

# Radiation Belts in a Waning Solar Cycle

**Urban Seismic Networks**

**Fungal Burrows in Rocks**

**Triggers of Geyser Eruptions**

**Sasha Ukhorskiy**  
JHU/APL

# Van Allen Probes Mission

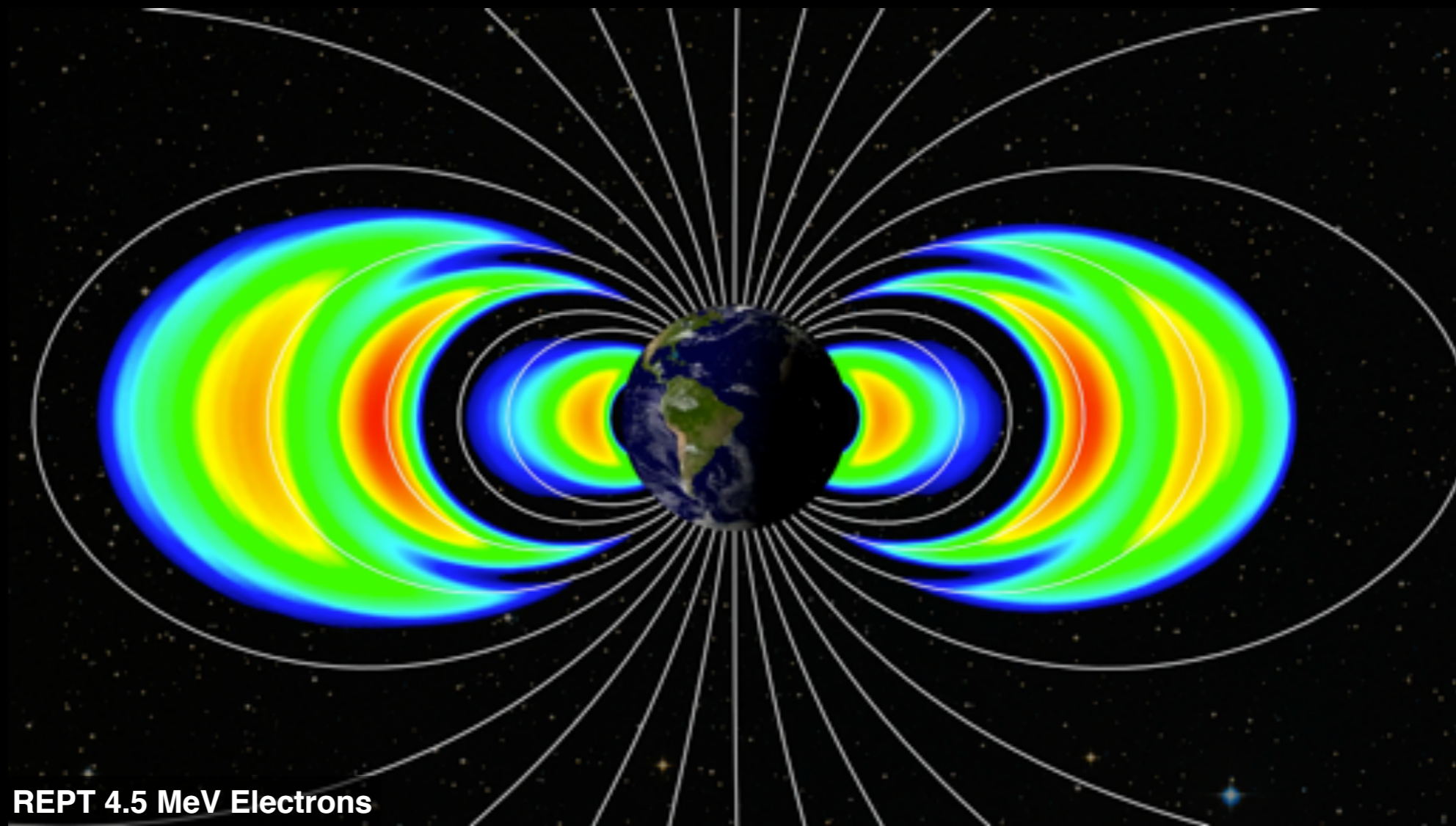


- Goals and design
- Unprecedented capabilities - New discoveries
- Systemwide understanding & Predictability
- Real-time space weather broadcast
- Science Gateway

# Van Allen Probes (RBSP) Mission

*Understand dynamic variability of the radiation belt and ring current environment  
in response to varying solar wind driving*

September 02, 2012 Geomagnetic Storm



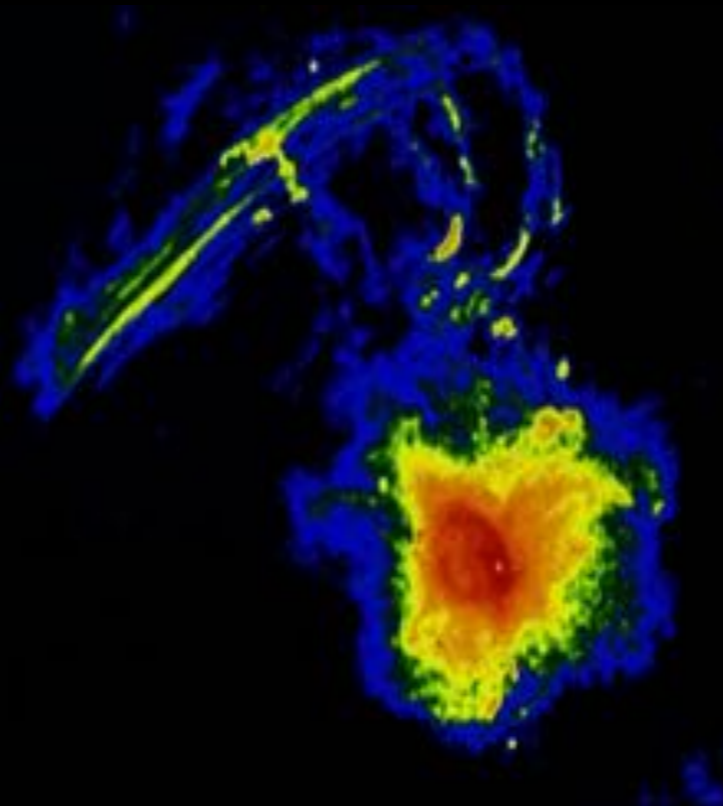
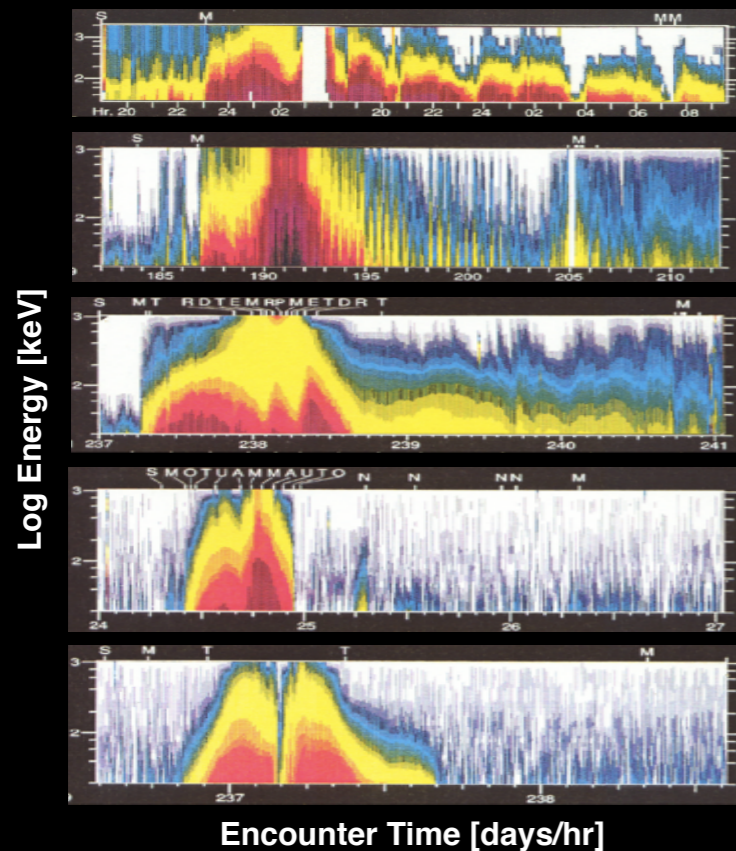
During geomagnetic storms the intensities of high-energy particles in the near-Earth space vary by orders of magnitude on the timescales from minutes to days. This dynamic variability is controlled by the shifting balance among multiple acceleration and loss mechanisms which interact with particle motion at various spatial and temporal scales.

# Fundamental Physics with Practical Importance

Planetary Belts

Galactic Center

Space Weather



**Fundamental Science:** Earth's radiation belts are a natural laboratory for investigating how charge particles are accelerated to high energies at magnetized planets of the solar system and other astrophysical objects.

**Space Weather:** Nowcasting and predictive understanding of radiation belt dynamics is critical for mitigating hazardous effects of space radiation.

