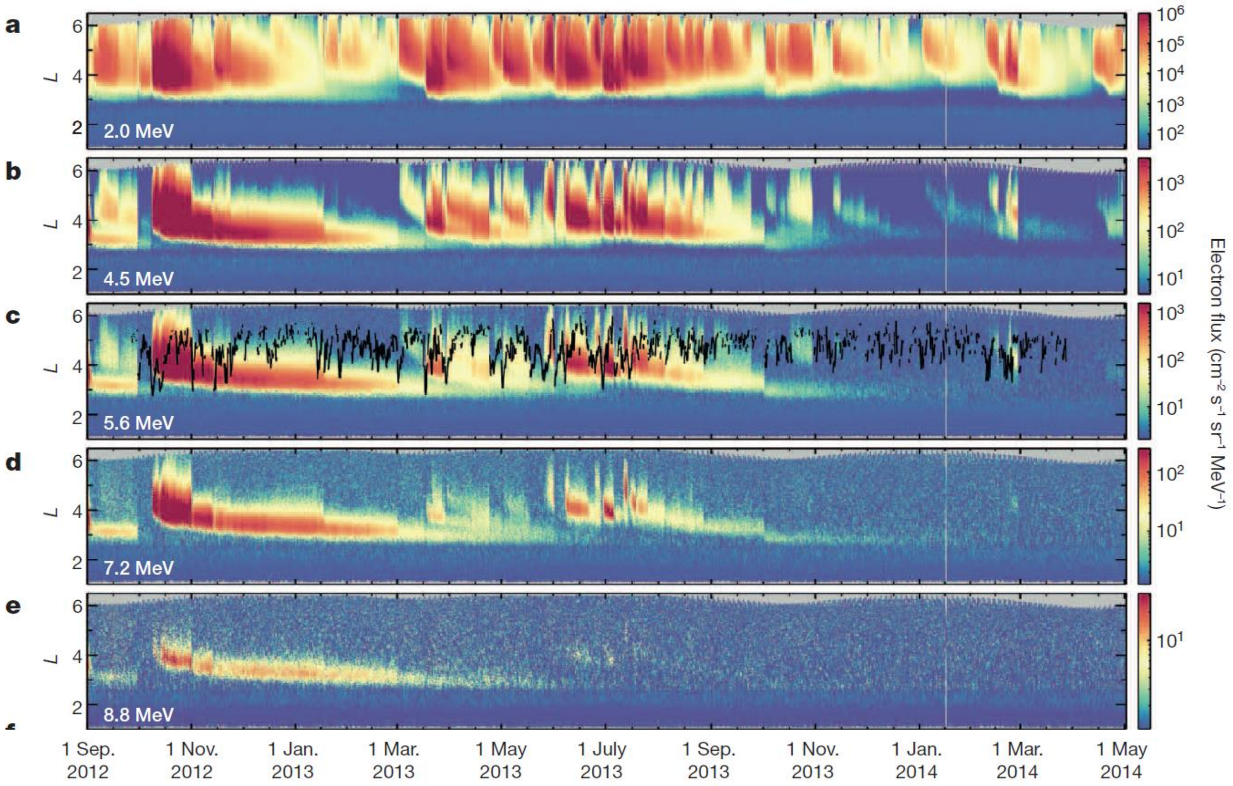
(Baker et al., 2013)

- Abundant 100s of keV electrons but limited >MeV electrons exist in the inner radiation belt;
- Three-belt structure of radiation belts is found.

Radiation Belt Electron Measurements of the Van Allen Probes



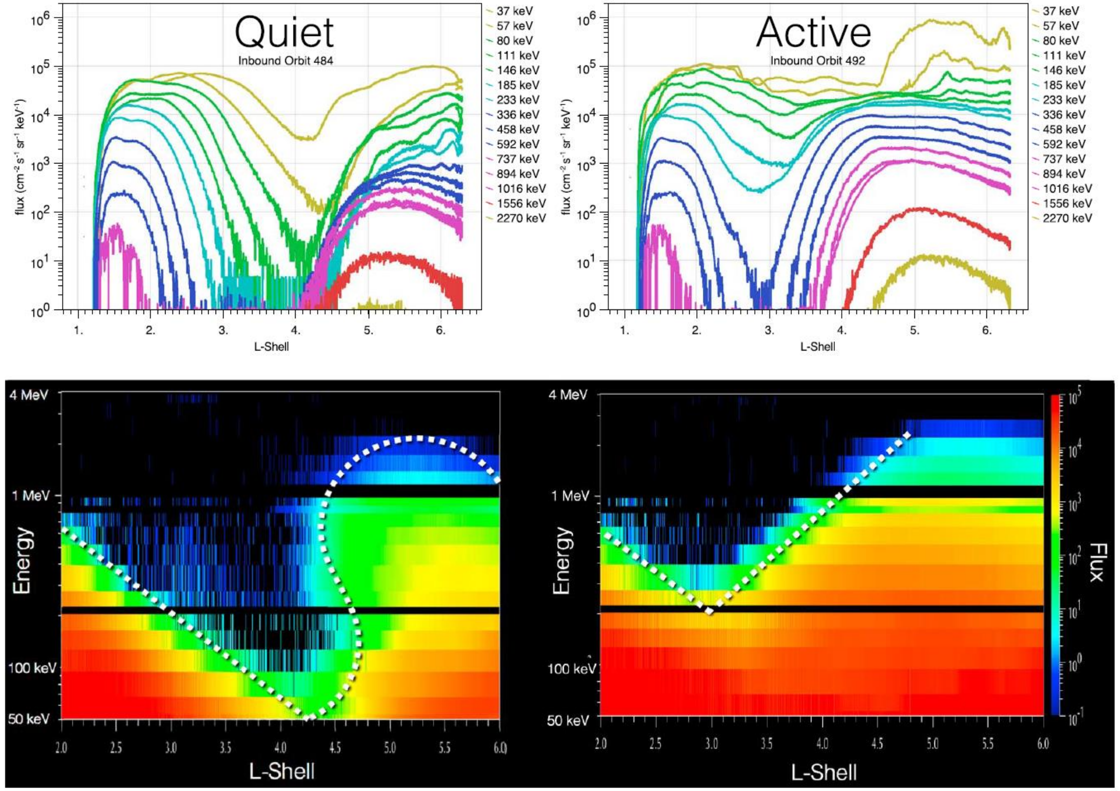
(Claudepierre et al., 2019)



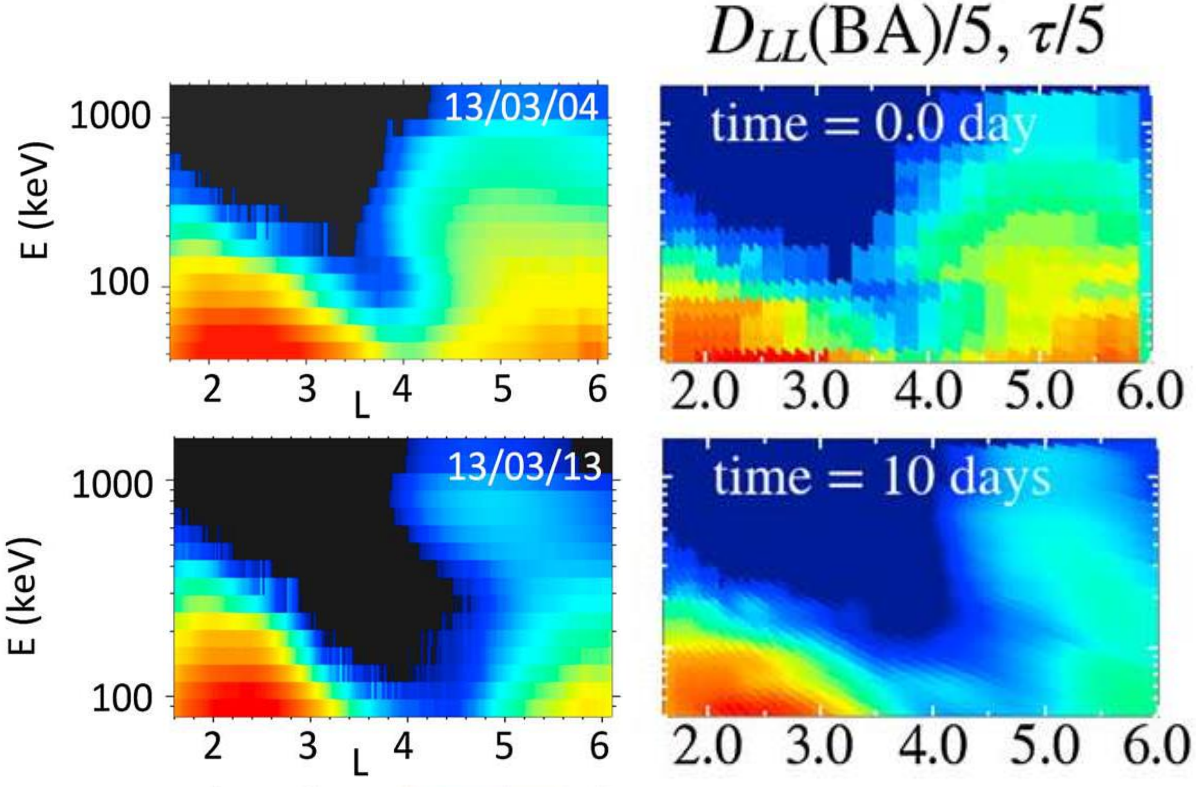
(Baker et al., 2014)

- Impenetrable barrier for multi-MeV electrons exists.

