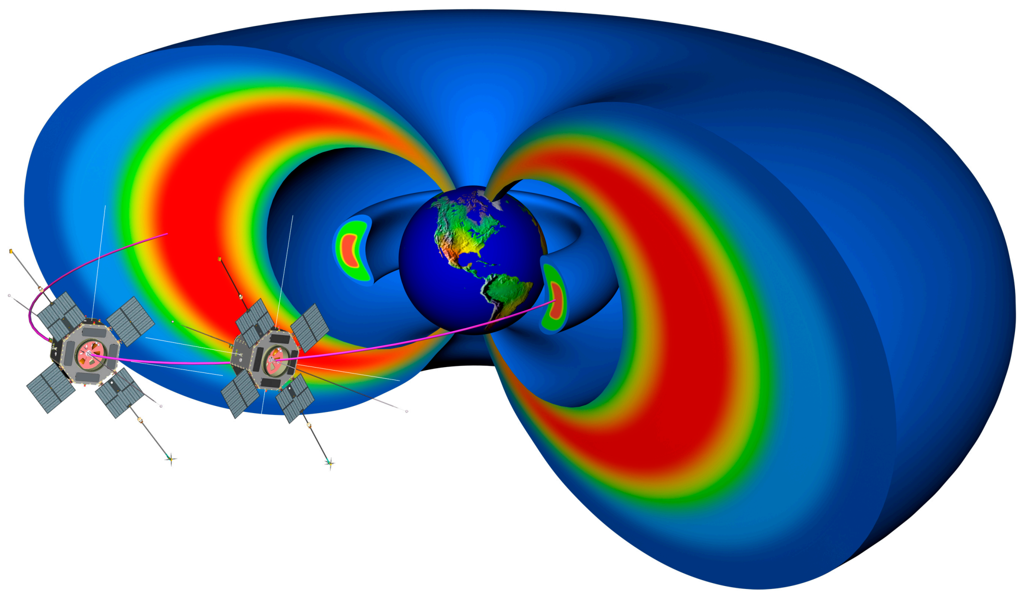
Van Allen Probes:
Motivation, Science, and Mission Design



David G. Sibeck
Mission Scientist
NASA/GSFC

Acknowledgements: JHU/APL Project Science team and SWG members

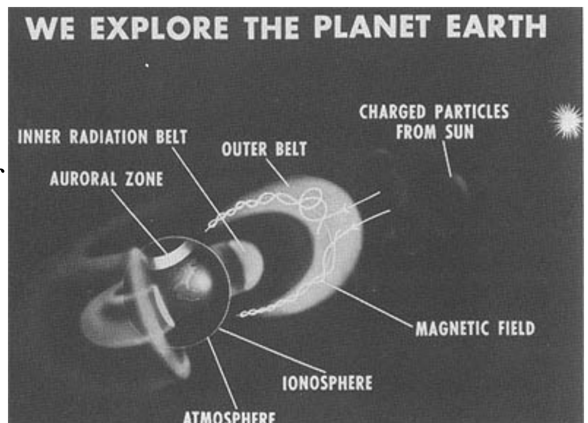
Outline

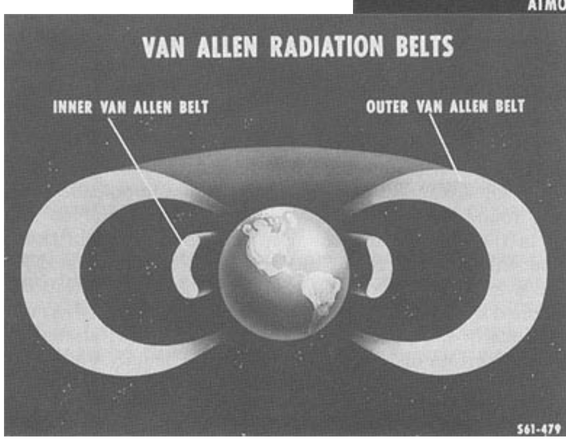
- Discovery of the radiation belts
- Motivation: Mapping a hazard, trying to predict
- Science objectives and Van Allen Probes mission design
- Research Results

Van Allen's Discovery of Radiation Belts

- Put space physics in the news…

Artistic images of Van Allen belts, NASA/Langley, circa 1961





Cover of TIME in '59 and '64

A Series of Spaceflights…

Mission	Date	Perigee/Apogee	Inclination
Sputnik-1	10/27/1957	215 x 939 km	65.1

Radio Beacons at 20.005 and 40.01 MHz,
but no Geiger-Mueller Tube.

A Series of Spaceflights…

Mission	Date	Perigee/Apogee	Inclination
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Sputnik-2	11/3/1957	212 x 1660 km	65.33

Had a Geiger-Mueller Tube, but no tape recorder, so only saw the radiation belts, at times when USSR could not receive a signal. Australians and S. Americans received the signal but didn't know they were receiving observations of radiation belts.

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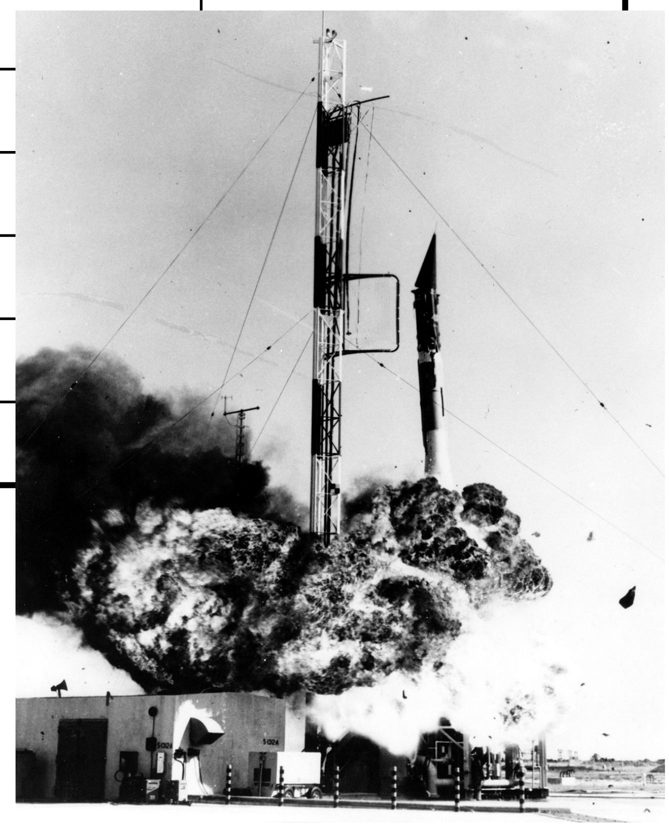

Explosion was televised live. Not good. Satellite was thrown clear and is in the Smithsonian Museum

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Explorer-1*	1/31/1958	358 x 2550 km	33.24 inner
Explorer-2	3/5/1958	Failed	Failed
Vanguard-1	3/17/1958	654 x 3969 km	34.25
Explorer-3**	3/26/1958	186 x 2799 km	33.38 inner
Sputnik-3***	5/15/1958	217 x 1864 km	65.18 outer
Explorer-4**	7/26/1958	263 x 2213 km	50.3 inner

*Geiger-Müller tube (Ep > 30 MeV, Ee > 3 MeV saturated above 2000 km)