# Mission Configuration and Science Investigation

## Near-equatorial orbit (10°)

- direct measurements of the acceleration region

## Two identical spacecraft with variable separation (30 days)

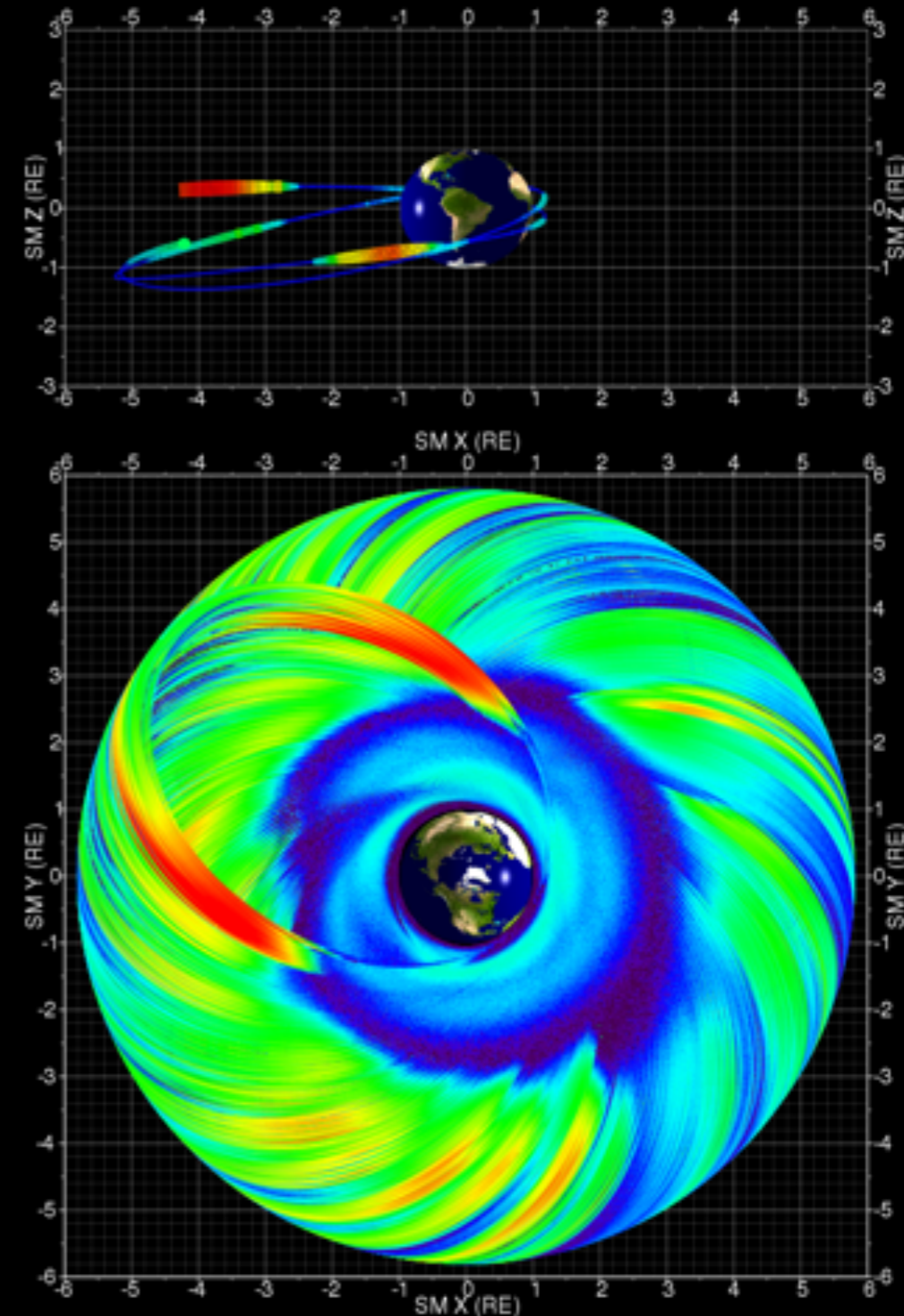
- separation of temporal and spatial effects
- sampling different scales/mechanisms

## Complete MLT coverage

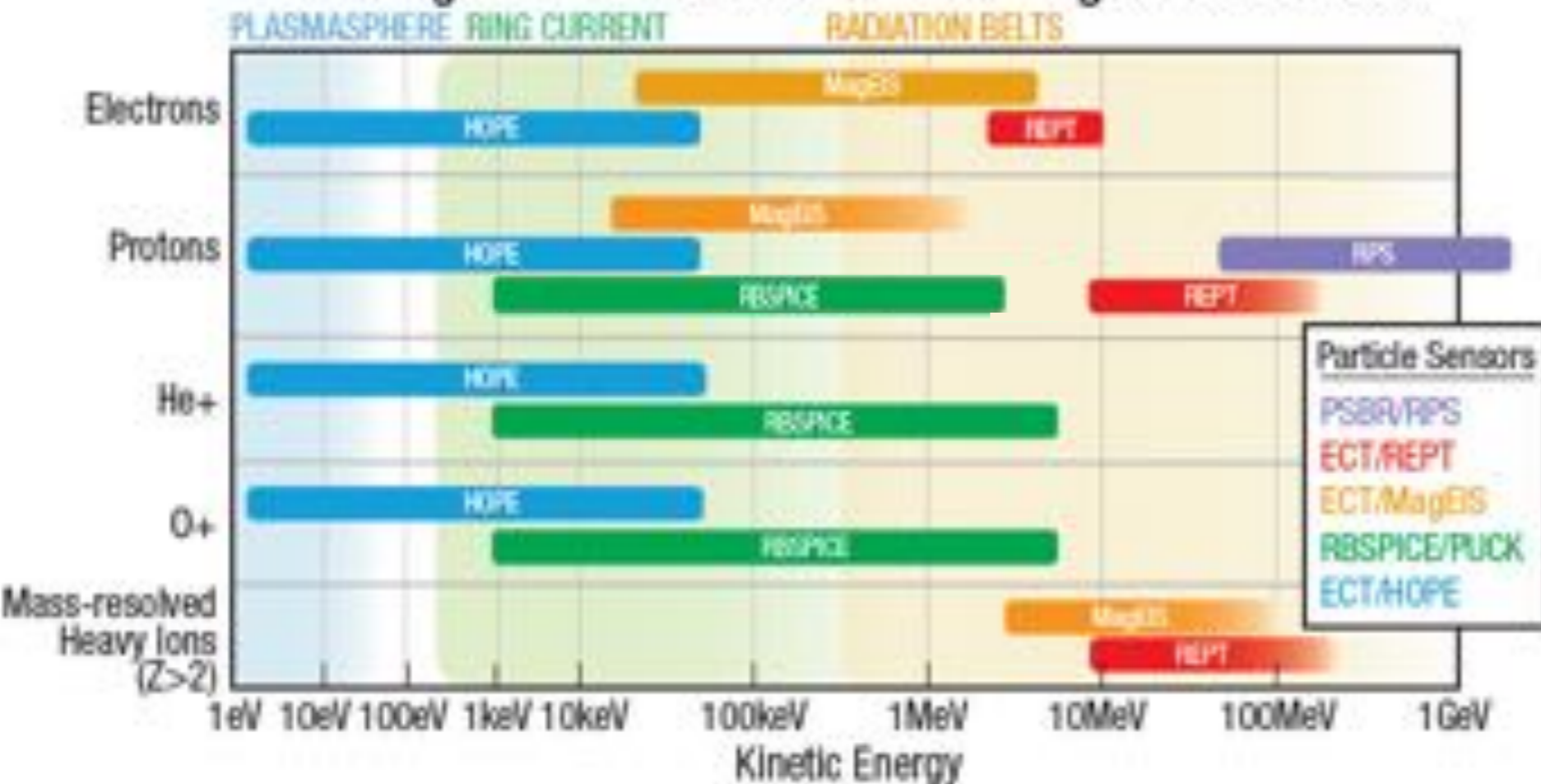
- spans different physical mechanisms/interaction regions

## Van Allen Probes Instrument Investigations

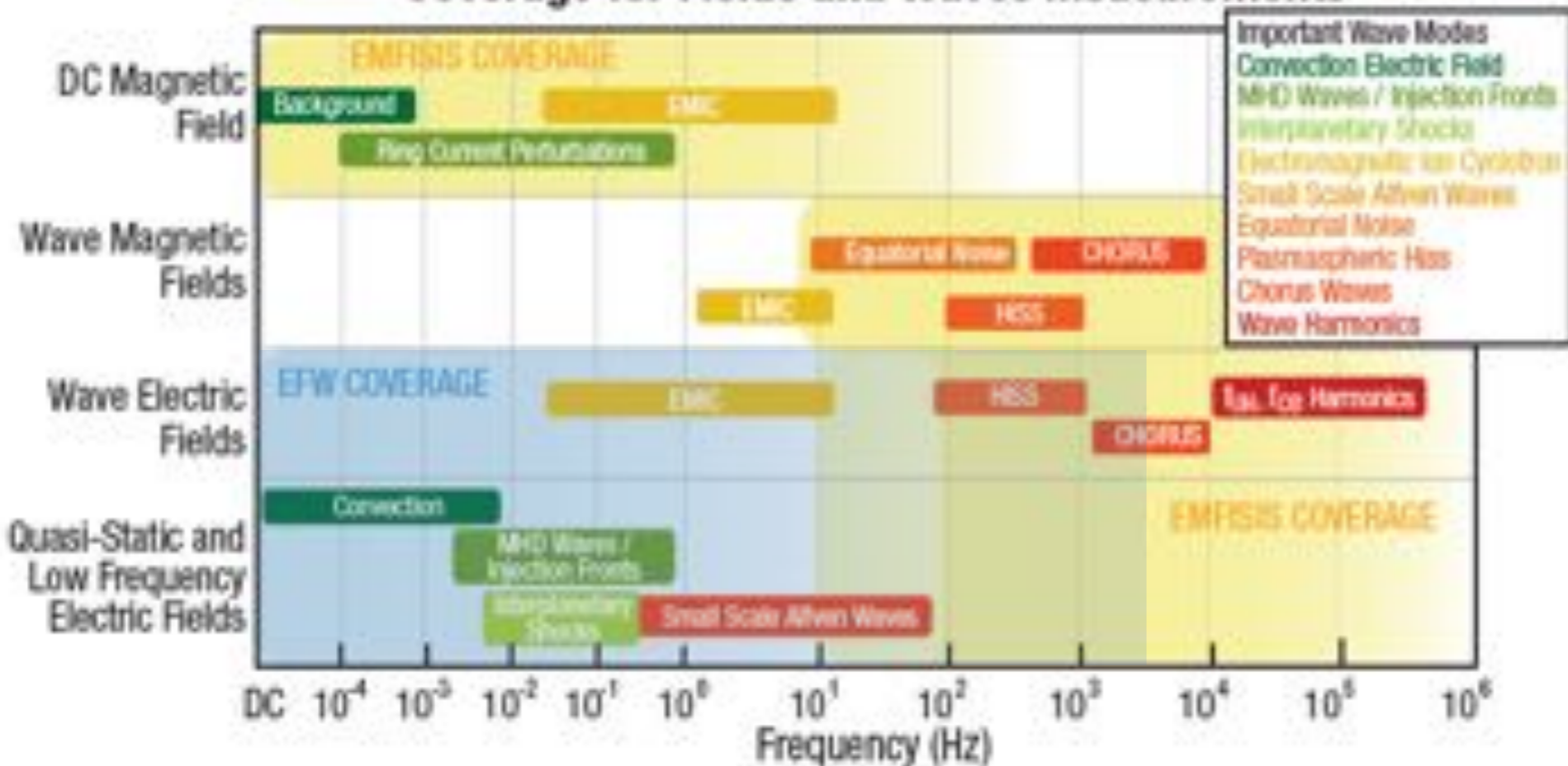
Instruments	Science Teams
Energetic Particle, Composition and Thermal Plasma Suite (ECT), including: Helium, Oxygen, Proton, and Electron spectrometer (HOPE) Magnetic Electron Ion Spectrometer (MagEIS) Relativistic Electron-Proton Telescope (REPT)	<b>Harlan Spence</b> , PI, University of New Hampshire <b>Key Partners:</b> LANL, SwRI, Aerospace Corp., LASP Herbert Funsten, LANL J. Bernard Blake, Aerospace Corp. Daniel Baker, University of Colorado LASP
Electric and Magnetic Field Instrument Suite and Integrated Science (EMFISIS)	<b>Dr. Craig Kletzing</b> , PI, University of Iowa <b>Key Partners:</b> NASA/GSFC, University of New Hampshire
Electric Field and Waves Instrument (EFW)	<b>John Wygant</b> , PI, University of Minnesota <b>Key Partners:</b> University of California, Berkeley; LASP
Radiation Belt Storm Probes Ion Composition Experiment (RBSPICE)	<b>Louis Lanzerotti</b> , PI, New Jersey Institute of Technology <b>Key Partners:</b> JHU/APL, Fundamental Technologies
Relativistic Proton Spectrometer (RPS)	<b>Joseph Mazur</b> , PI, Aerospace Corp.
Balloon Array for RBSP Relativistic Electron Losses (BARREL)	<b>Robyn Millan</b> , PI, Dartmouth College