L- and Energy-Dependent Features of Radiation Belt Electrons



(Reeves et al., 2016)

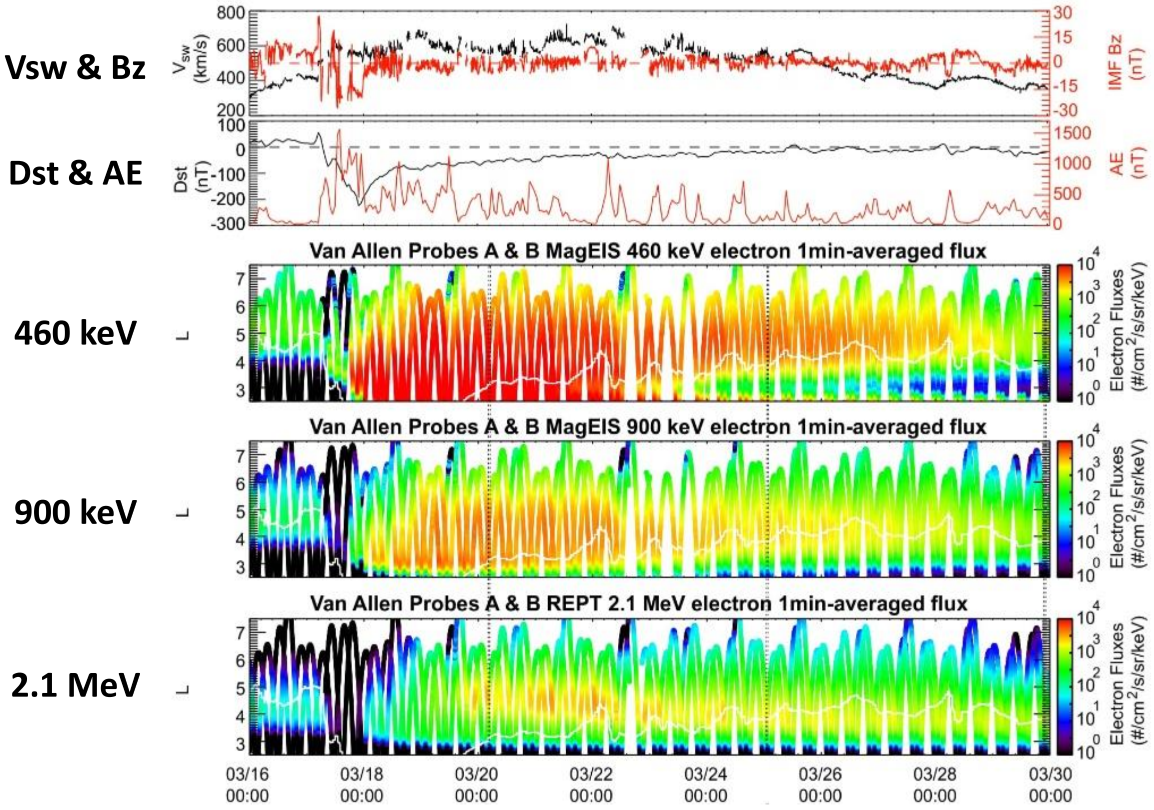


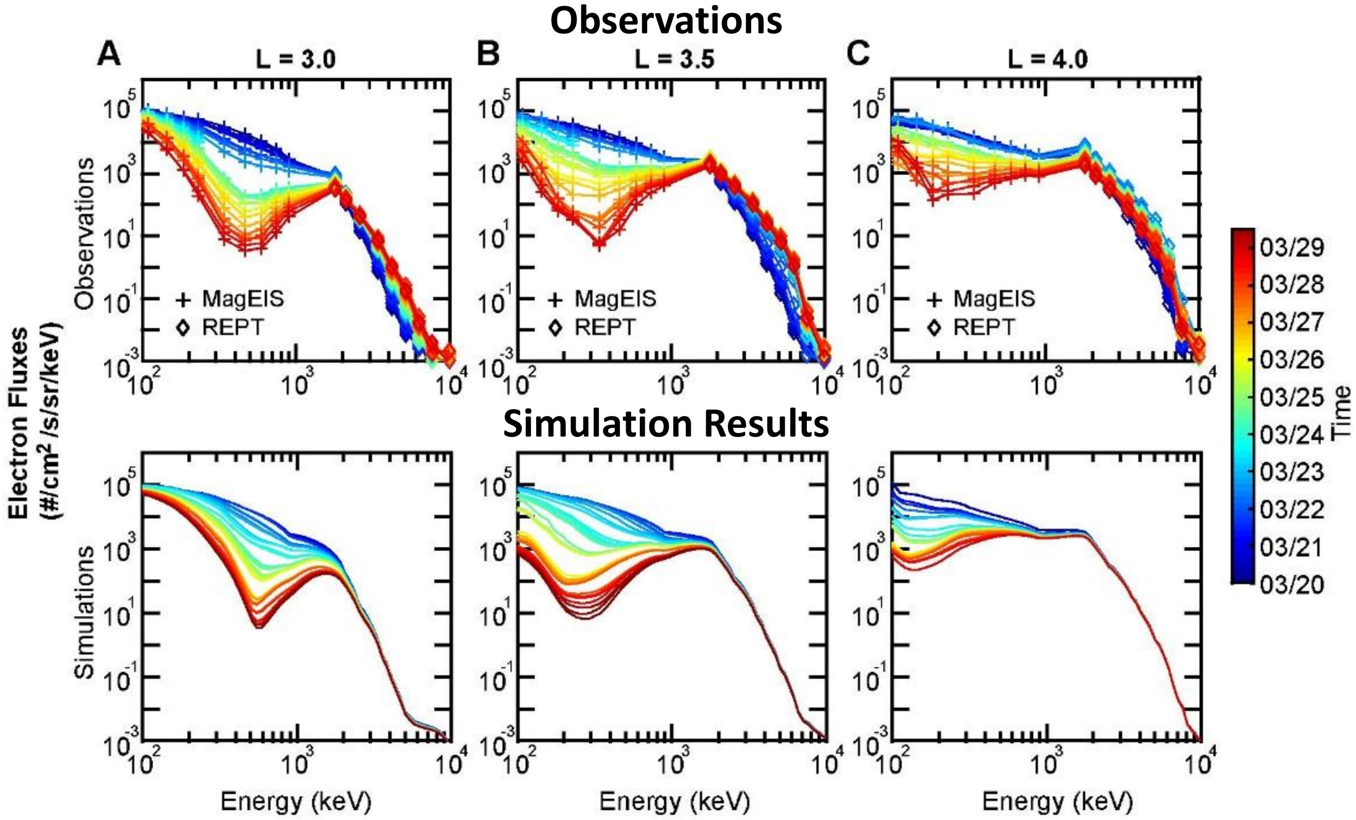
(Ripoll et al., 2016)

- S-shaped structure in energy-L distribution is generally present during quiet times and disappears during active times;
- S-shaped structure is formed as a result of plasmaspheric hiss wave scattering.