**Geiger-Müller tube and tape recorder- observed natural radiation belts

***Tape recorder failed so couldn't map belts

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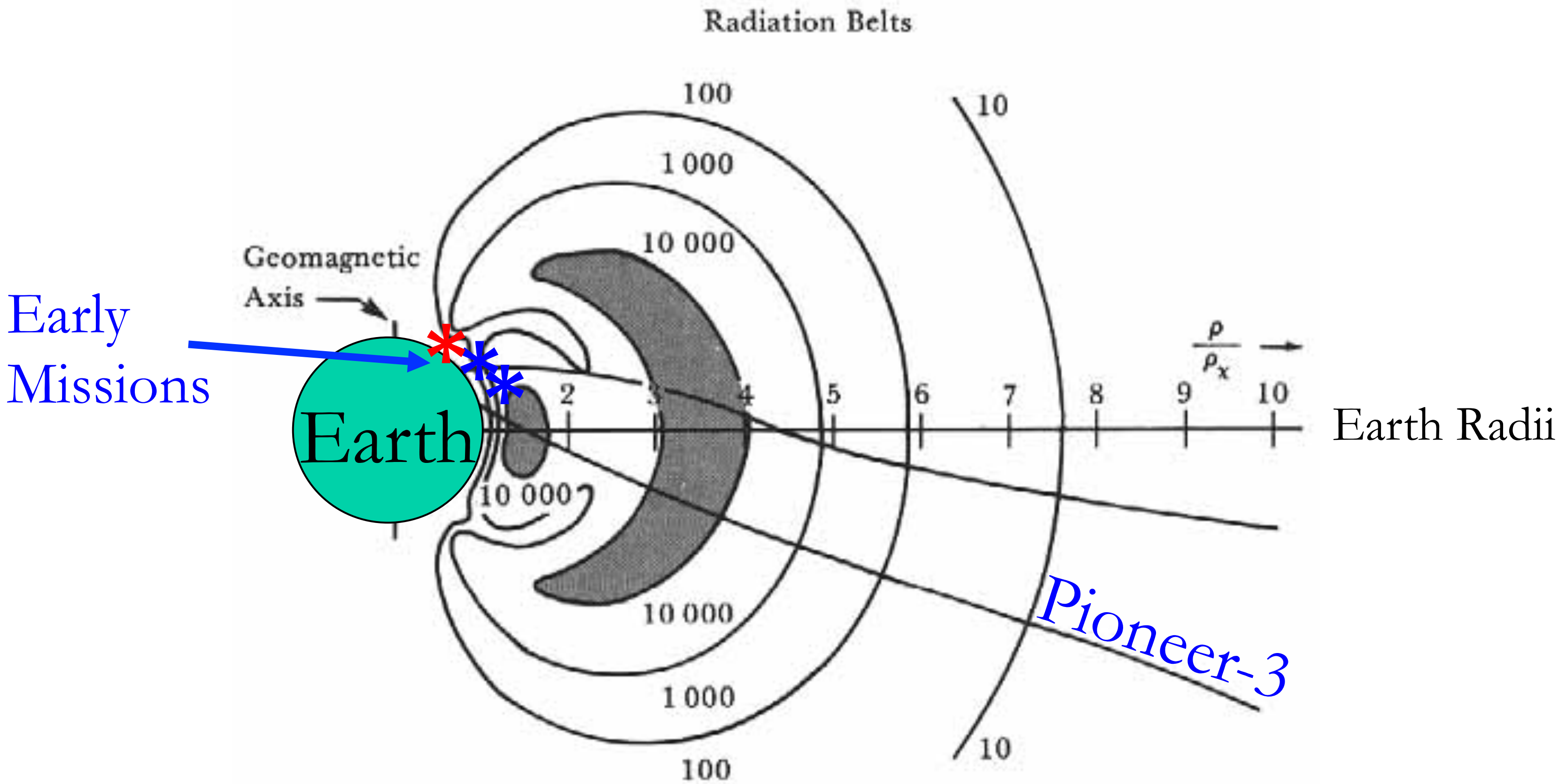
…led to the Discovery of Two Natural Radiation Belts…



- Pioneer 3, launched December 6, 1958, failed to reach the Moon, but flew through both the inner, outer radiation belts and showed they are separated by an empty slot.

…and Man-Made Radiation Belts

Event	Location	Date	Yield	Altitude	Decay
Argus I*	S. Atlantic	8/271958	1 kt	200 km	weeks
Argus II*	S. Atlantic	8/301958	1 kt	240 km	weeks
Argus III*	S. Atlantic	9/6/1958	1 kt	540 km	weeks
Starfish**	Johnston Is.	7/9/1962	1.4 Mt	400 km	~1 year, maybe longer
USSR #184	Kap. Yar	10/22/1962	300 kt	290 km	1 month
USSR #187	Kap. Yar	10/28/1962	300 kt	150 km	1 month
USSR #195	Kap. Yar	11/1/1962	300 kt	59 km	1 month

* Observed by Explorer IV

**Observed by Ariel I, Injun, Telstar I, Traac

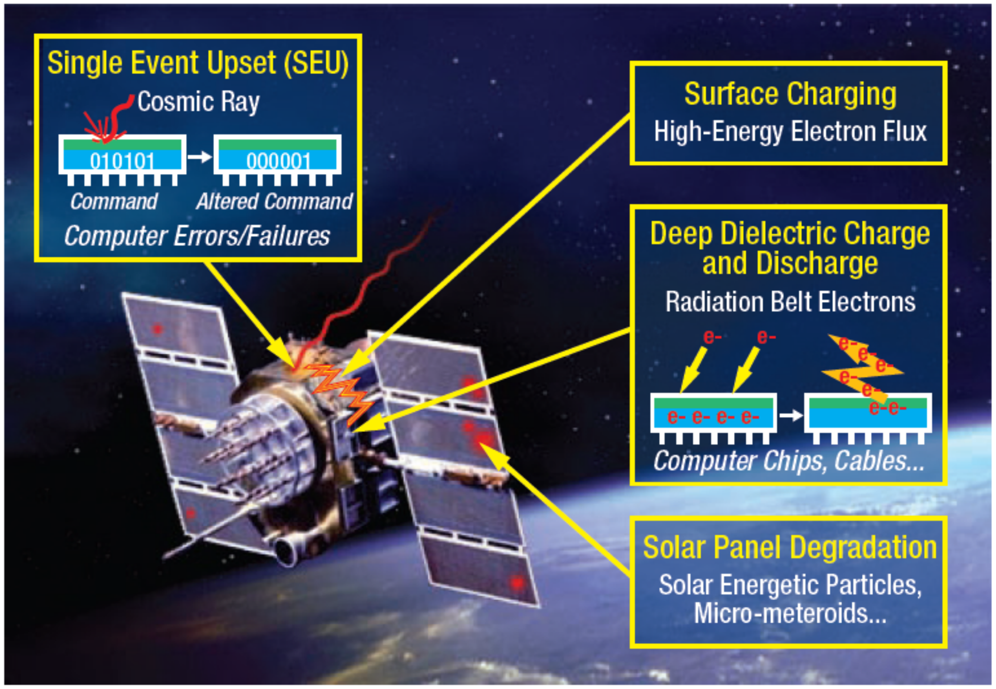
Hess, GSFC, 1964; Hoerlin, LANL, 1976

Van Allen, UI 1963

solar cell damage crippled 1/3 spacecraft in orbit

Radiation Belt Effects

- Spacecraft in the radiation belts suffer
  - •Single event upsets
  - •Surface charging
  - •Deep dielectric charge and discharge
  - •Solar panel degradation
- Information concerning radiation belt conditions help design spacecraft and determine mission lifetimes



Space radiation can produce electrical discharges from differential surface charging inducing large and damaging pulses into spacecraft electrical systems. Higher energy electrons penetrate vehicle surfaces and lead to discharges from charged dielectrics or floating conductors. Highly ionizing particles affect microelectronics, inducing bit-flips in memories, transients, and catastrophic latchup. Materials degrade due to total radiation dose. Further, the very high-energy protons of the inner belt pose health hazards to astronauts and flight crews in high-altitude aircraft.

(after Onsager et al.)