# Coverage for Electron and Ion Pitch Angle Distributions



# Coverage for Fields and Waves Measurements



# Instrument Performance

All instruments are healthy and returning quality data.

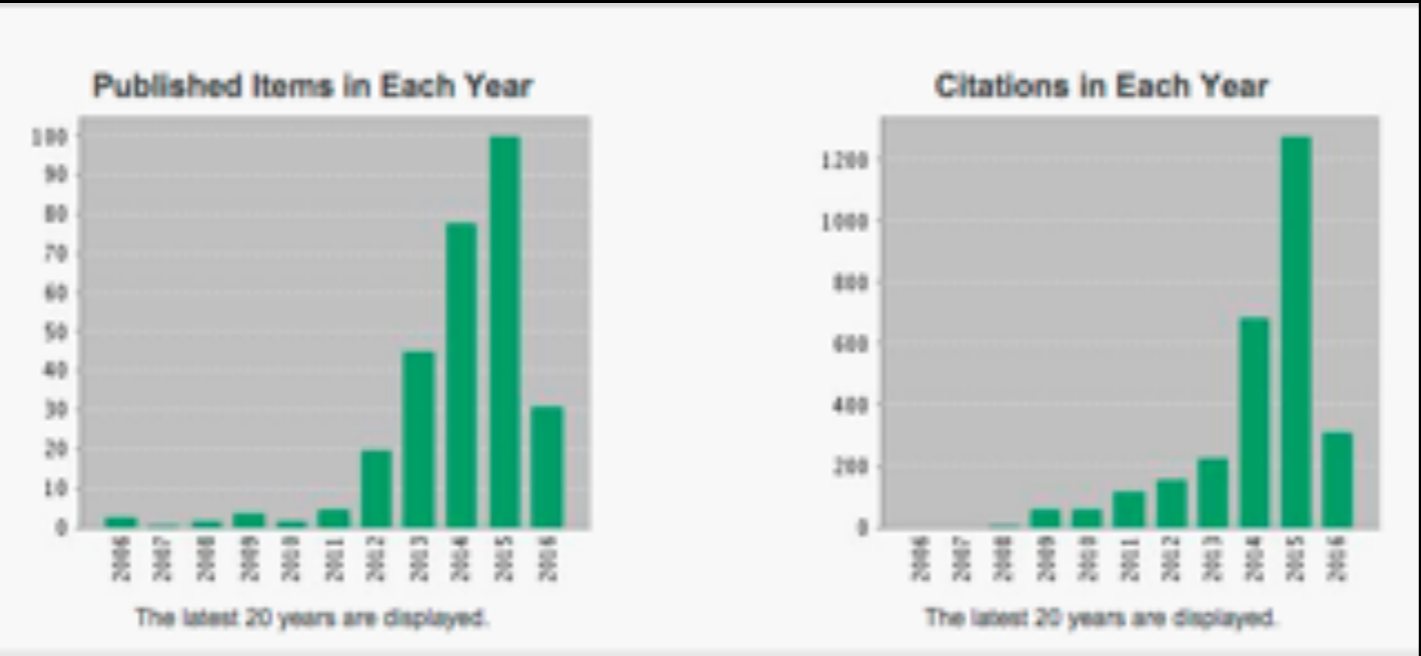
Overlapping energy/frequency ranges provide excellent basis for cross-calibration.

Data downlink increased by more than factor of 2 by modifying compression and on-board operation.

# Scientific Success of Van Allen Probes

- More than 300 publications. More than 2900 citations
- More than 50% of publications are lead by authors not directly funded by Van Allen Probes
- H-index of 24 (Web of Science)
- High-profile results include: Nature (6 pub.), Science (2 pub.), Nature Publishing Group (4 pub.), Physical Review Letters (2 pub.)
- Special Issue of Space Science Reviewers (Volume 179, 2013)
- Special Issue of Geophysical Research Letters (26 pub.)
- 2 Special Issues of Journal of Geophysical Research (>50 pub.)
- Steady stream of press releases with new results featured on NASA and JHU/APL websites
- International press interest, popular science radio shows and magazine articles

## Steady rise of publications and citations



Health & Science  
**Van Allen probes spy third band before it disappears**  
 NASA: The instruments on the Van Allen Probes  
 science FRIDAY  
 LISTEN WATCH READ EDUCATE DONATE ABOUT  
 VIEW CURRENT WEEK  
 Listen  
 A Natural Particle Accelerator, Far Above the Planet  
 Listen to daily updates from Studio 360 on Flipboard.  
 NASA Science News  
 VAN ALLEN PROBES DISCOVER A NEW RADIATION BELT  
 Feb. 28, 2013. Earth's radiation belts were one of the first discoveries of the Space Age. A new finding published in today's issue of Science shows that we still have much to learn about them. NASA's Van Allen Probes, launched last August, have revealed a previously unknown third radiation belt around Earth.  
 "Even 55 years after their discovery, Earth's radiation belts still are capable of surprising us," said Nancy Front, Van Allen Probes deputy project scientist at the Johns Hopkins University Applied Physics Laboratory in Laurel, Md. "We thought we knew the radiation belts, but we don't."  
 A video from the Goddard Space Flight Center recaps the discovery of the new radiation belt. Click.  
 Previous observations of the Van Allen belts dating back to the late 1950s have documented two distinct regions of trapped radiation surrounding our planet, known as the inner and outer radiation belts. Particle sensors aboard the Van Allen Probes quickly revealed the existence of a transient, third radiation belt. Scientists observed the third belt for four weeks before a powerful interplanetary shock wave from the sun annihilated it.

nature International weekly journal of science  
 archive - volume 507 - issue 7492 - letters - article - figure 1  
**Figure 1: Zebra stripe patterns in energetic electron distributions from the inner radiation belt.**  
 From  
 Rotationally driven 'zebra stripes' in Earth's inner radiation belt  
 A. Y. Ukhorskiy, M. I. Sitenov, D. G. Mitchell, K. Takahashi, L. J. Lanzetta, B. H. Mauk  
 Nature 507, 338–340 (20 March 2014) | doi:10.1038/nature13046  
 Quiet time  
 04/14/13 (D<sub>st</sub> = -15 nT) 06/28/13 (D<sub>st</sub> = -11 nT) 07/19/13 (D<sub>st</sub> = -3 nT) Radiation belt model  
 Geomagnetic storms  
 03/19/13 (D<sub>st</sub> = -47 nT) 03/29/13 (D<sub>st</sub> = -60 nT) 06/03/13 (D<sub>st</sub> = -64 nT) Radiation belt model  
 K (keV) L (RE) L<sub>min</sub> (RE) L<sub>max</sub> (RE) L<sub>min</sub> (RE) L<sub>max</sub> (RE) L<sub>min</sub> (RE) L<sub>max</sub> (RE) L<sub>min</sub> (RE) L<sub>max</sub> (RE)