Laboratory for Atmospheric and Space Physics
University of Colorado Boulder

Bump-On-Tail (BOT) Energy Spectrum of Radiation Belt Electrons

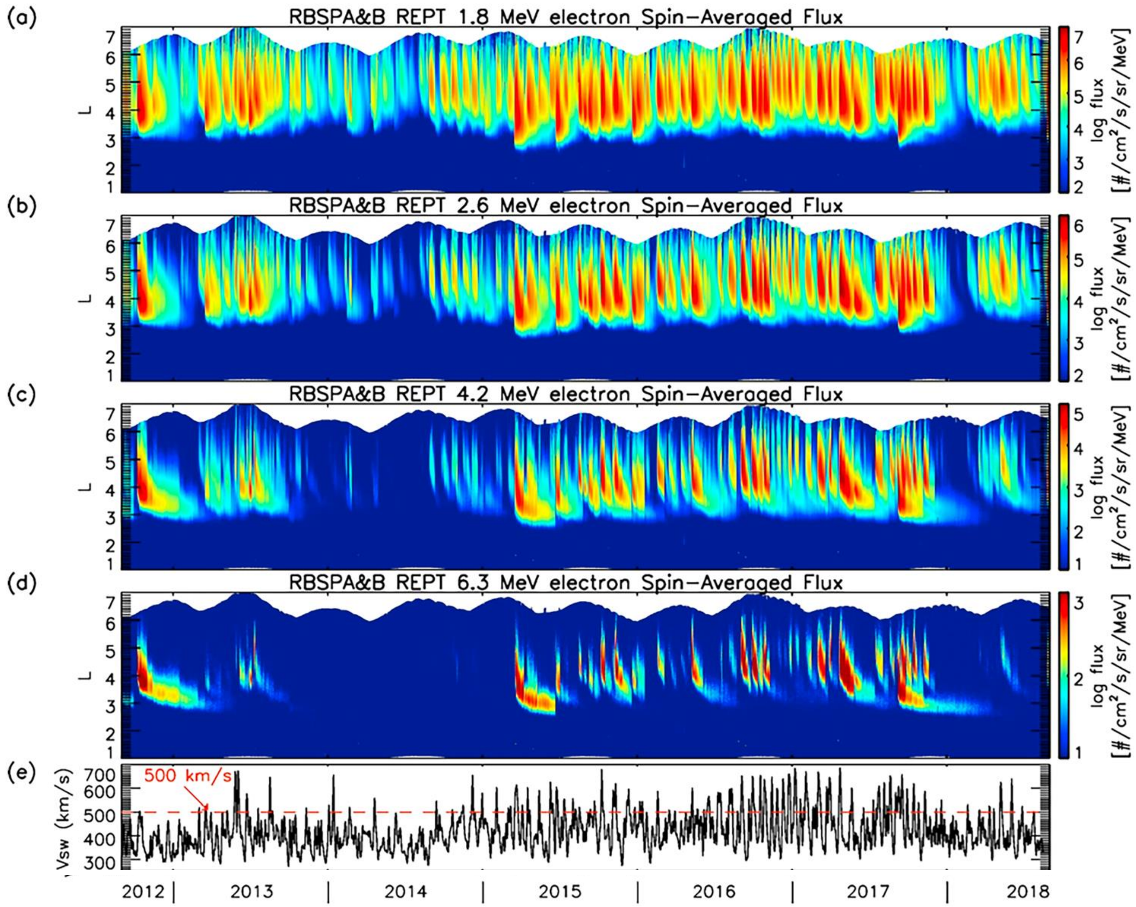




(Zhao et al., 2019)

- Reversed energy spectrum of ~100s of keV – 2 MeV electrons is reported;
- BOT energy spectrum is actually the most prevalent energy spectrum inside the plasmasphere at L>~2.6;
- Plasmaspheric hiss wave scattering is responsible for the formation of BOT energy spectrum.

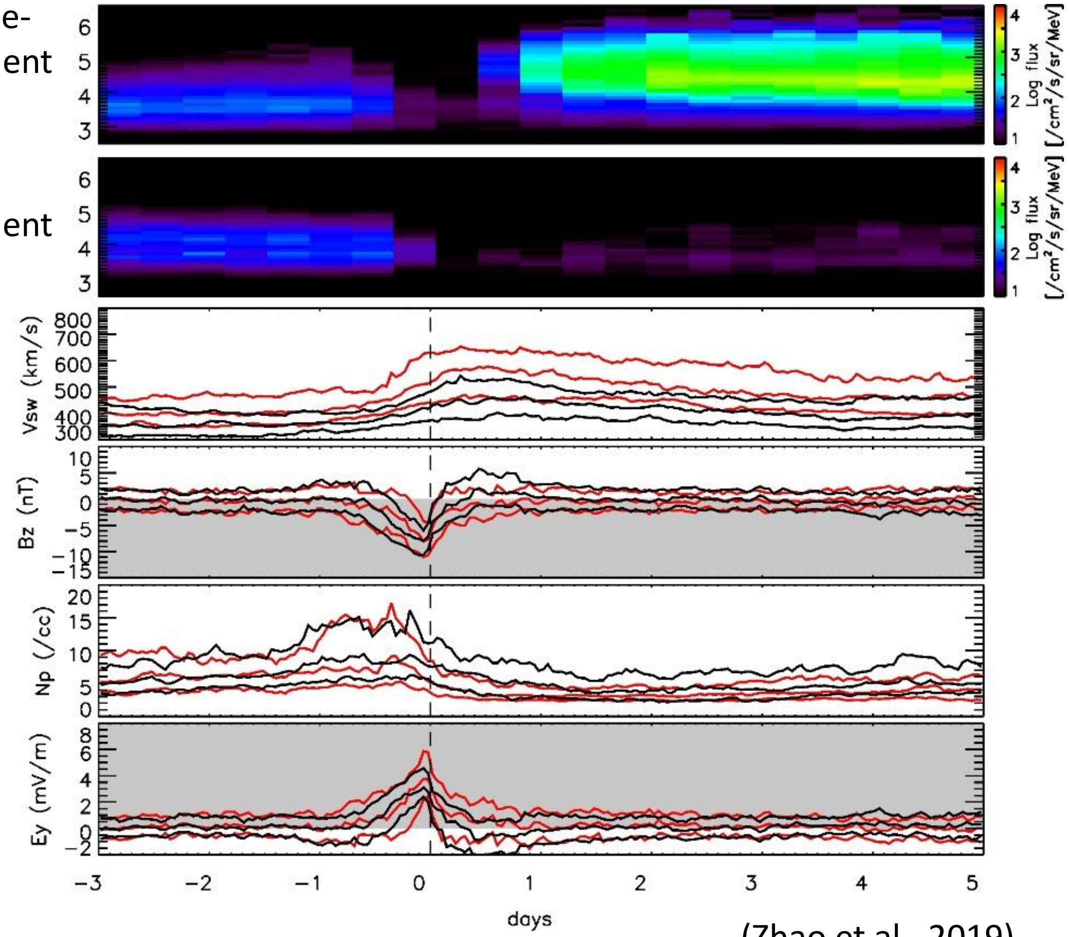
Effects of Solar Wind on Radiation Belt Electrons



(Baker et al., 2019)