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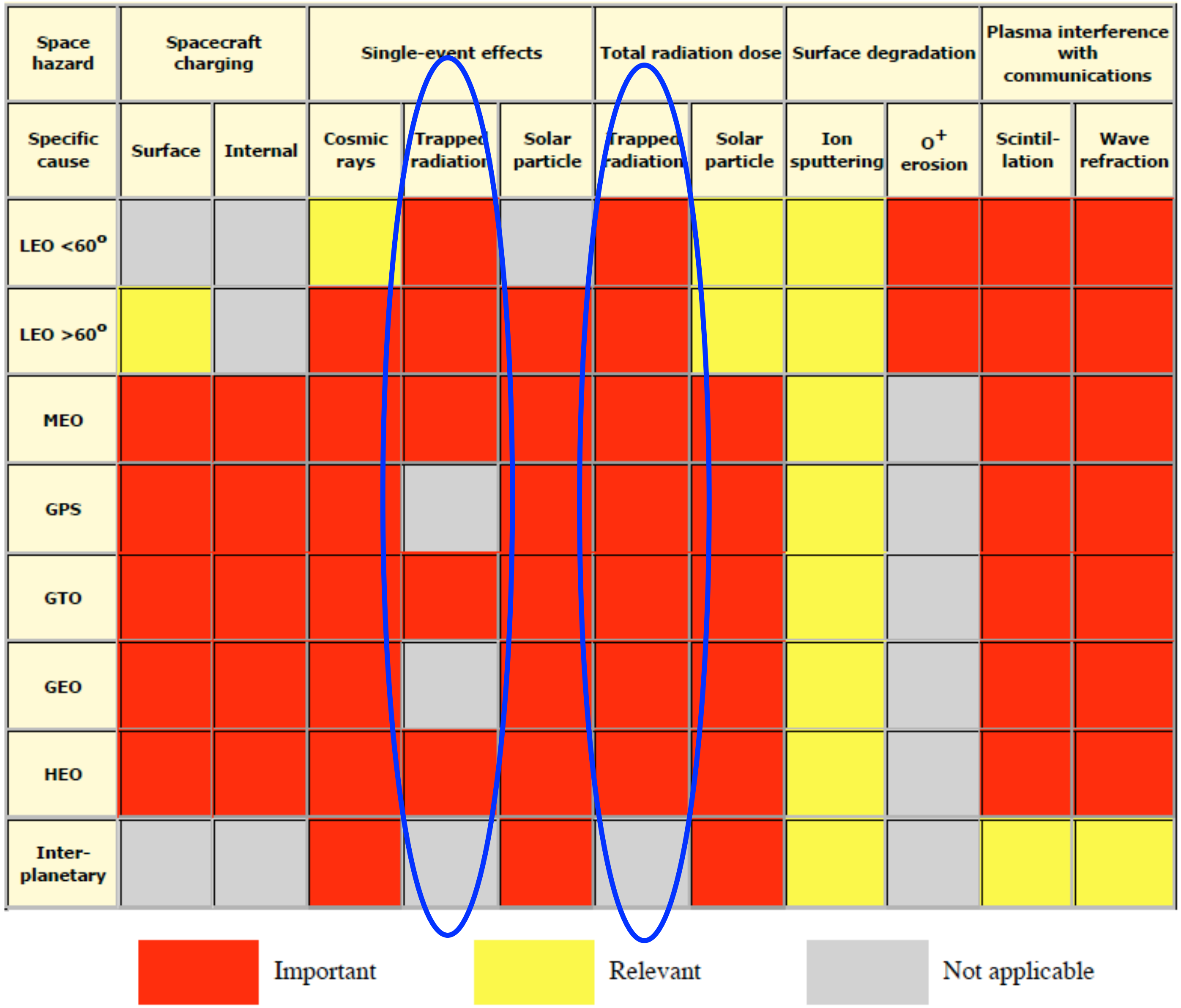
Space Environment Hazards



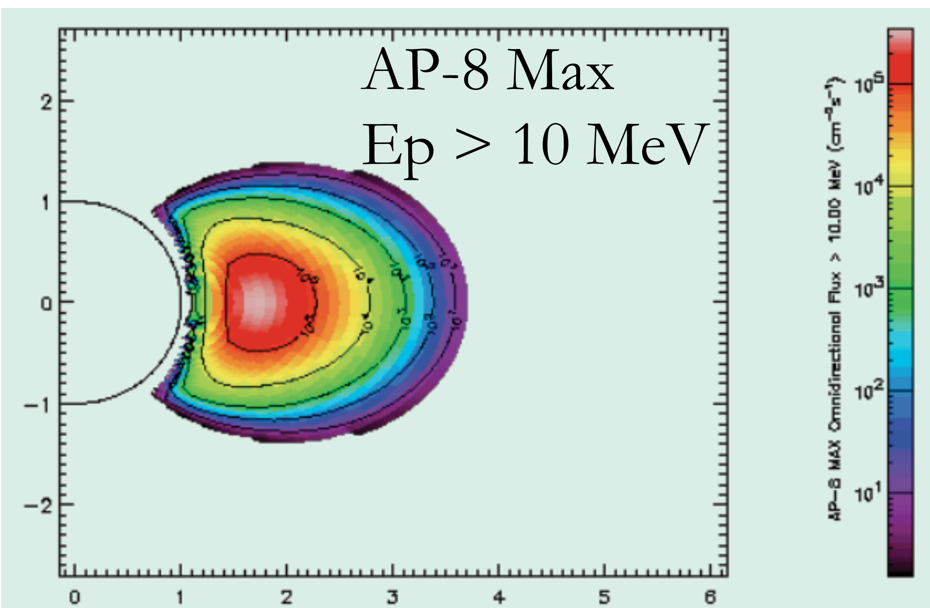
Space environment hazards for typical orbits. Key: LEO <60°—low Earth orbit, less than 60 degrees inclination; LEO >60°—low Earth orbit, more than 60 degrees inclination; MEO—medium Earth orbit; GPS—Global Positioning System satellite orbit; GTO—geosynchronous transfer orbit; GEO—geosynchronous orbit; HEO—highly elliptical orbit; O^+—atomic oxygen.

Compiled by Mazur, Aerospace http://www.aero.org/publications/crosslink/summer2003/02.html

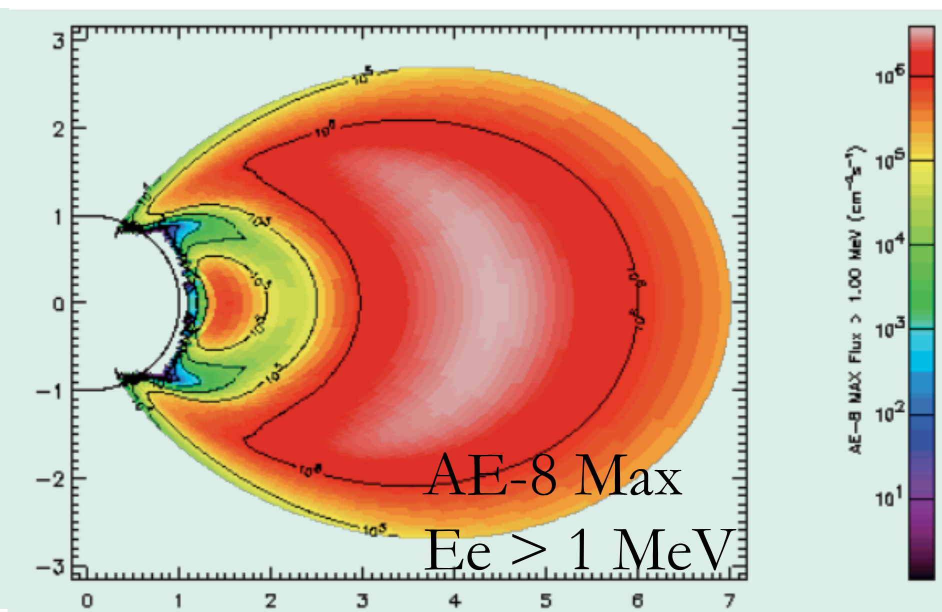
Static Models for the Radiation Belt: AP-8 and AE-8 [Vette, GSFC, 1991]