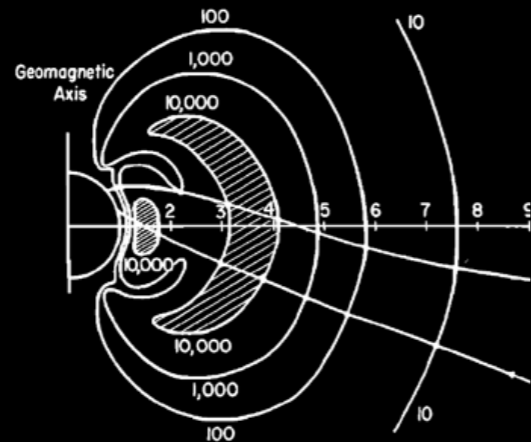
nature International weekly journal of science  
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 News & Comment News 2015 April Article  
 NATURE | NEWS  
**Mystery of Earth's radiation belts solved**  
 Van Allen belts accelerate their own particles rather than just trapping them.  
 Ron Cowen  
 25 July 2013  
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 NASA's Van Allen Probes have demonstrated that the Van Allen belts replenish themselves just days after they are disturbed by solar storms.  
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**Third 'Van Allen Radiation Belt' Makes Appearance around Earth**  
 NASA probes observed the new belt for weeks before a solar shock wave wiped it out  
 March 1, 2013 | By Ron Cowen and Nature magazine  
 When NASA scientists launched twin spacecraft to probe the Van Allen radiation belts last summer, they were expecting to study two rings of high-energy particles circling Earth. Instead they found three, overturning a 50-year-old model of the giant rings' structure.  
 First discovered in 1958, the Van Allen belts have been thought to comprise two reservoirs of high-speed, electrically charged particles, corralled into separate  
 SKY & TELESCOPE THE ESSENTIAL GUIDE TO ASTRONOMY  
 HOME NEWS OBSERVING EQUIPMENT RESOURCES & EDUCATION COMMUNITY MULTIMEDIA  
**Van Allen Probes Peek at Radiation Belts**  
 By Monica Young | December 5, 2012  
 The twin Van Allen Probes have only been spaceborne for 60 days, but they've already returned heaps of data about the radiation belts, whose "killer electrons" endanger satellites.  
 Much like a president's first 100 days, the beginning of a mission can say a lot about what's in store for the years to come. The Van Allen Probes have only been spaceborne for two months, but they complete an elongated orbit every 9 hours that takes them speeding through the two radiation belts encircling the Earth. In their twice-daily journey, they have already returned more data about the Van Allen belts than scientists have been able to access over the past 50 years, since the belts were first discovered.  
 NASA NEWS News, features & press releases MISSIONS Current, future, past missions & launch dates MULTIMEDIA Images, videos, NASA TV & more CONNECT Social media channels & weblogs ABOUT NASA Leadership, organization, budget, careers & more  
 For Public | For Educators | For Students | For Media  
 Van Allen Probes  
 Mission Overview News & Media Resources Spacecraft & Instruments Science Multimedia BARREL Launch All NASA Missions  
 Van Allen Probes Shed Light on Decades-old Mystery  
 December 20, 2013  
 Graphic depiction of NASA's Van Allen Probe orbiting with Earth's radiation belts. Image Credit: NASA  
 New research using data from NASA's Van Allen Probe mission helps resolve decades of scientific uncertainty over the

# Unprecedented Measurement Capabilities - New Unexpected Discoveries

## James Van Allen

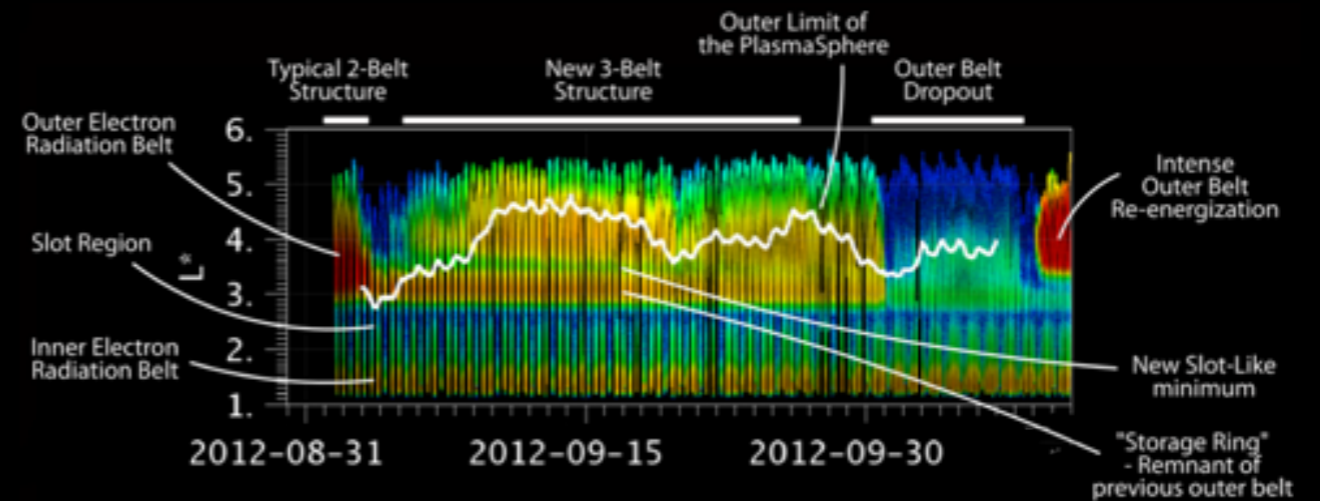


Explorer 1



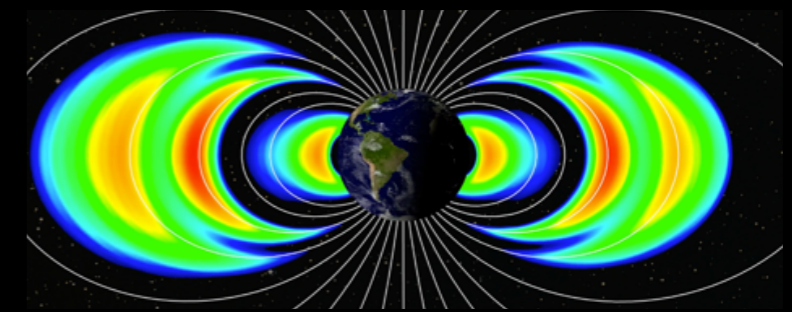
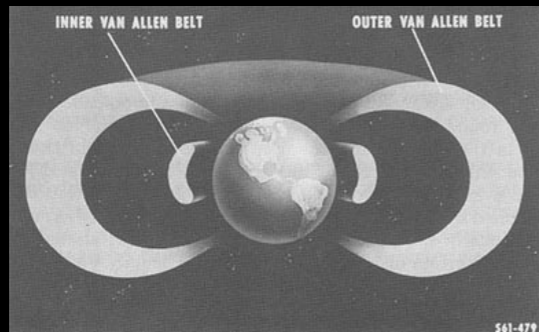
[Van Allen, JGR 1959]

## Van Allen Probes



RBSP

[Baker et al., Nature 2012]

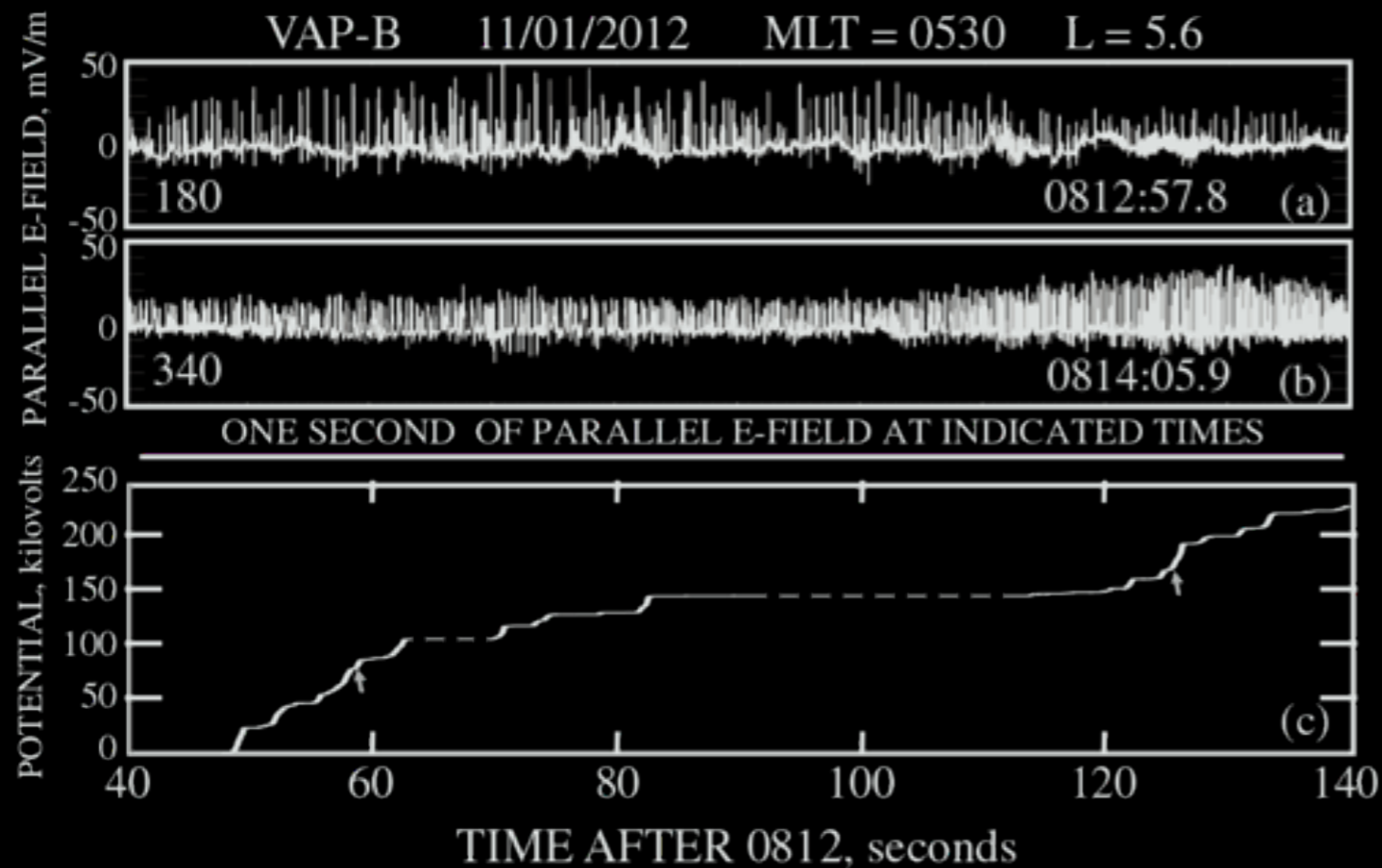


The Van Allen Probes unveiled several new and unanticipated structures, discovered new energization processes, and revealed the critical importance of dynamic hot plasma injections, which radically changed our understanding of Earth's inner magnetosphere and radiation belts.