5.2 MeV e- enhancement events

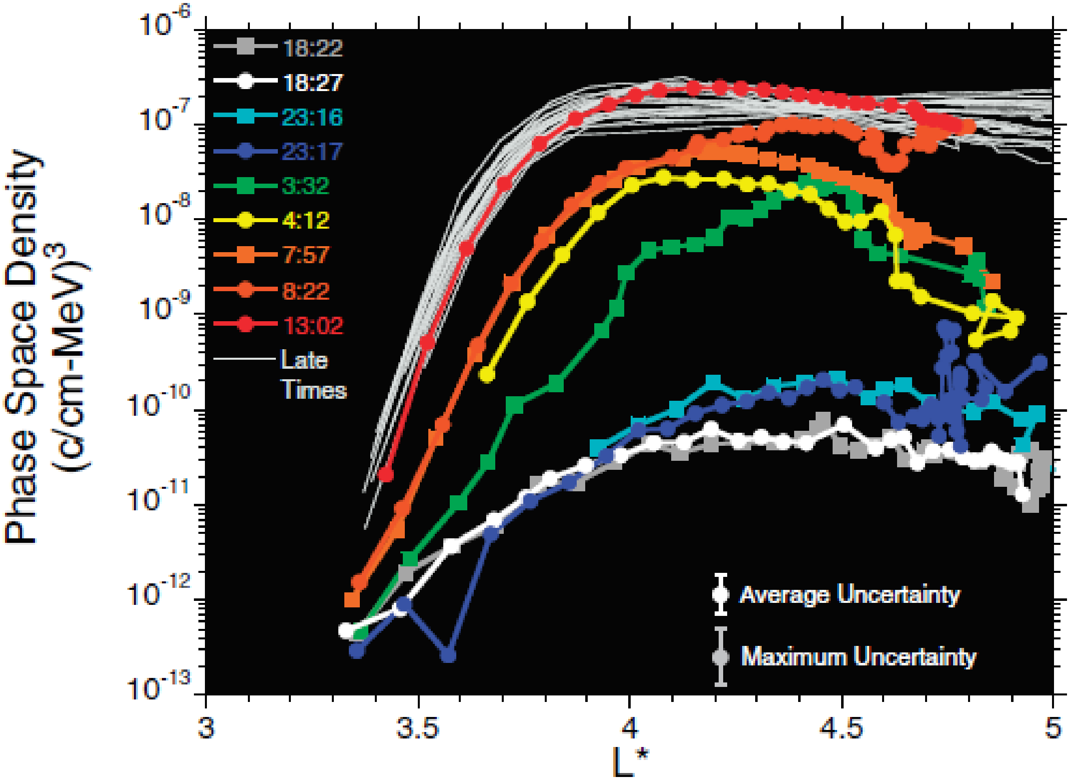
Non-enhancement events



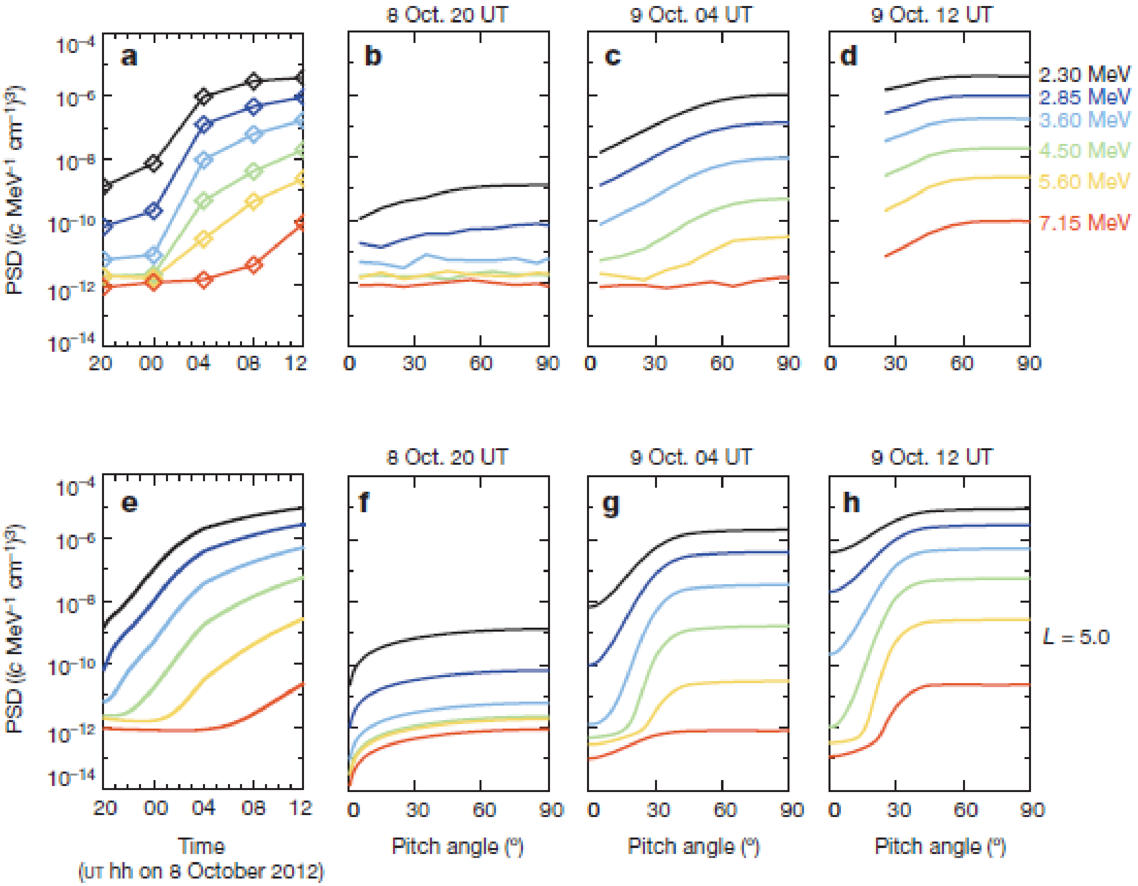
(Zhao et al., 2019)

- Multi-MeV electrons present clear energy-dependent behaviors;
- Solar wind speed is shown to be the most influential solar wind parameter causing multi-MeV electron flux enhancements.

Acceleration Mechanism of Radiation Belt Electrons



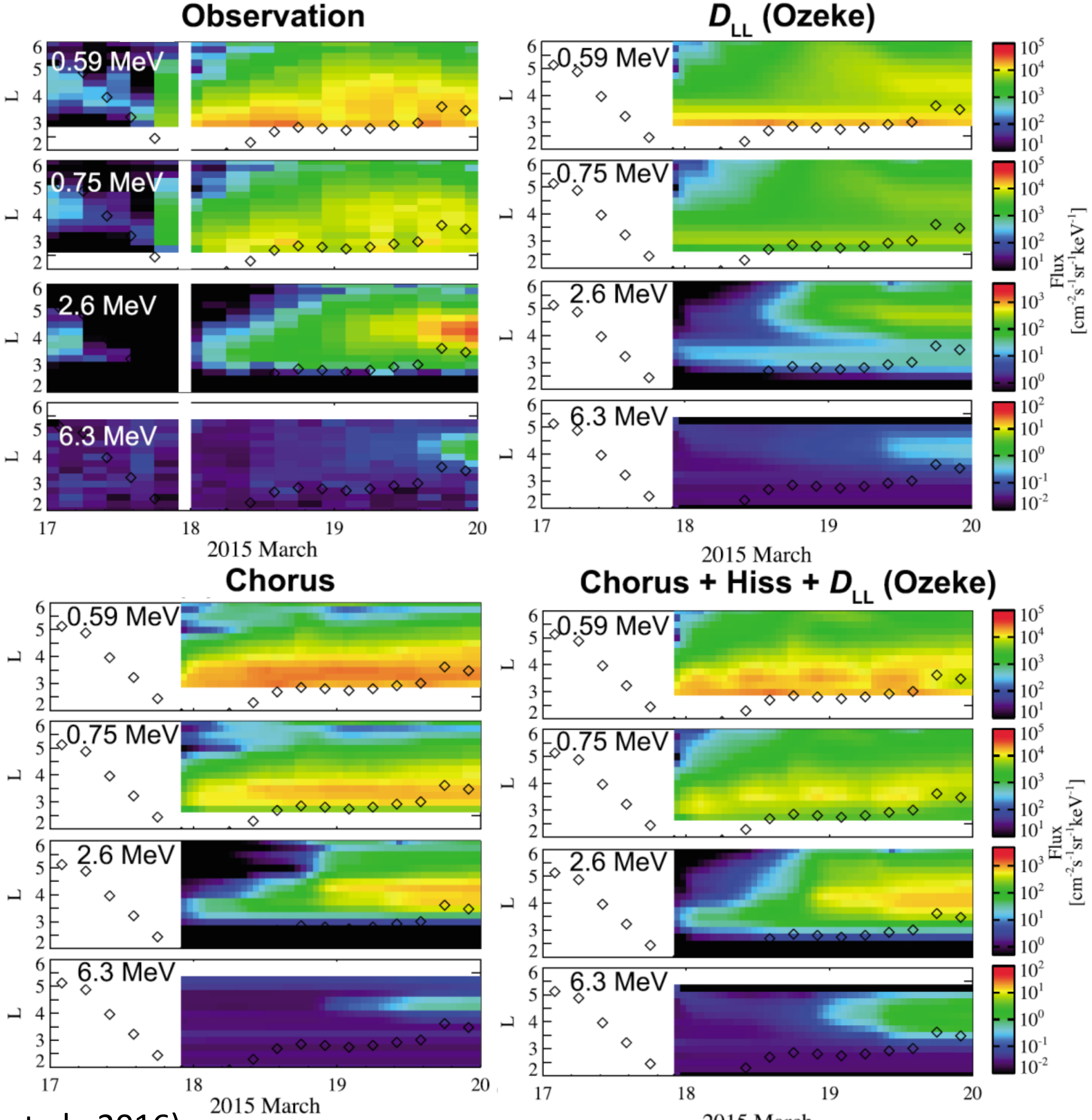
(Reeves et al., 2013)



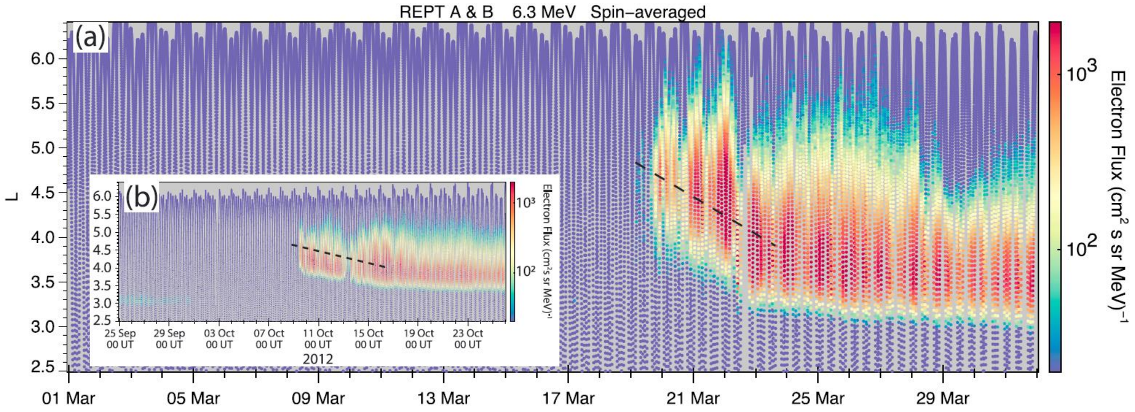
(Thorne et al., 2013)

- Local acceleration caused by whistler mode chorus waves is found to be the main acceleration mechanism for ~2 – 7 MeV electrons in the outer radiation belt during the storm of Oct 2012.