Protons 0.1 < Ep < 400 MeV and Electrons 0.04 < Ee < 7 MeV

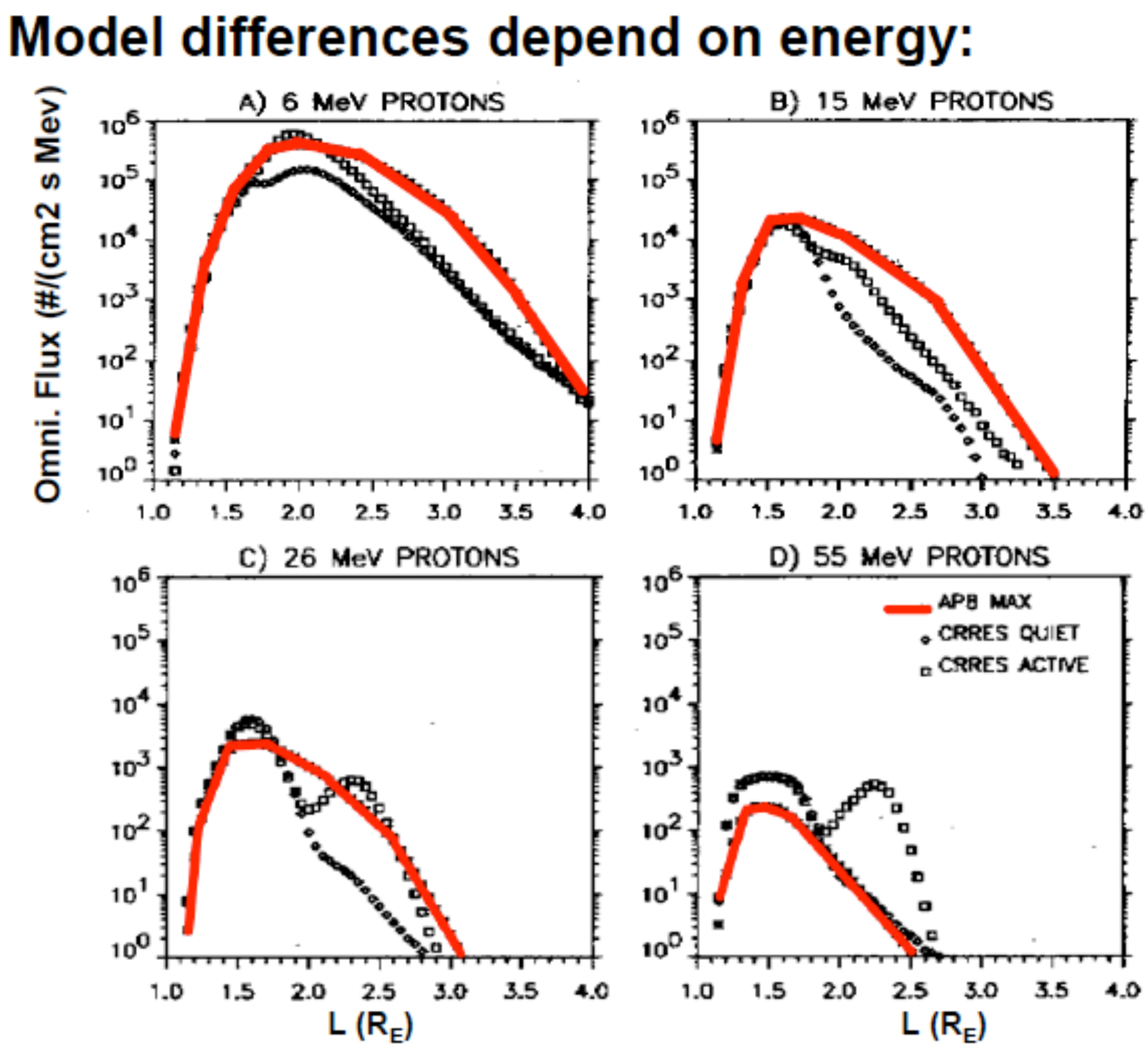
Inner Belt



Outer Belt

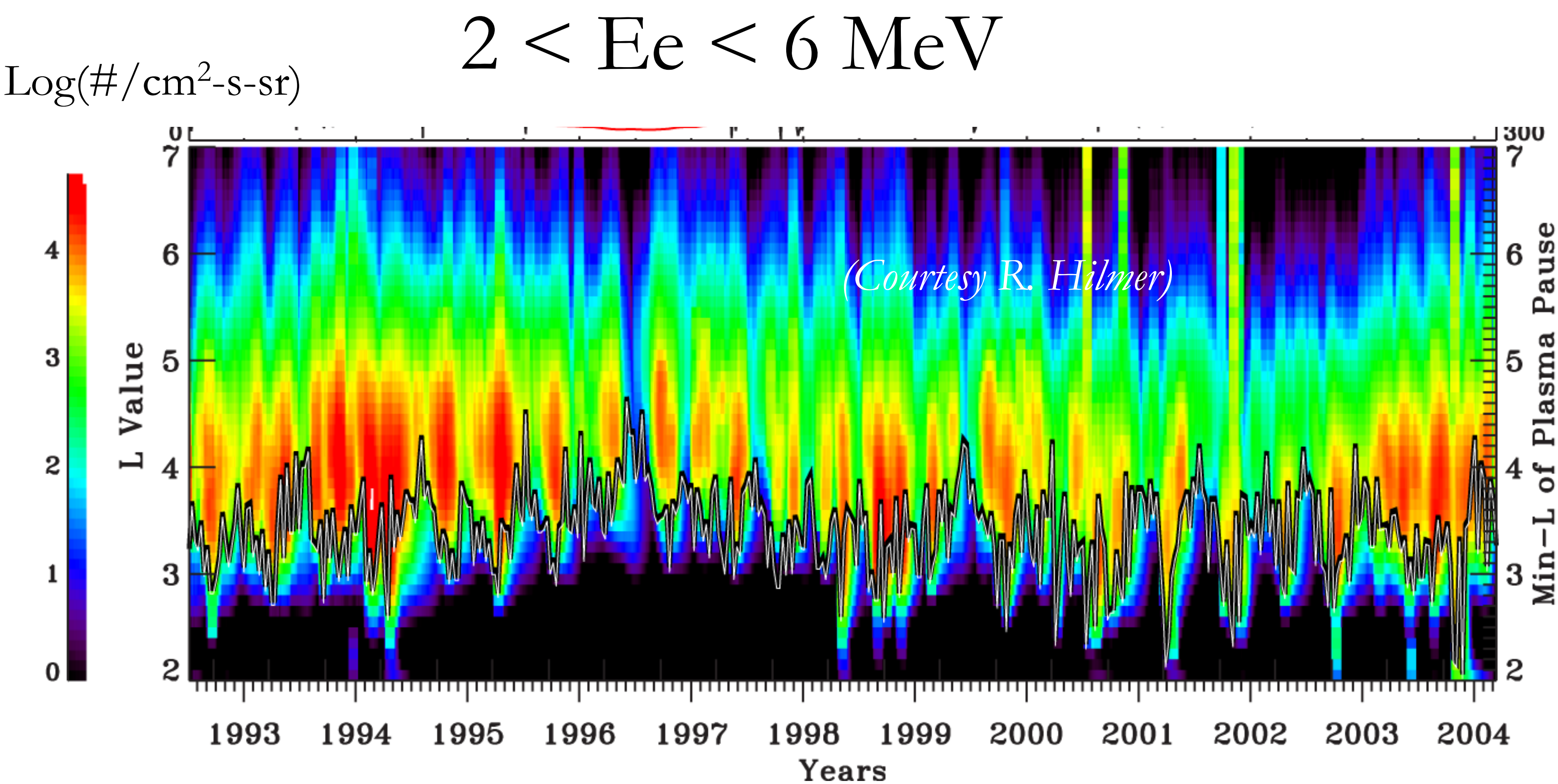


but models disagree…



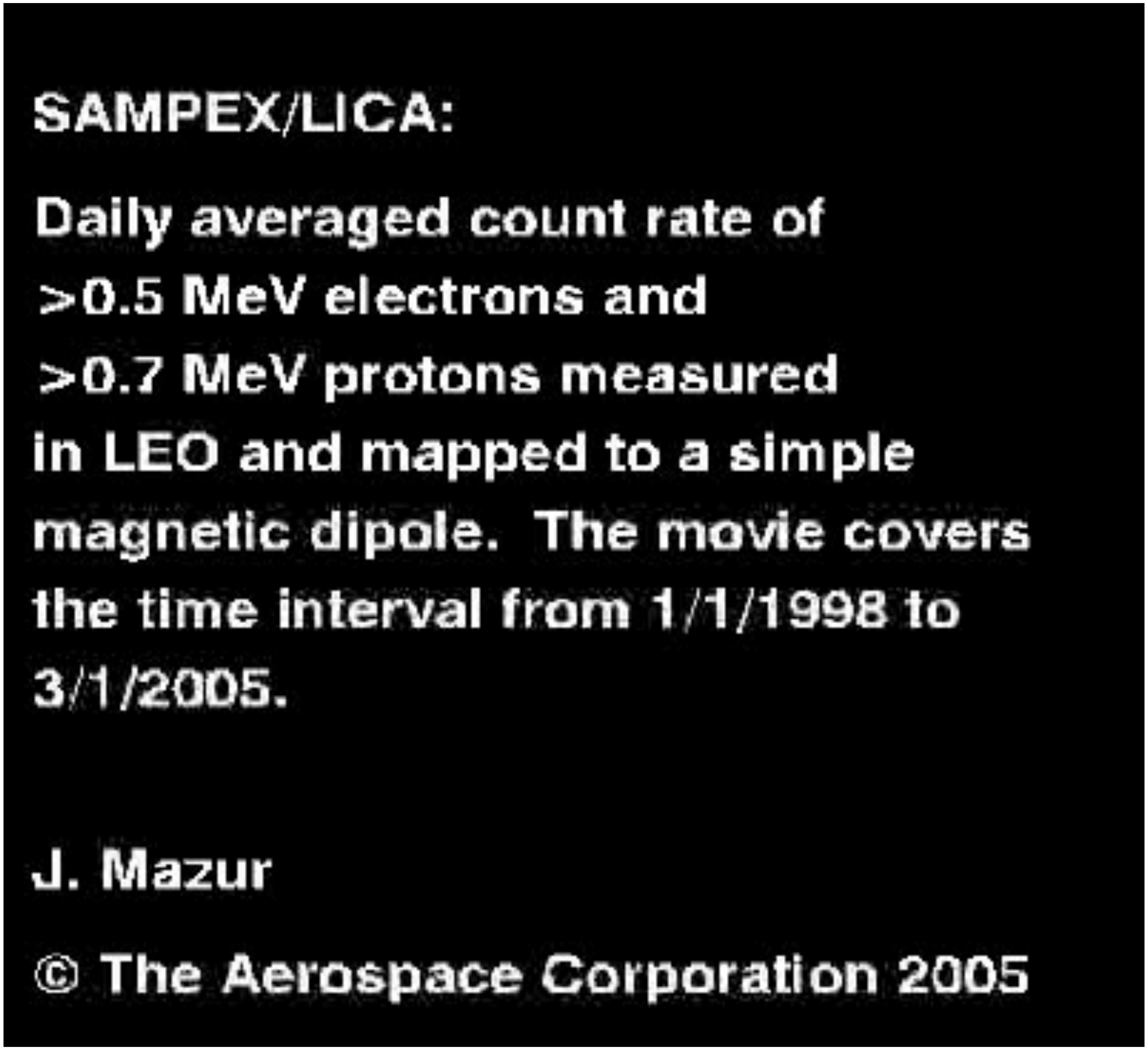
Guild et al. [2010]