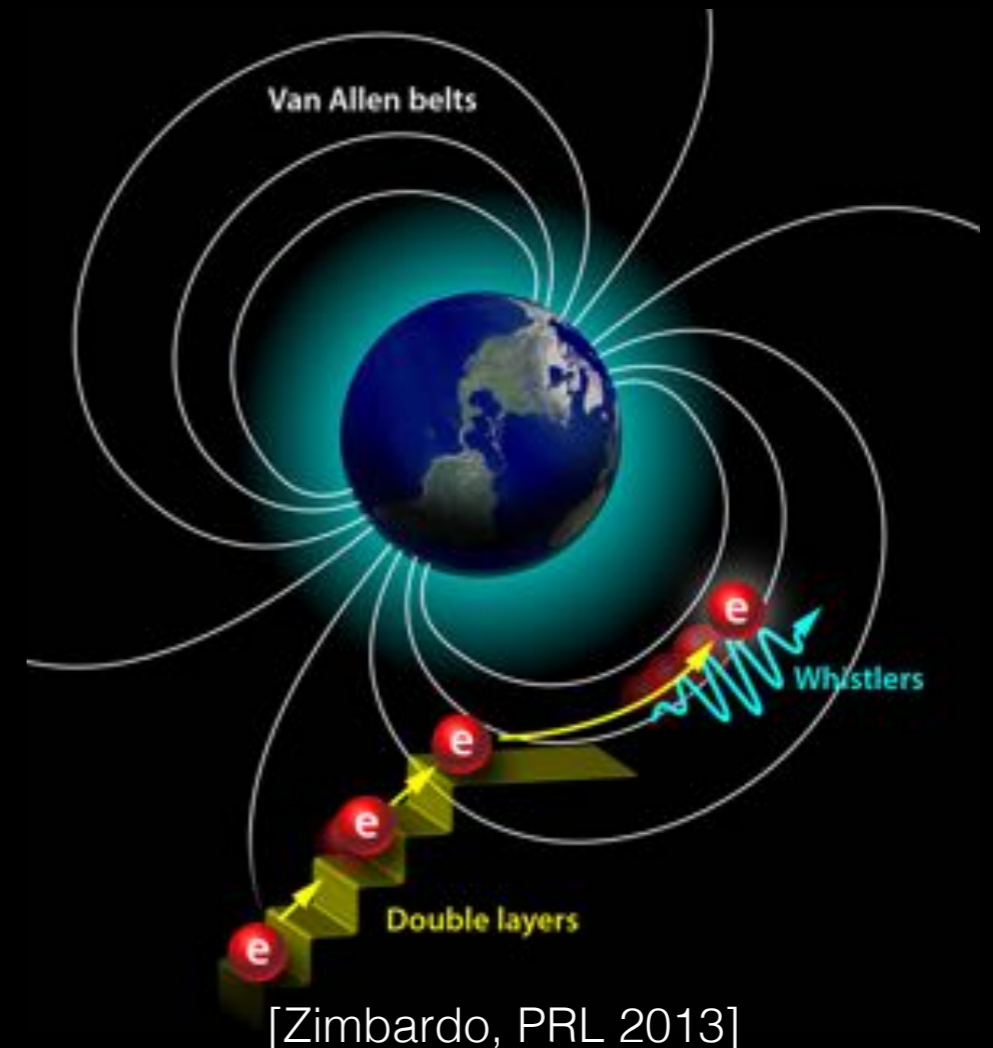


# Double Layers - New Rapid Acceleration Mechanism

*Unprecedentedly high data rate burst mode & “scientist in the loop” approach*



[Mozer et al., 2013; 2014; 2015; 2016]



[Zimbardo, PRL 2013]

About 7000 double layers were observed in one minute. Each double layer is detected as an electric field spike of a duration of  $\sim 0.45$  ms and a potential step of about 30 V. The double layers propagate along the magnetic field lines at 3100 km/s, the speed of an electron acoustic wave that can exist in a plasma containing both hot and cold electron populations.

Electron acceleration can be described as a two-step process: first, electrons are accelerated to keV energy by the potential drop due to streams of double layers. Once they have enough energy, they can interact resonantly with whistler waves and be quickly accelerated to MeV energies.

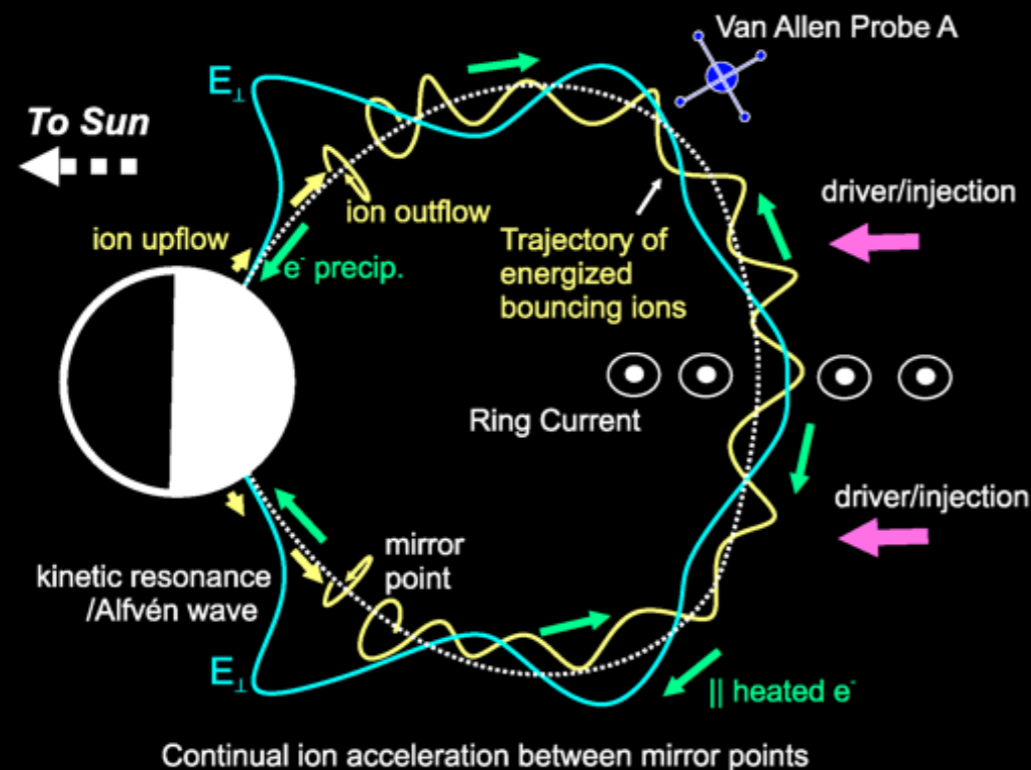
# Kinetic Alfvén Waves (KAWs)

*Newly discovered prevalent wave activity deep in the the inner magnetosphere*

Van Allen Probes observed large-amplitude KAWs in association with plasma injections [Chaston et al., 2015a] and shock-induced magnetopause compressions [Malaspina et al., 2015].

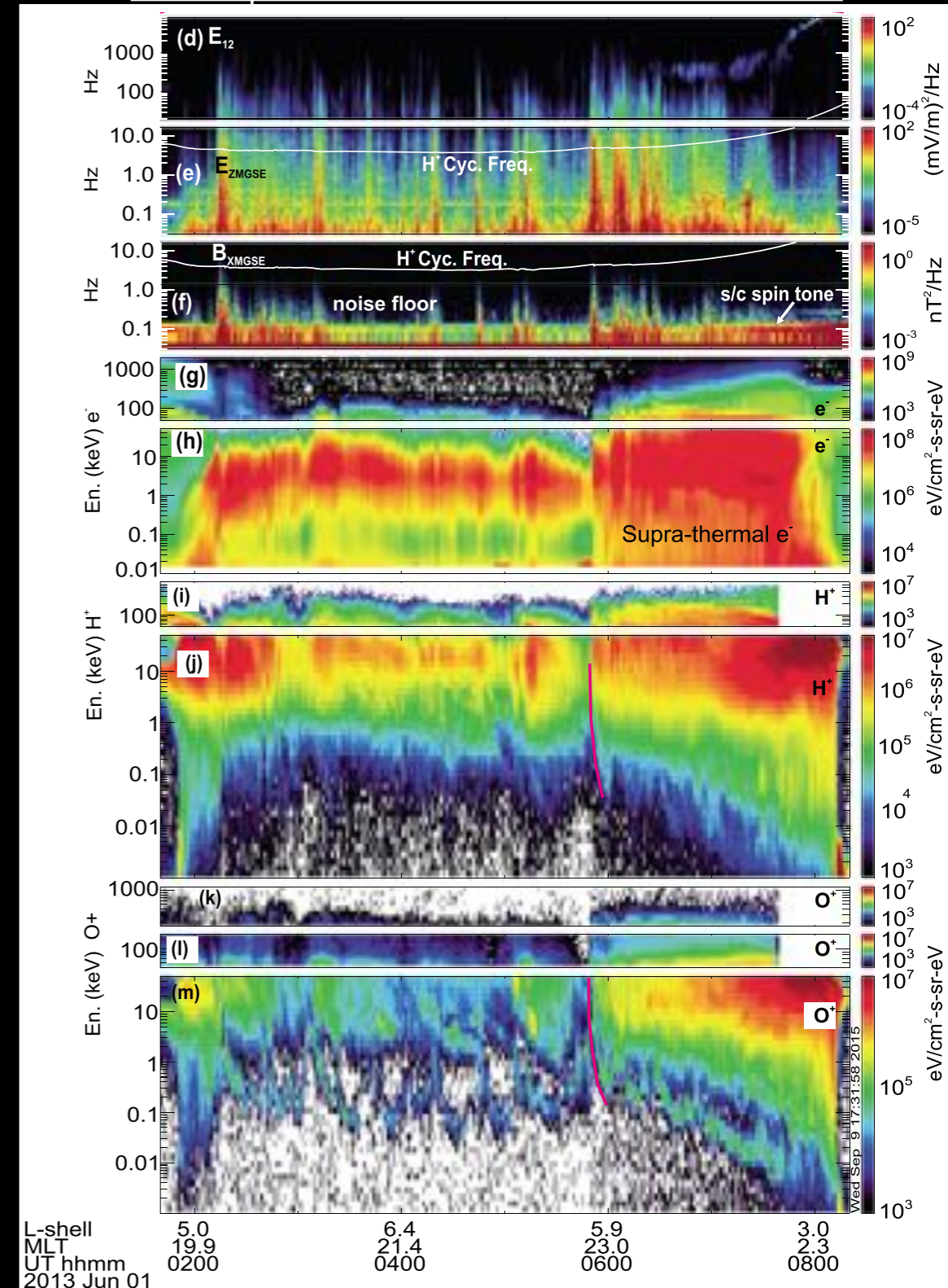
KAWs can dramatically affect relativistic electron and energetic ion populations by:

- Pitch-angle scattering and atmospheric loss of MeV electrons
- Multiple-bounce acceleration of ring current ions to >50 keV
- Field-aligned heating of thermal electrons to 1 keV



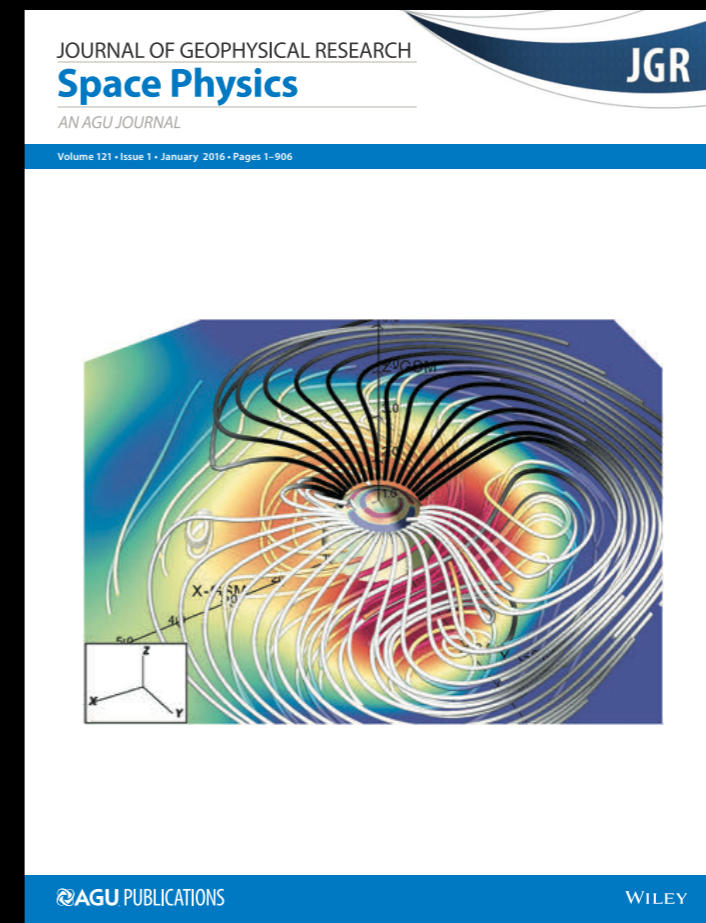
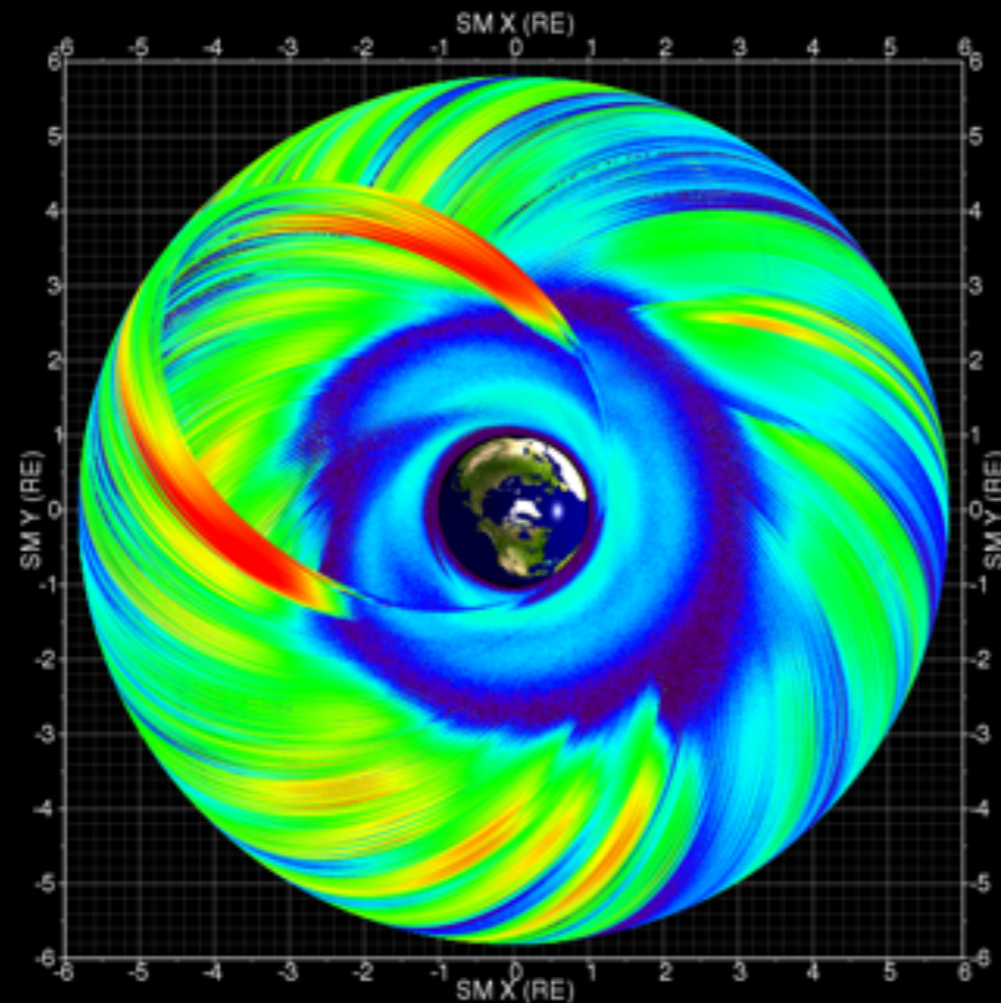
[Chaston et al., 2015b]

Main phase of 1 June 2013 storm



# Comprehensive Dynamics-Configuration Sampling - Systemwide Understanding & Predictability

*Almost 4 yr, 2x full MLT coverage, >65 geomagnetic storms*

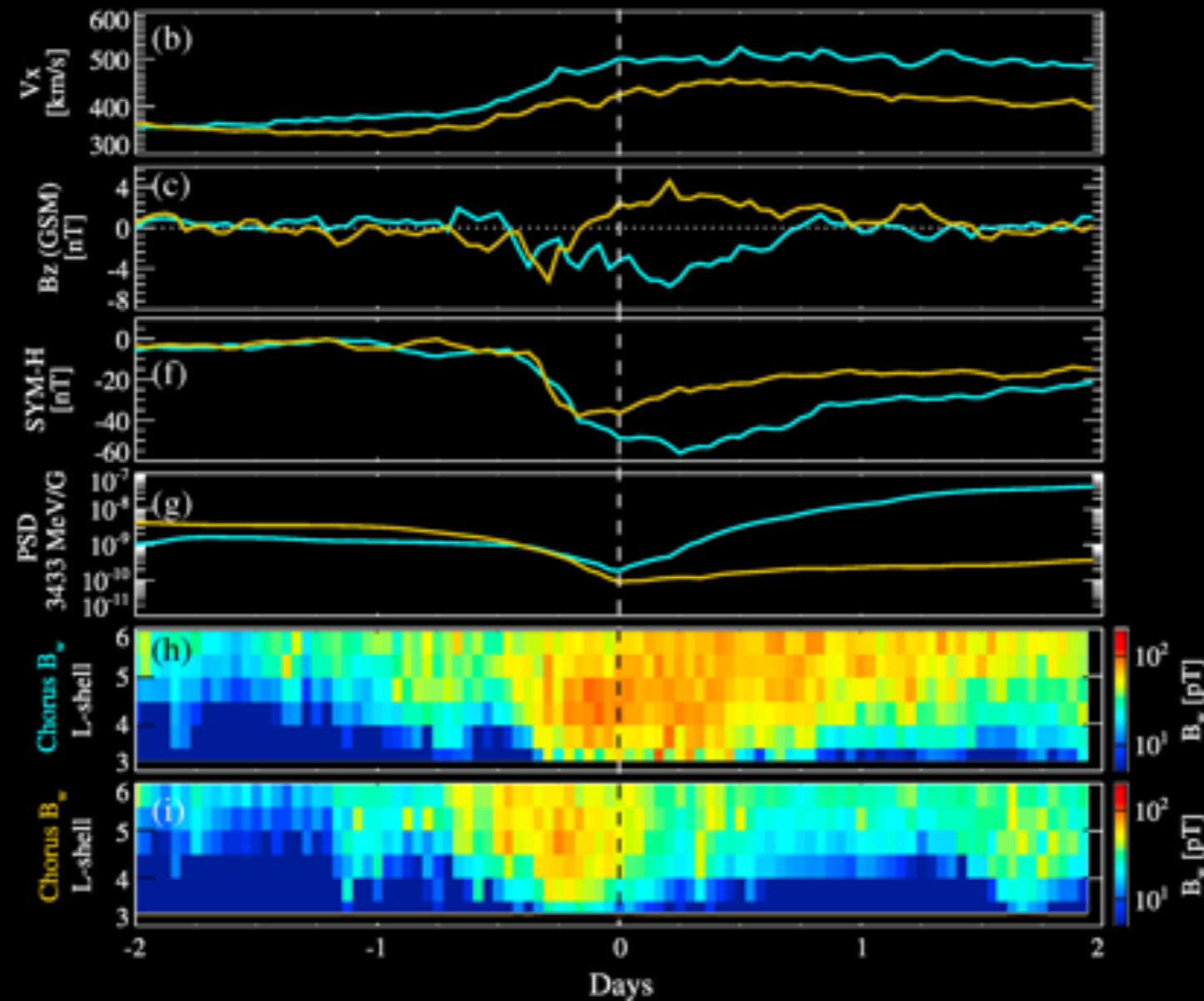


[Stephens et al., 2016]