Acceleration Mechanism of Radiation Belt Electrons

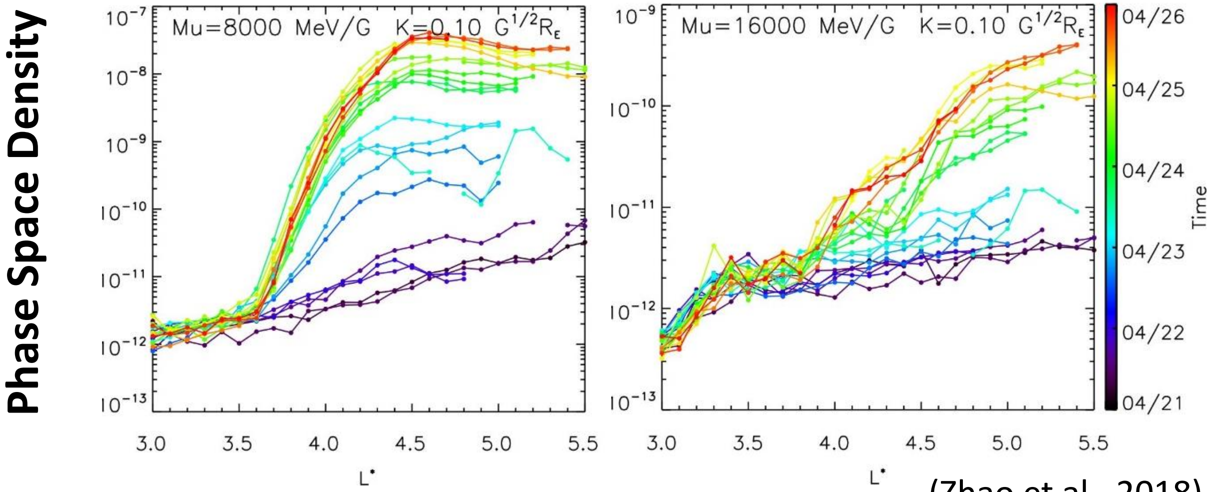


(Li et al., 2016)



(Jaynes et al., 2018)

μ=8000 MeV/G **μ=16000 MeV/G** **K=0.1 $G^{1/2}R_E$**



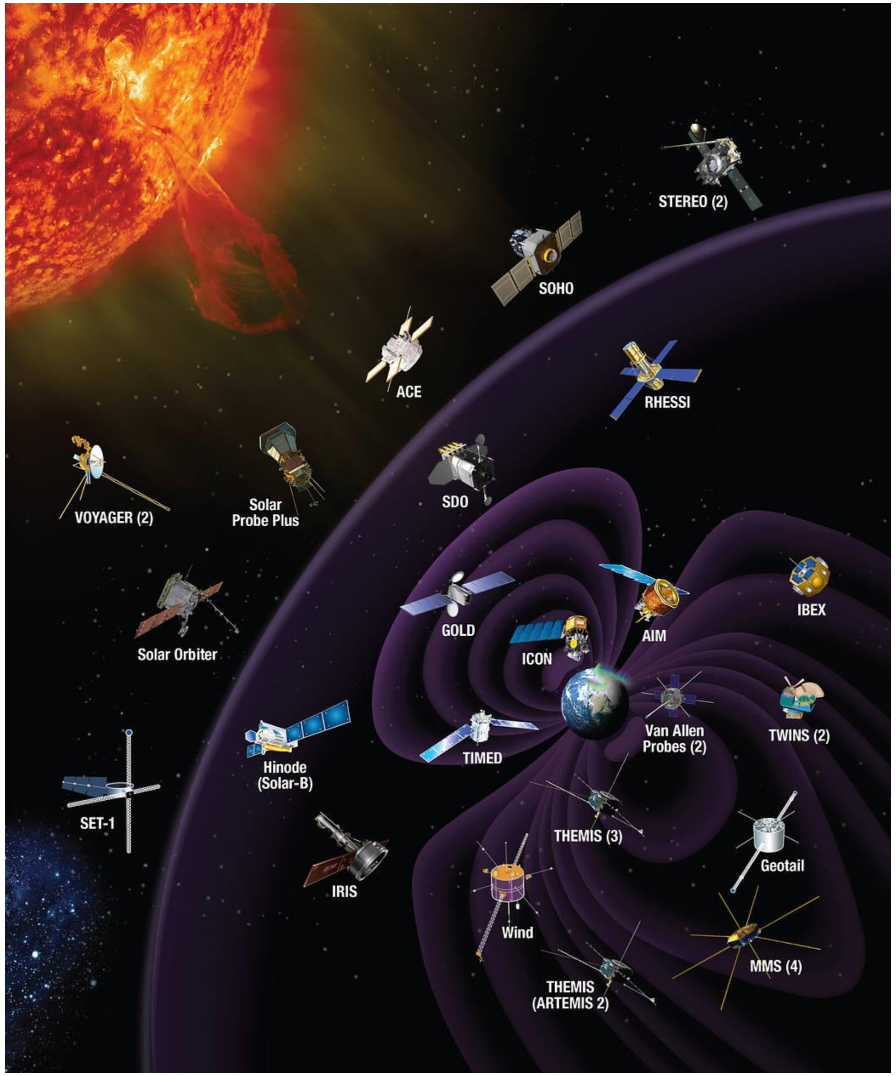
(Zhao et al., 2018)

- Inward radial diffusion is also a very important acceleration mechanism for radiation belt electrons.

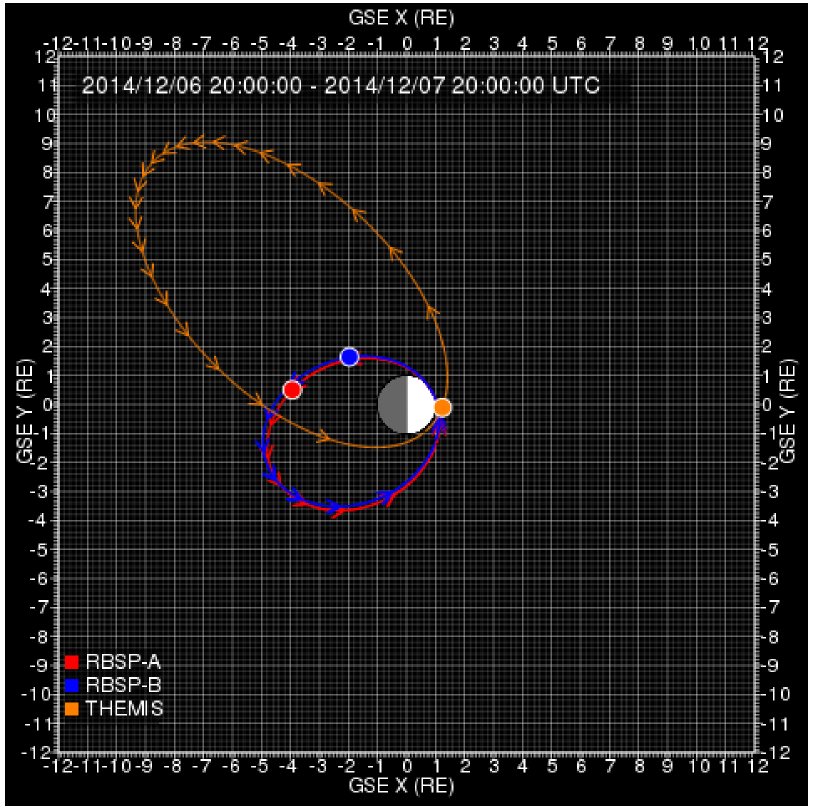
System Understanding of Radiation Belt Particle Dynamics through Multi-Spacecraft and Ground-Based Observations and Modeling