and Radiation Belt Fluxes are not Static



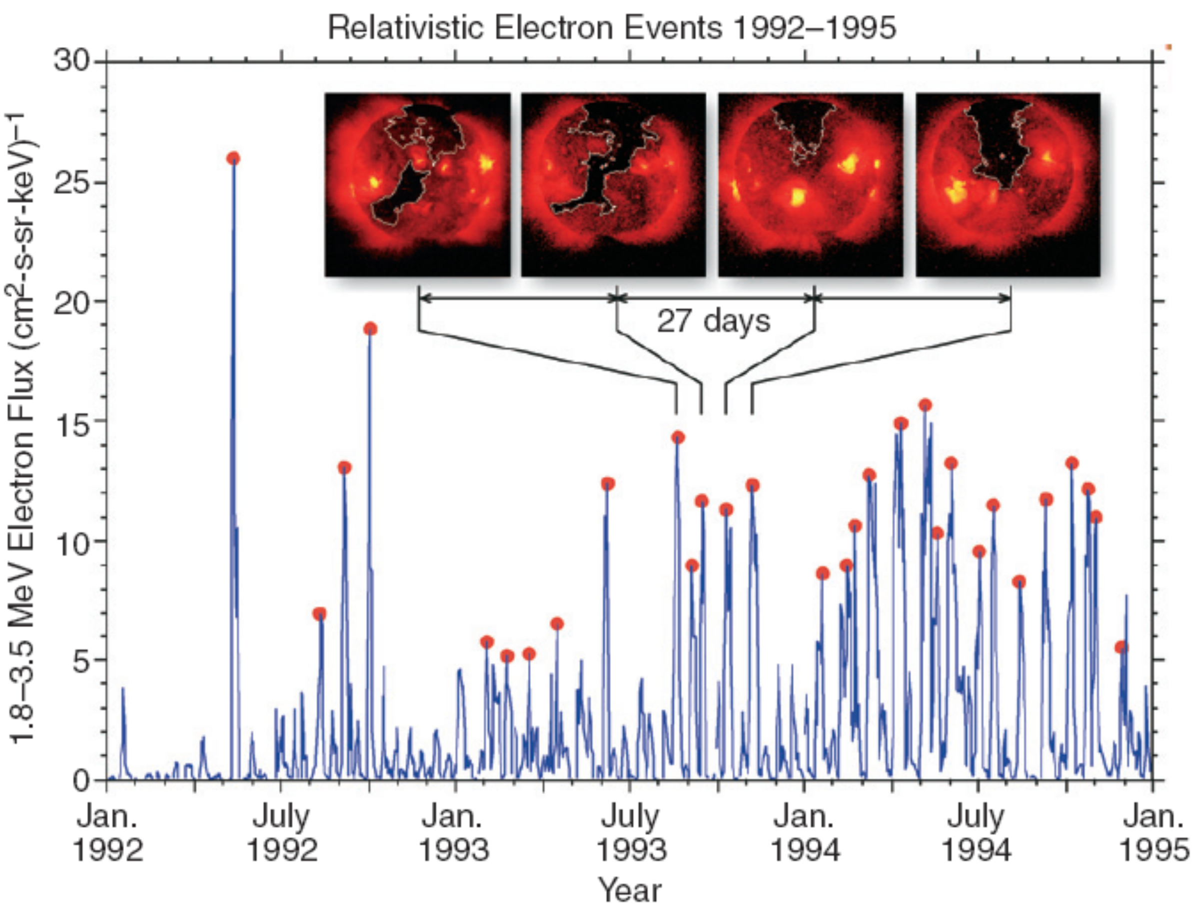
- **SAMPEX** (1992 - present) observed the low-altitude extensions of the radiation belts and revealed that radiation belt fluxes are far from static (X. Li)

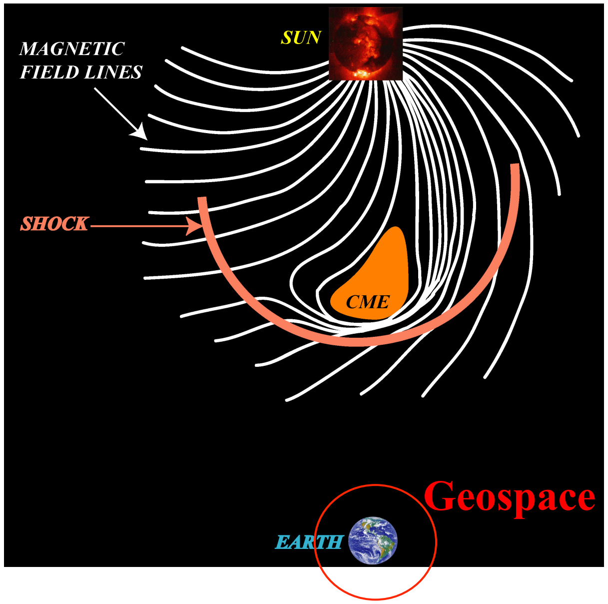
Radiation Belt Variability over 7 Years



(Movie courtesy Joseph Mazur, Aerospace)

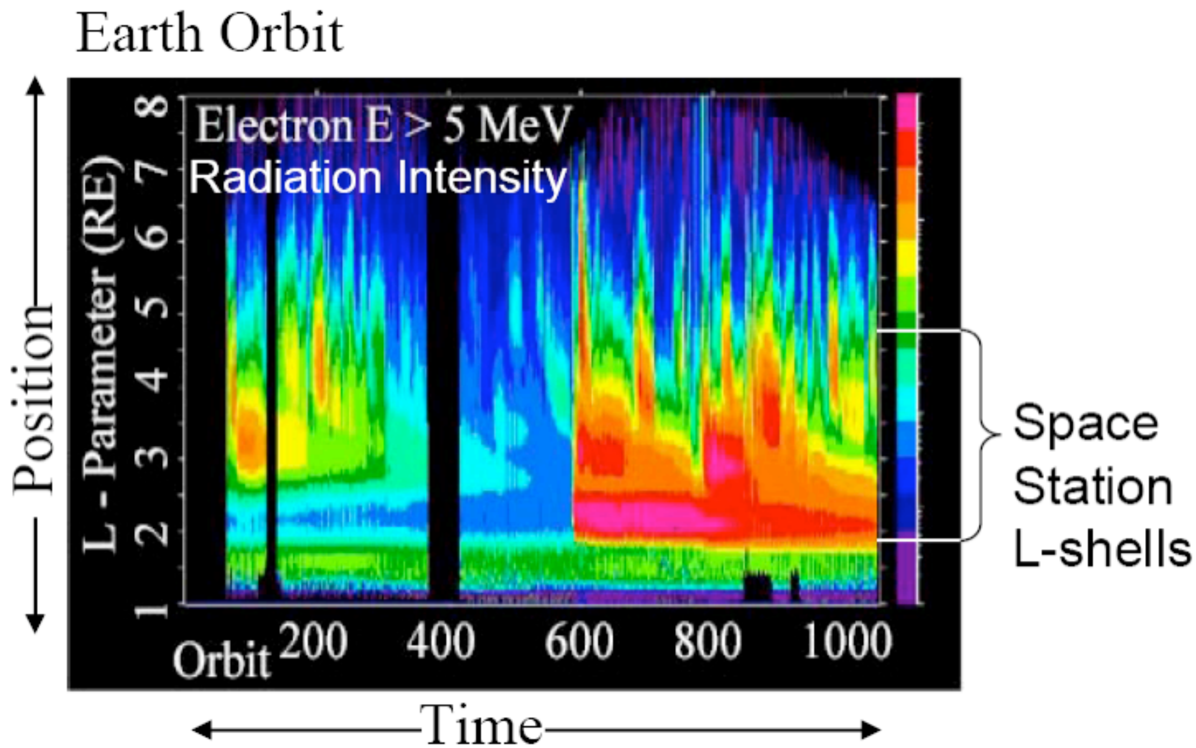
Some of the Variability is Predictable: Solar/Solar Wind Drivers