Over past 4 years the Van Allen Probes lines of apsides made 2 full circles around Earth providing comprehensive measurements of the inner magnetosphere over more than 65 geomagnetic storms. This unprecedented dynamics-configuration sampling enabled: (1) major development of key empirical models; (2) unveiling the the solar wind drivers of the radiation belt activity critical for the development of predictive models.

# Solar Wind Drives of Radiation Belt Dynamics

*Superposed epoch analysis of 2.5 yr of the RBSP data identified key solar wind drivers of relativistic electron acceleration*

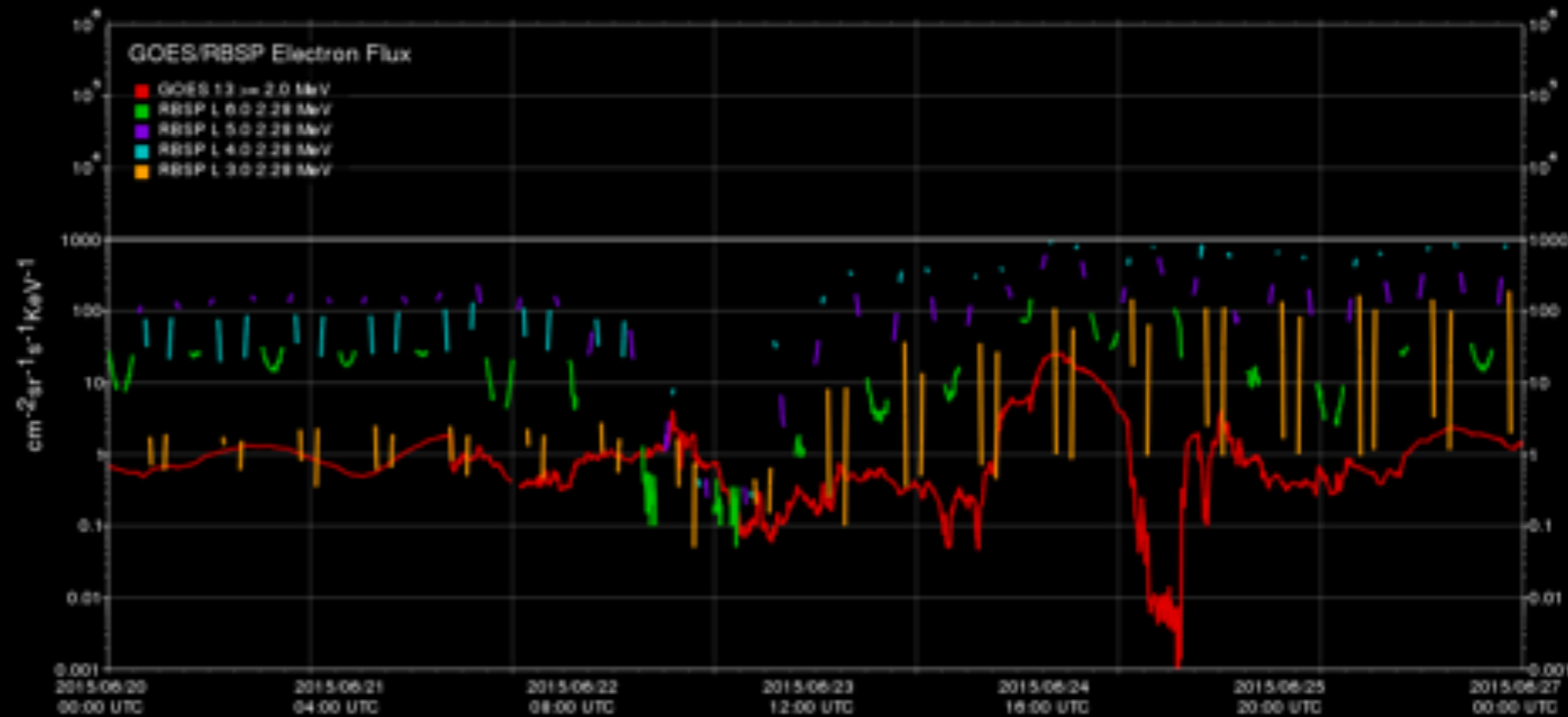
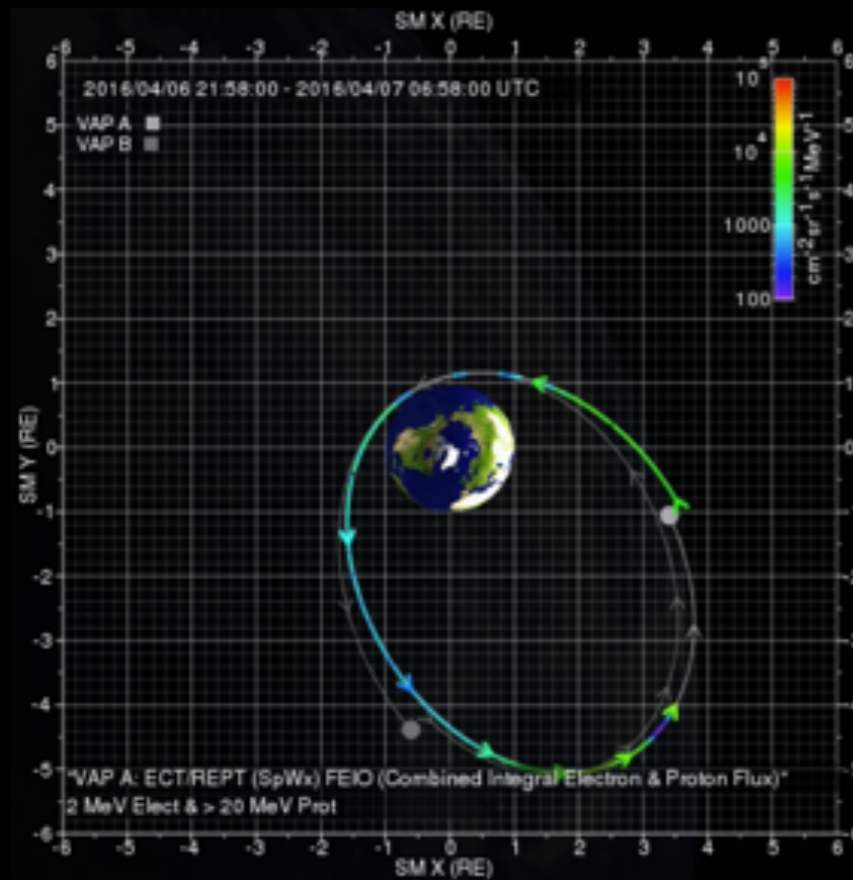


[Li et al., 2015]

- (1) Prolonged southward  $B_z$ : enhanced magnetospheric convection, seed population
- (2) High solar wind speed: ULF activity, radial transport and acceleration
- (3) Low SW dynamic pressure: no magnetopause losses
- (4) Enhanced chorus activity: local acceleration