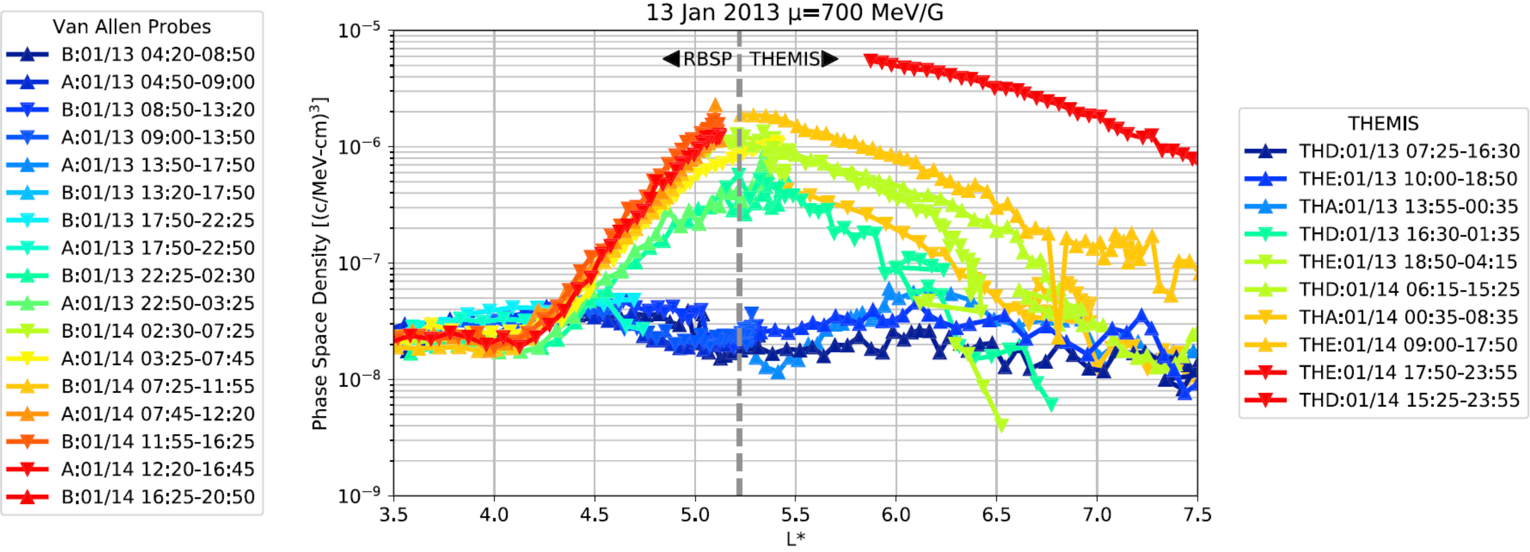
- Single-point measurements have limitations in revealing underlying physical mechanisms on the radiation belt particles due to spatial/temporal ambiguities and limited coverage;

- Through coordinated measurements from multi-spacecraft and ground-based observations, combining with theoretical and modeling efforts, advanced understandings of radiation belt particle dynamics on both local and global scales can be gained.



Multi-Satellite Observations Provide Comprehensive Understanding of Radiation Belt Electron Acceleration Mechanism



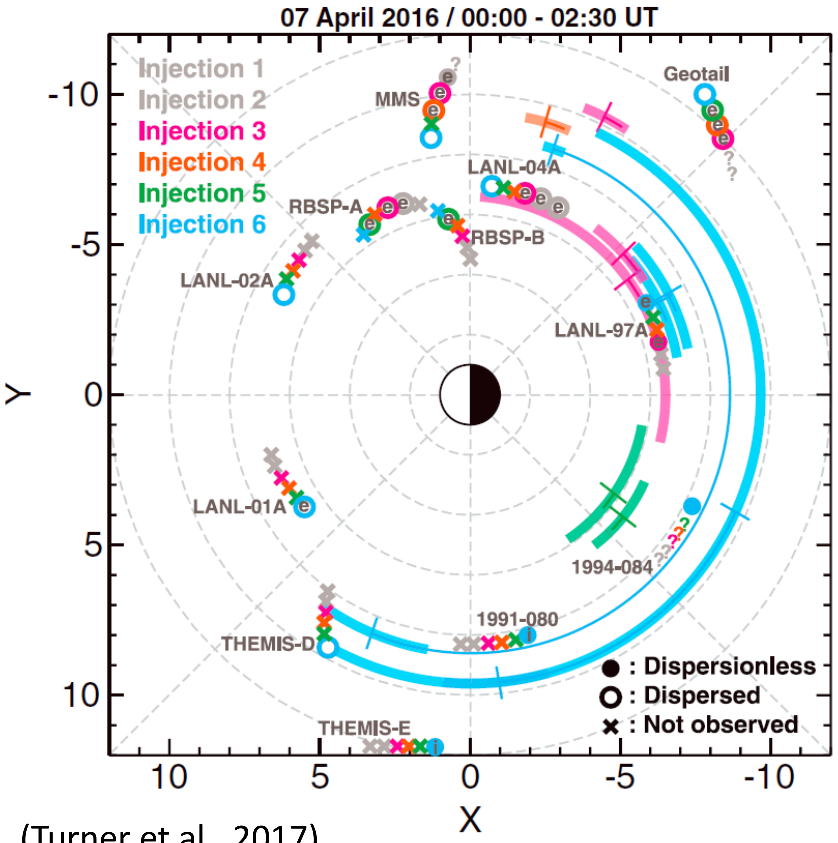


Event type	Van Allen Probes only	THEMIS & Van Allen Probes
Local acceleration dominant	24 (22)	70 (38)
Other	56 (20)	10 (4)
Total	80 (42)	80 (42)

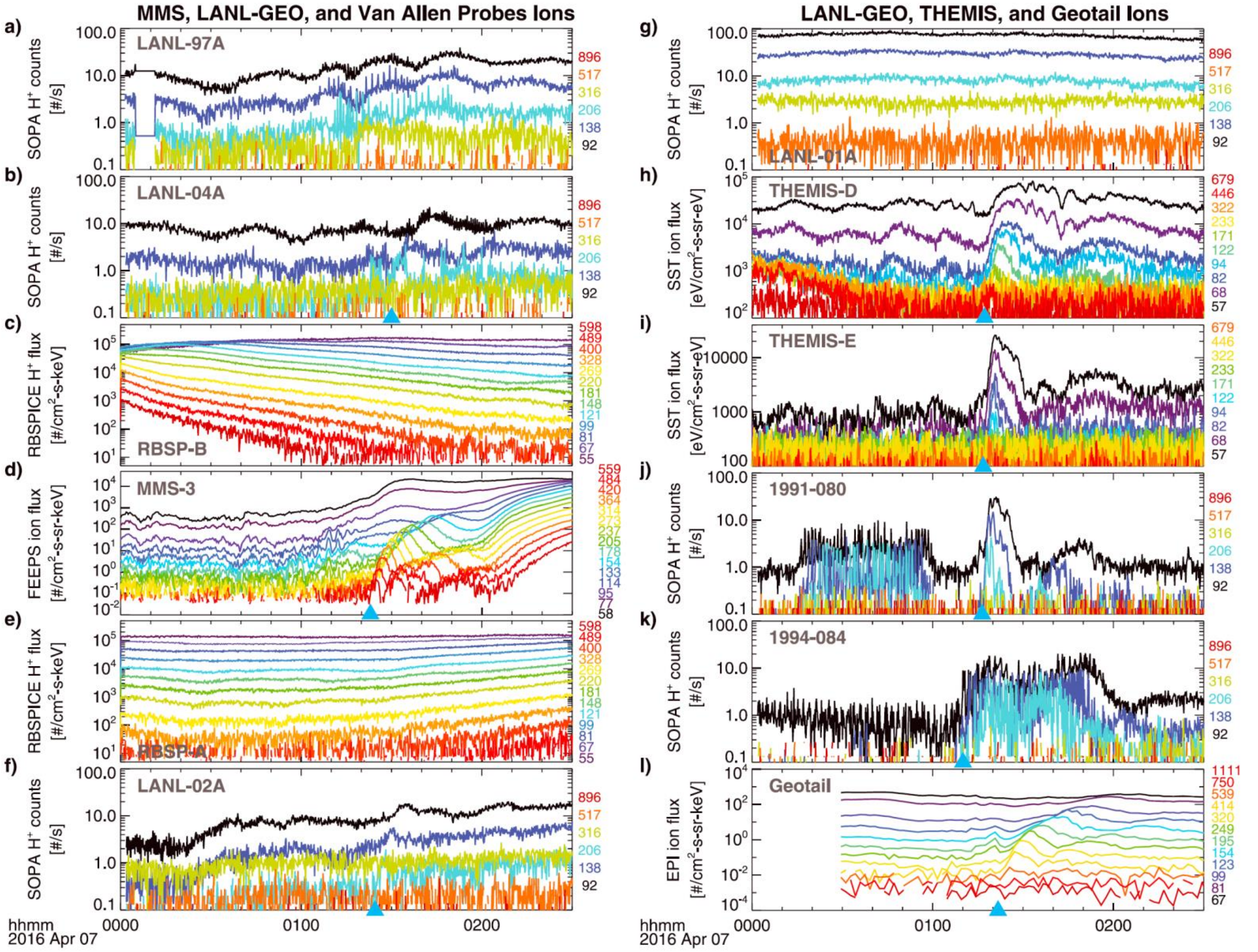
(Boyd et al., 2018)

- Using Van Allen Probes data only (L^* up to ~5.5), ~30% radiation belt electron enhancements show clear local acceleration dominant feature;
- Combining data from Van Allen Probes and THEMIS, most enhancements are found to be dominated by local acceleration.