Geomagnetic storms and radiation belt enhancements are related to recurrent high speed solar wind streams [Reeves, 1998] and CMEs

Belts can Appear within Minutes



(1 Orbit = 590 min)

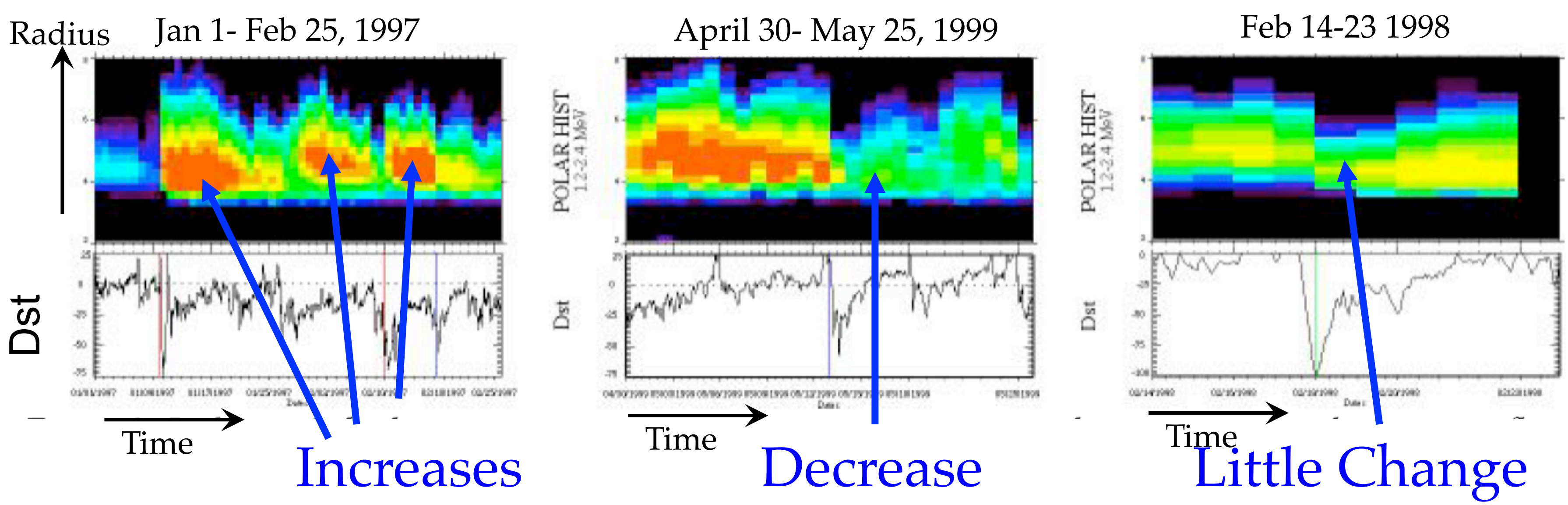
- CRRES observed the sudden creation of new radiation belts on March 24, 1991 [Blake et al., 1992]

- Related to an interplanetary shock slamming into the magnetosphere

Some Radiation Belt Responses are Unpredictable

Response of radiation belt electrons to geomagnetic storms
(measured by geomagnetic index Dst) cannot yet be predicted.

12-24 MeV electrons



We do not understand the fundamental physics: the response of acceleration and loss mechanisms to solar-induced geomagnetic storms

Reeves et al., 2003.

Van Allen Probes Objectives

- **The primary science objective of the Van Allen Probes mission is to provide understanding, ideally to the point of predictability, of how populations of relativistic electrons and penetrating ions in space form or change in response to variable inputs of energy from the Sun.**

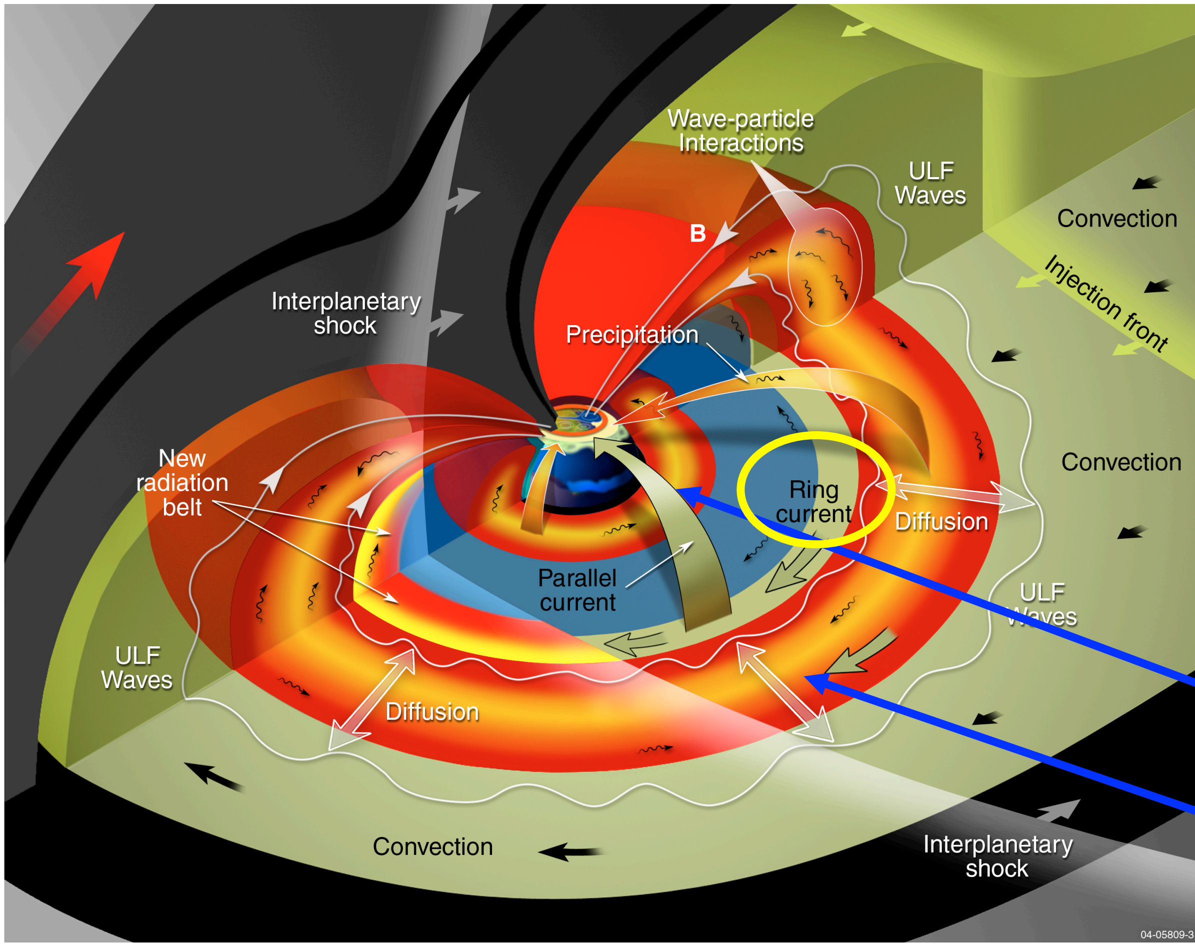
- Three overarching science questions:

  - 1. Which physical processes produce radiation belt enhancement events?