# Real Time SpWx Data from Radiation Belts

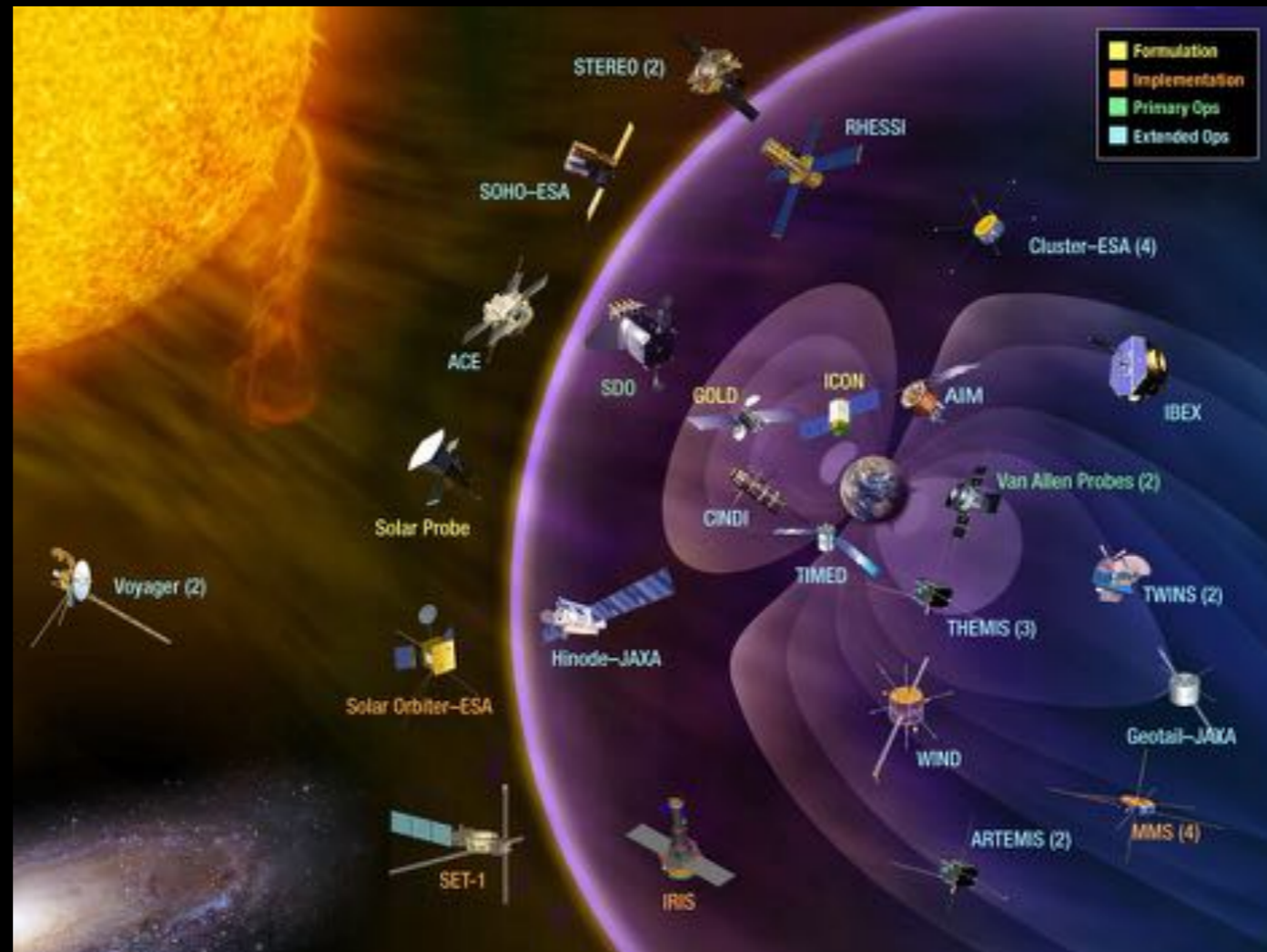
*Predict the response of the radiation belts to solar storms to protect space assets in the near-Earth space*



*Van Allen Probes near-real-time data products soon to be re-broadcasted by NOAA SWPC*

- All instruments continuously broadcast a subset of their science data in real time
- Van Allen Probes partners with three foreign institutions who operate ground stations that receive the broadcast:
  - Korea Astronomy and Space Science Institute (KASI)
  - Institute of Atmospheric Physics, Czech Republic
  - National Commission for Space Activities (CONAE), Argentina
  - National Institute of Space Research (INPE), Brazil
- The data are collected and processed at APL and then disseminated via Science Gateway tools

# Van Allen Probes Central Place in HSO



- Perfectly positioned in the inner magnetosphere to observe the causal link in the chain from the Sun to the Earth.
- Exquisitely complete particle and fields observation capabilities. Real-time space weather data.
- Measures global distributions of high-energy electrons and ions over 2-4 hr.
- Missions observing solar influences (ACE, SDO, Wind, MMS), magnetotail connections (THEMIS, MMS), as well as other inner magnetosphere aspects (TWINS), all participate in Van Allen Probes Science.

# Science Gateway

<http://rbspgway.jhuapl.edu>

The screenshot shows the 'Van Allen Probes SCIENCE GATEWAY' website. At the top, there is a navigation bar with links: GATEWAY HOME, MISSION HOME, SPACE WEATHER, DATA, INSTRUMENTS, ANALYSIS, ORBIT TOOLS, and GENERAL. A 'Logout' button is visible in the top right corner. Below the navigation bar, there is a search bar and a 'VIEW RESULTS' button. The main heading is 'SCIENCE GATEWAY: OVERVIEW'. A descriptive paragraph states: 'The Science Gateway provides access to data, models, software and tools in support of the Van Allen Probes mission for researchers, students and the general public.' Below this, there is a row of eight interactive tool thumbnails: 'Orbit Plot', 'Space Weather', 'Spectrograms/Line', 'L-Shell Plots', 'Orbit Context', 'ASCII Orbit List', 'Bibliography', and 'SOC Links'.

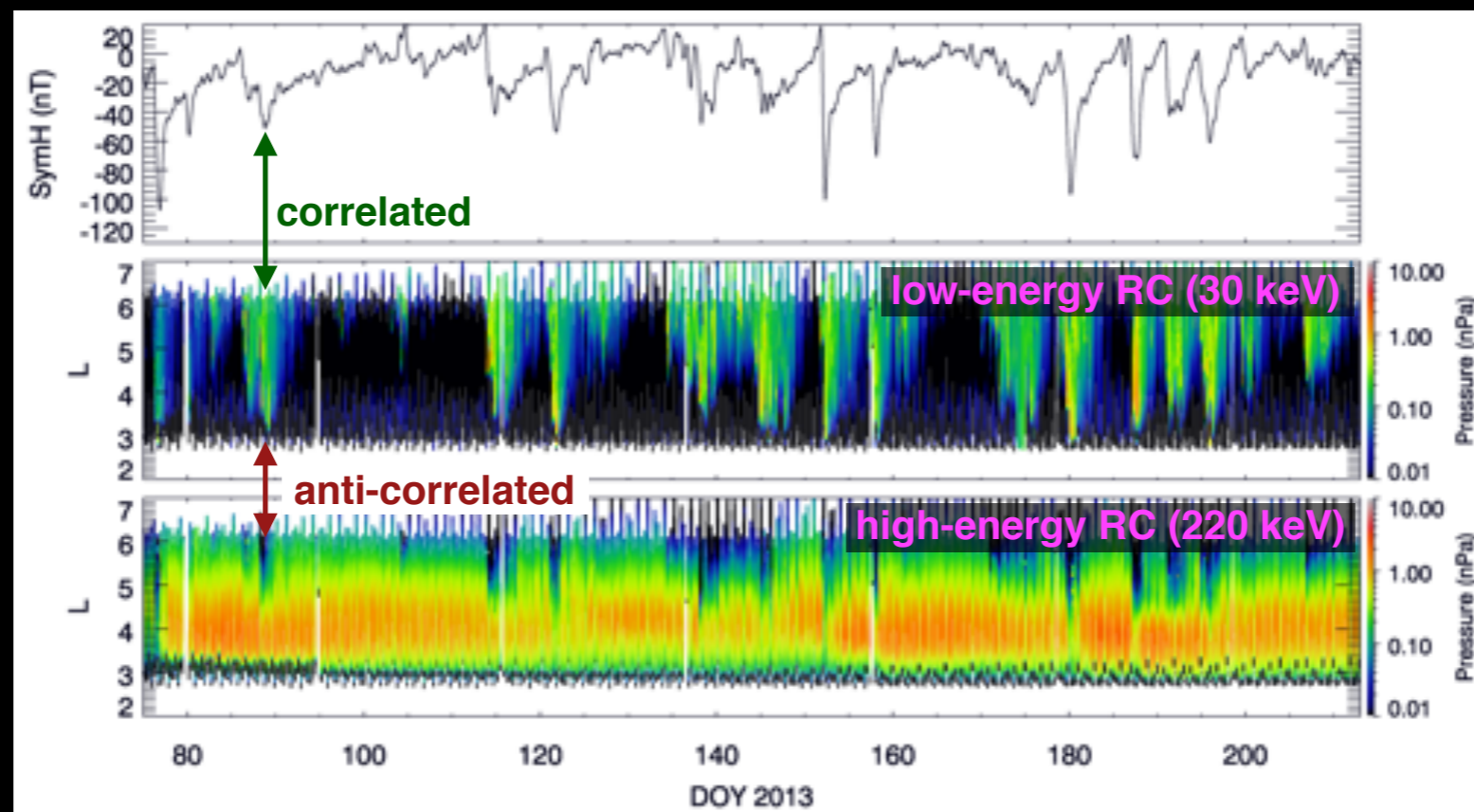
- Interactive plotting of all high-level data products from all instrument teams
- Digital data download (CDF)
- Latest (TS07D) magnetic field model, magnetic ephemeris, and adiabatic invariants
- SpWx data
- Multi-mission orbit tools
- Bibliography

Backup Slides



# High-Energy Ring Current

*RBSPICE* revealed persistent ring current attributed to high-energy protons



[Gkioulidou et al., 2016]

The magnitude and the phase of geomagnetic storms are quantified with the ground-based Sym-H index, which had been associated with the strength of the near-Earth ring current carried by energetic (keV) ions injected from the magnetotail by large-scale electric fields (convection).

High-resolution wide-energy-range ion measurements by RBSPICE provided long-term tomographic reconstruction of the energy composition of the ring current.

It showed that while the lower-energy (<80 keV) component is highly correlated with Sym-H and varies on the timescale of magnetospheric convection, the higher energy component (>100 keV) is anti-correlated with Sym-H and varies on much longer timescales similar to radiation belt electrons.

High-energy ring current persists and grows in quiet time after the storm decay to energy levels comparable to the energy of the total storm-time current.

# Van Allen Probes Reveal the Structure of Electric Currents in the near-Earth Space

Empirical models based on *in situ* magnetic field measurements from past and present spacecraft missions provide a robust framework for modeling and forecasting storm-time electrodynamics of Earth's magnetosphere.

Van Allen Probes addition to the HSO dramatically increased the sampling of the inner magnetosphere. Magnetic field measurements collected by the Probes provided the first data-derived reconstruction of the three-dimensional current system inside  $4 R_E$ , which could not be resolved with the data from previous missions.

JGR (vol 121) cover shows a data-derived reconstruction of the inner magnetosphere-ionosphere current system from [Stephens et al., 2016].