Multipoint Measurements Provide Global Pictures of Substorm Injections

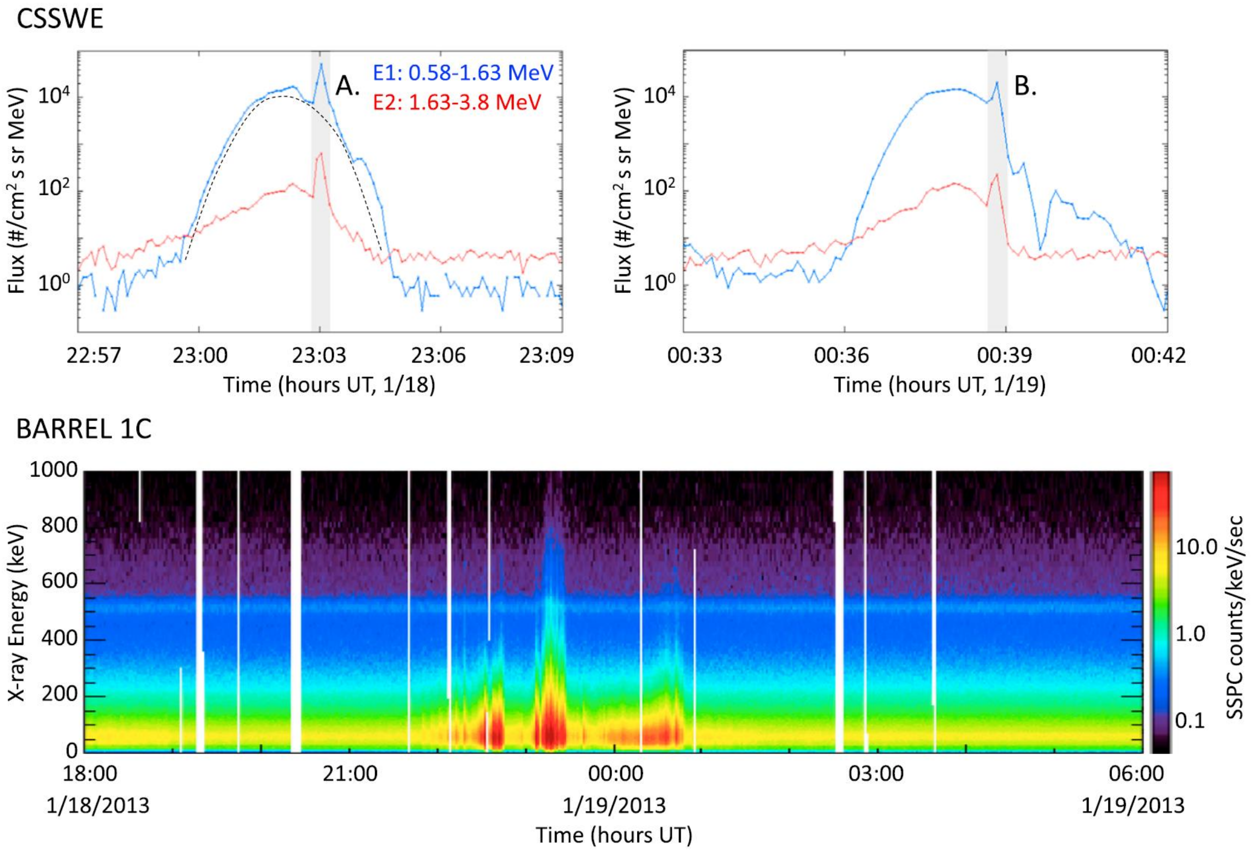


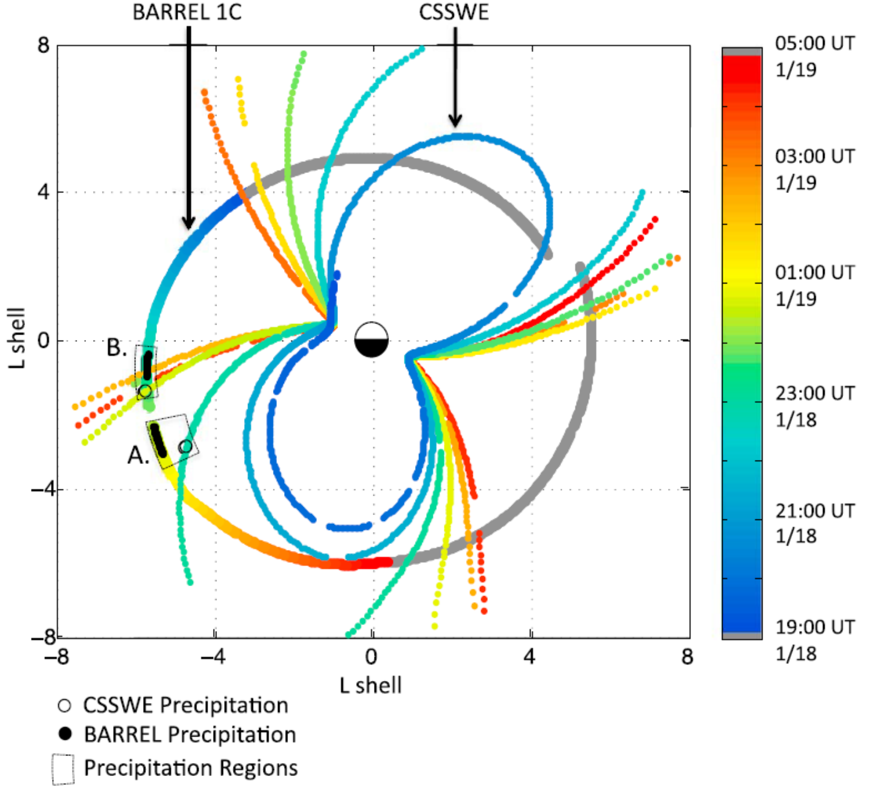
(Turner et al., 2017)



- Multipoint measurements provide comprehensive information of spatial and temporal evolution of substorm injections.

Multipoint Measurements Provide Important Information of Electron Precipitation

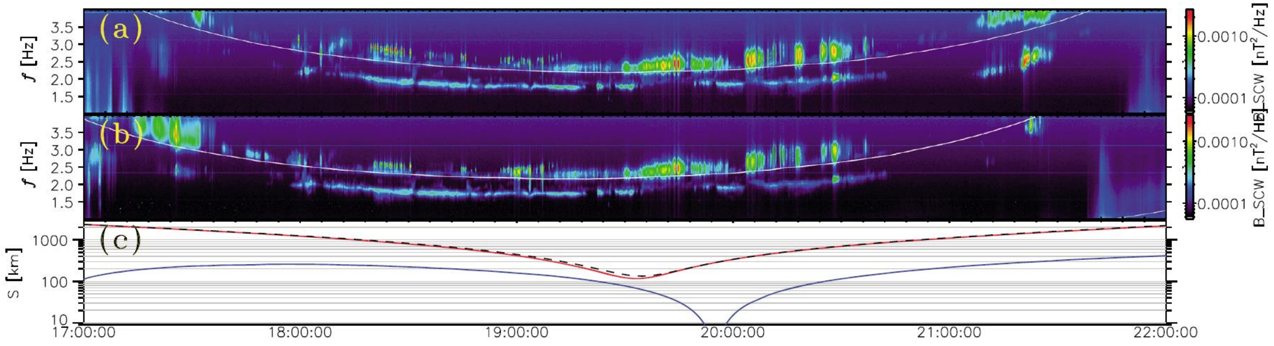


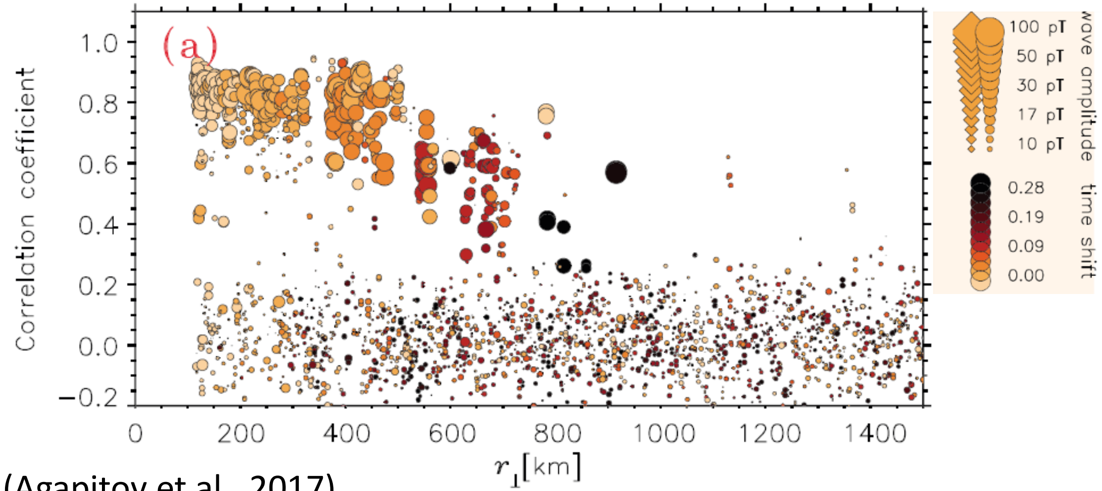


(Blum et al., 2013)

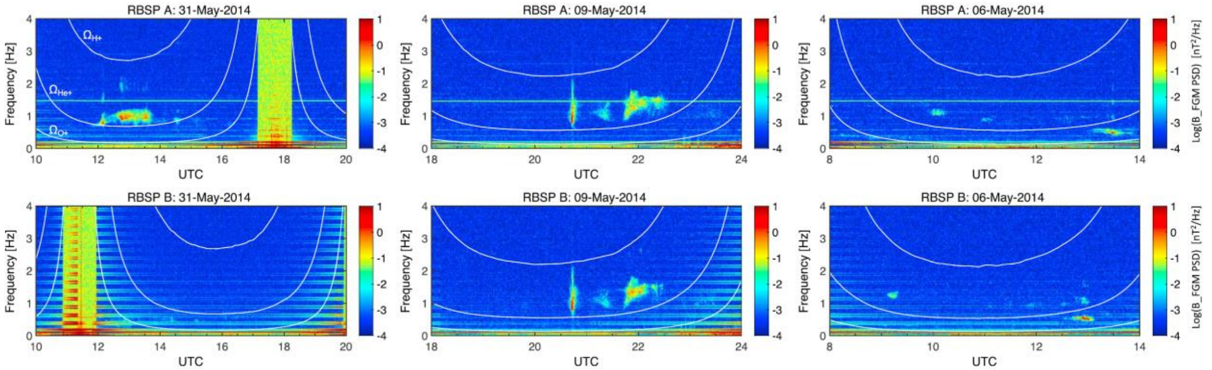
- Both CSSWE and BARREL observed the same precipitation band structures of radiation belt electrons;
- Using data from CSSWE and BARREL, the precipitation regions can be better confined in L and MLT and the electron precipitation can be better quantified.

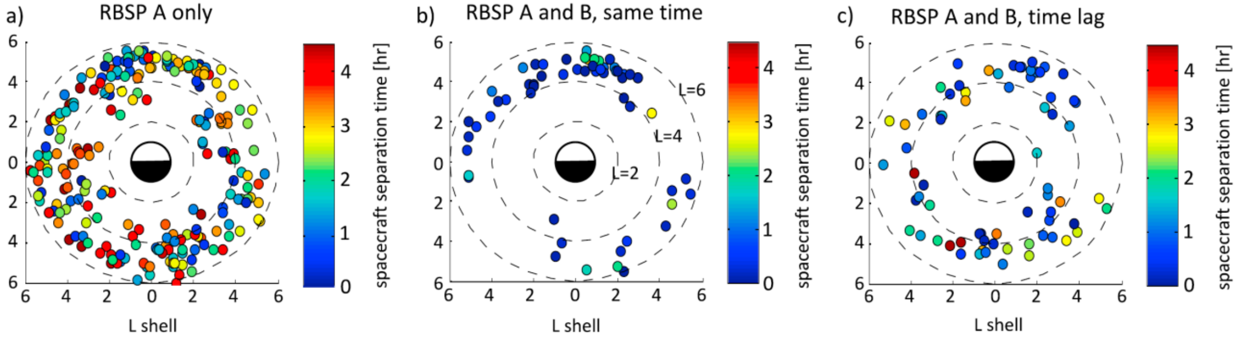
Multipoint Measurements Provide Better Understanding of Radiation Belt Wave Properties





(Agapitov et al., 2017)





(Blum et al., 2017)

- Using conjunctive measurements from the two Van Allen Probes, the spatial and temporal scales of chorus waves and EMIC waves are revealed.

Summary

- Radiation belt particles exhibit significant variations under the effects of various source and loss mechanisms;

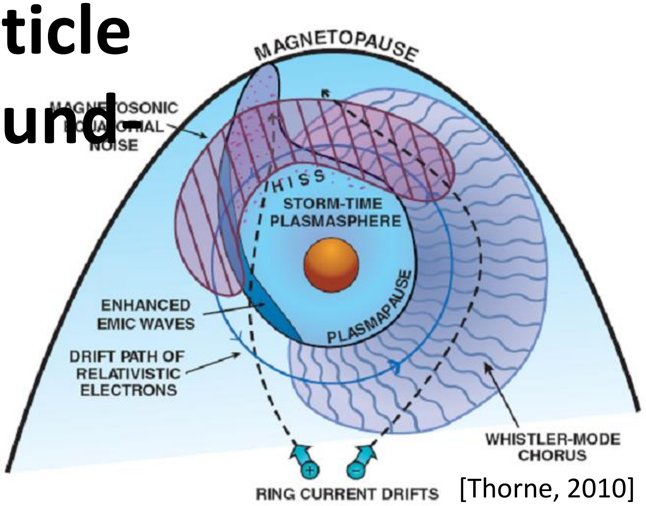
- Recent advances have been achieved on understanding the radiation belt particle dynamics thanks to the unprecedented measurements of the Van Allen Probes;

- Coordinated multi-spacecraft and ground-based measurements, combining with theoretical and modeling efforts, will further deepen our understanding of radiation belt particle dynamics.

Laboratory for Atmospheric and Space Physics
University of Colorado **Boulder**

Thank you!

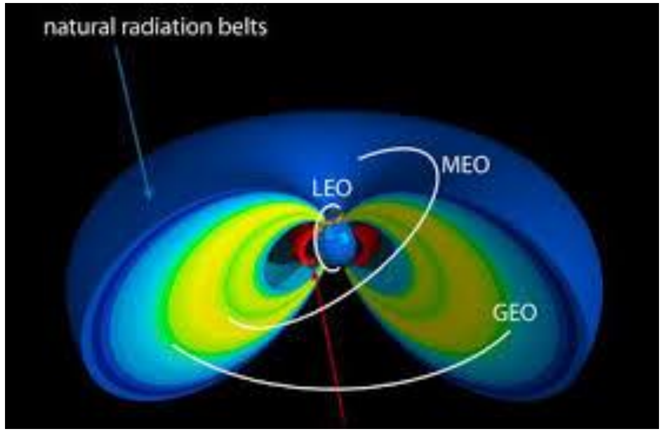
System Understanding of Radiation Belt Particle Dynamics through Multi-Spacecraft and Ground-Based Observations and Modeling

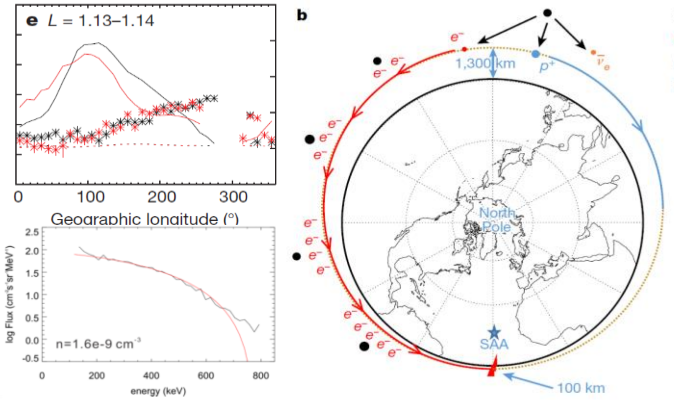


[Thorne, 2010]

- **The broad goal of this FG is to deepen understanding of radiation belt particle dynamics through coordinated multi-mission measurements, combining with theoretical and modeling efforts.**

- **Specific topics include:**
    - Improve the understanding of physical mechanisms related to radiation belt electron acceleration and loss on short timescales (minutes to hours);
    - Quantify the radiation belt electron precipitation into the atmosphere and understand the related physical mechanisms;
    - Improve the understanding of the properties and spatiotemporal distribution of waves and their effects on the radiation belt particles;
    - Advance the understanding of inner belt and slot region particle dynamics.





[Li et al., 2017; Zhang et al., 2018]