  - 2. What are the dominant mechanisms for relativistic electron loss?

  - 3. How do ring current and other geomagnetic processes affect radiation belt behavior?

Earth's Radiation Belts:
A Complicated Interplay of Many Processes



Creation and variation of radiation populations result from a complicated interplay of processes.

A broad range of simultaneous measurements is needed to sort them out

<u>Van Allen Belts</u>

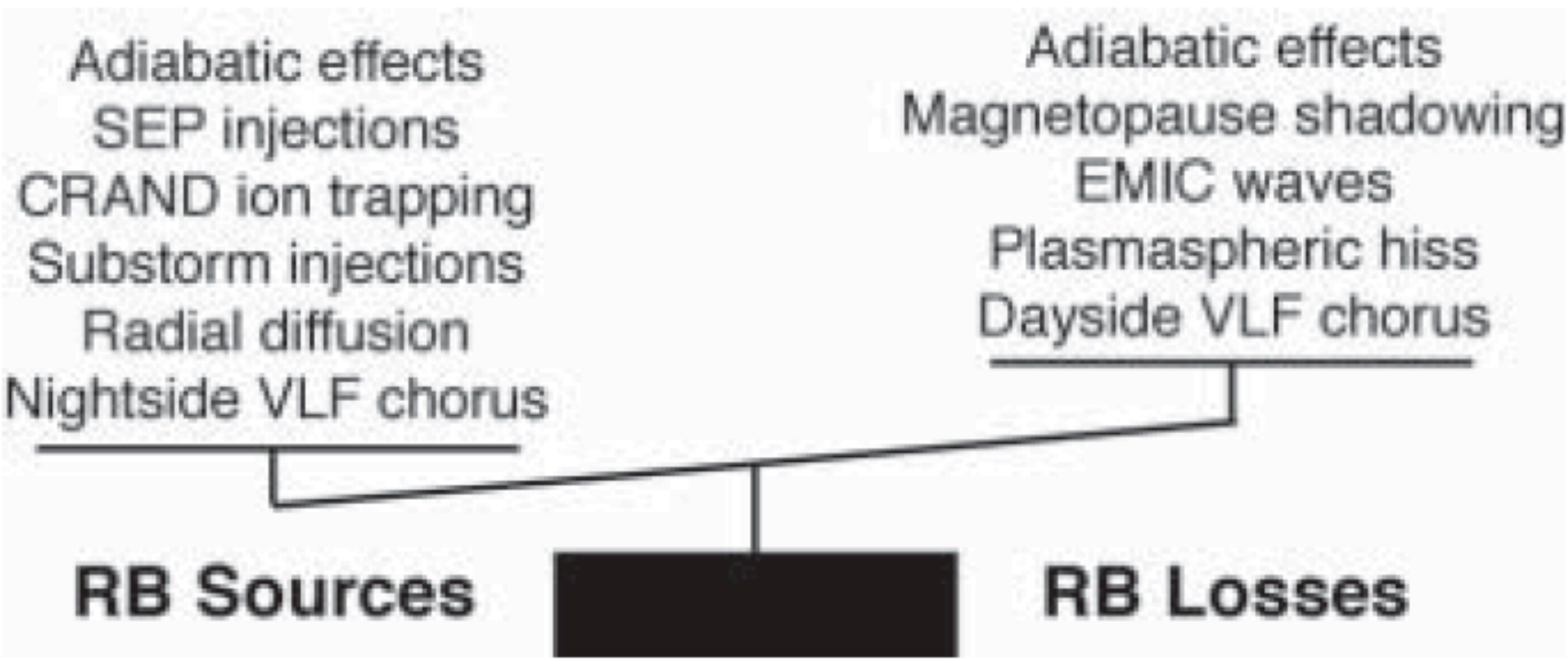
Inner Belt

~ 1-2 R_E

Outer Belt

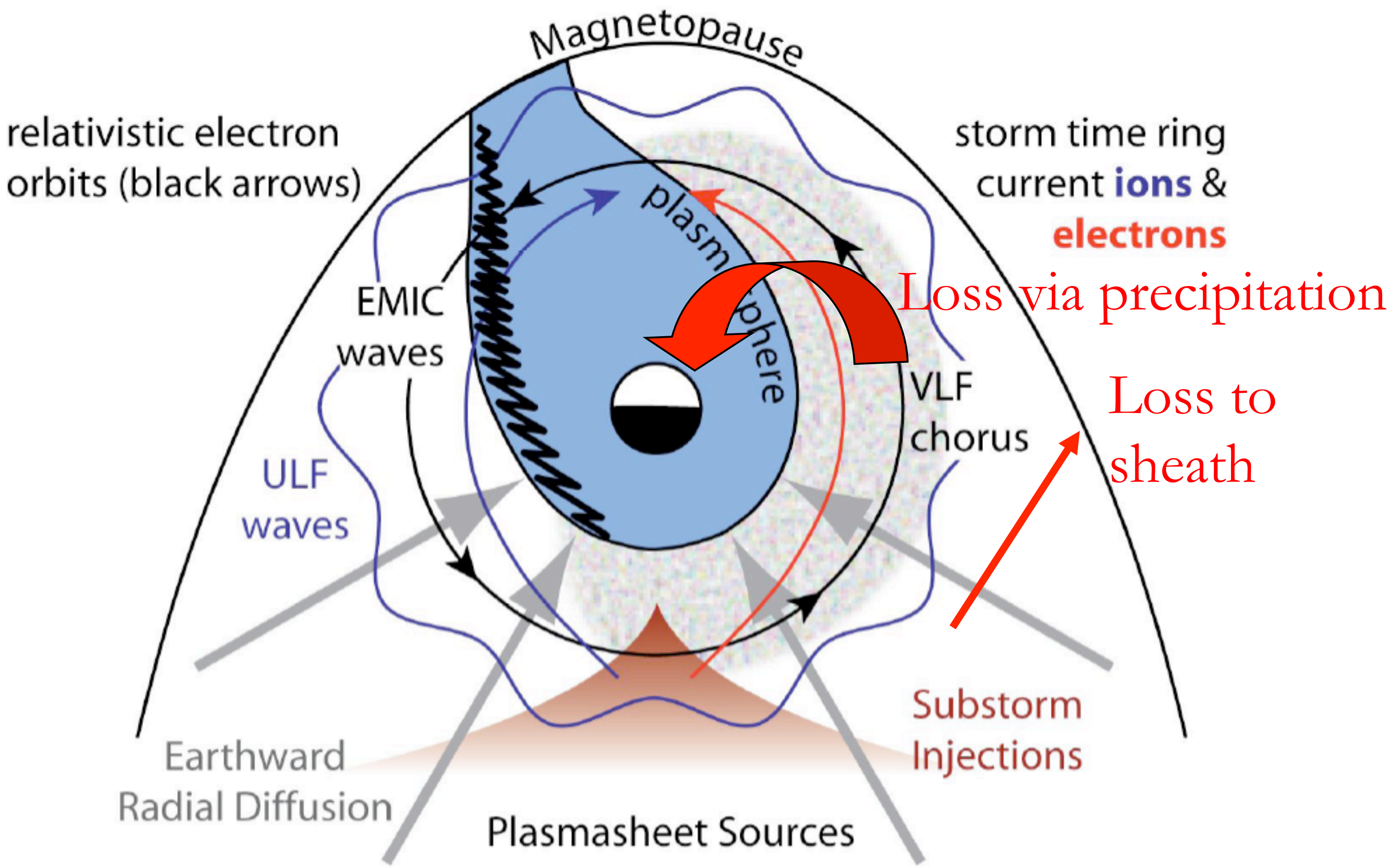
~2-6 R_E

Balance of Sources and Losses



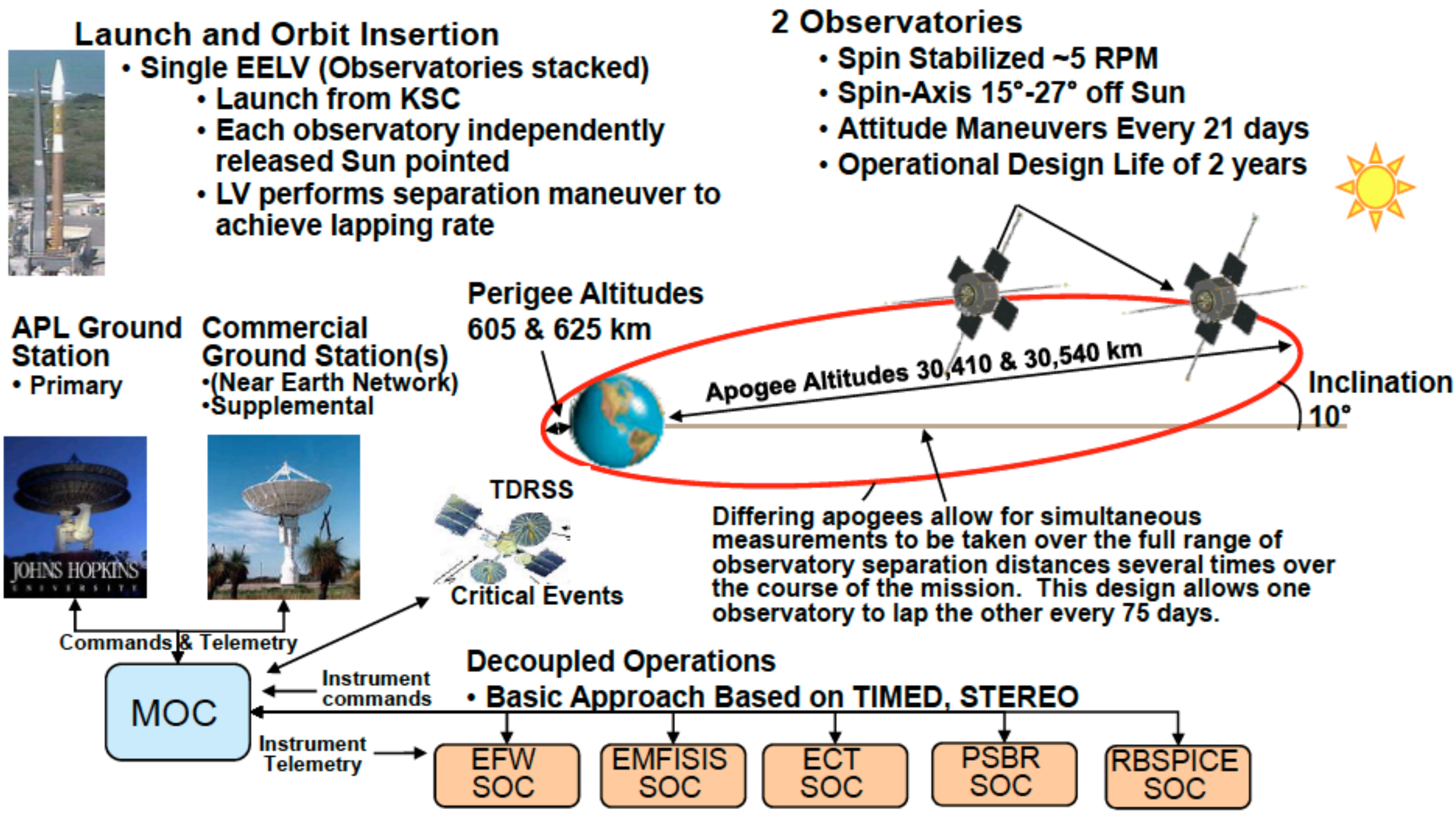
Liemohn [2007]

Competing Processes for
Acceleration, Transport, and Loss

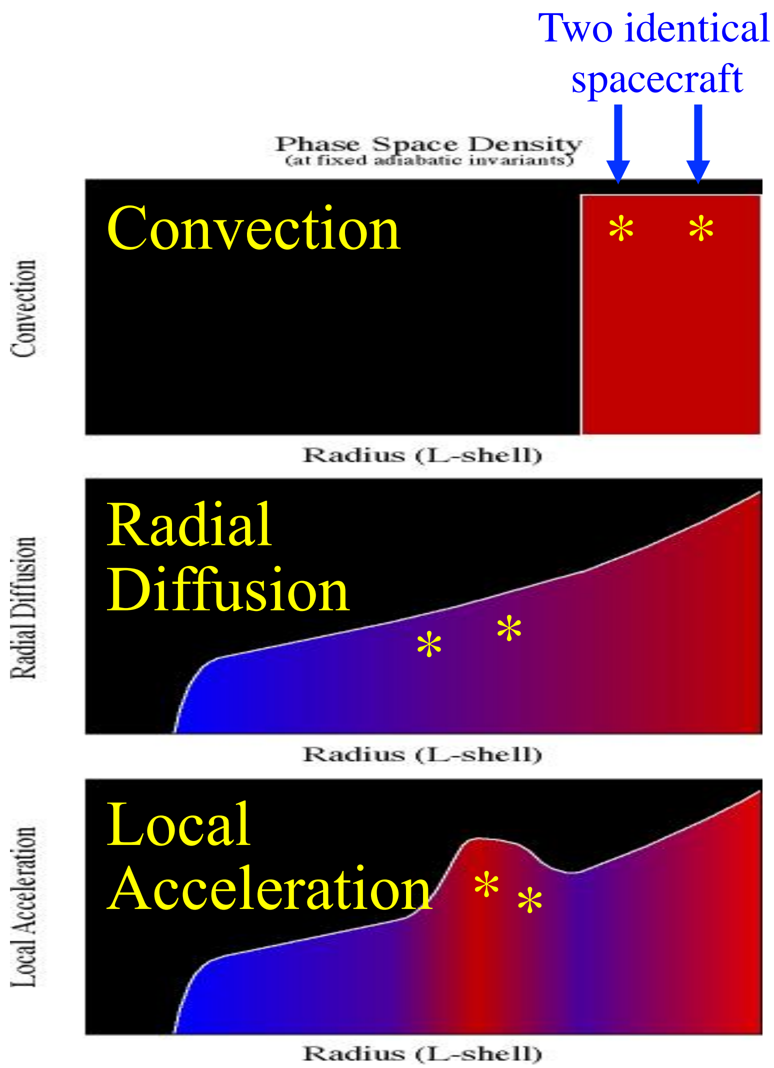


(Figure from Reeves, 2007)

Mission Concept



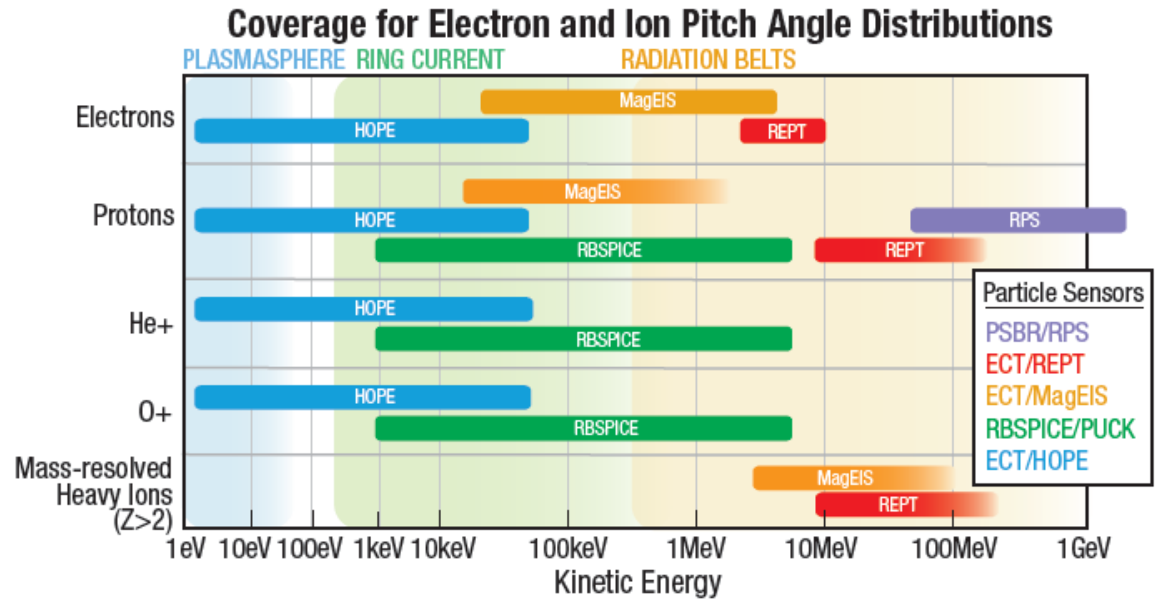
Two Spacecraft

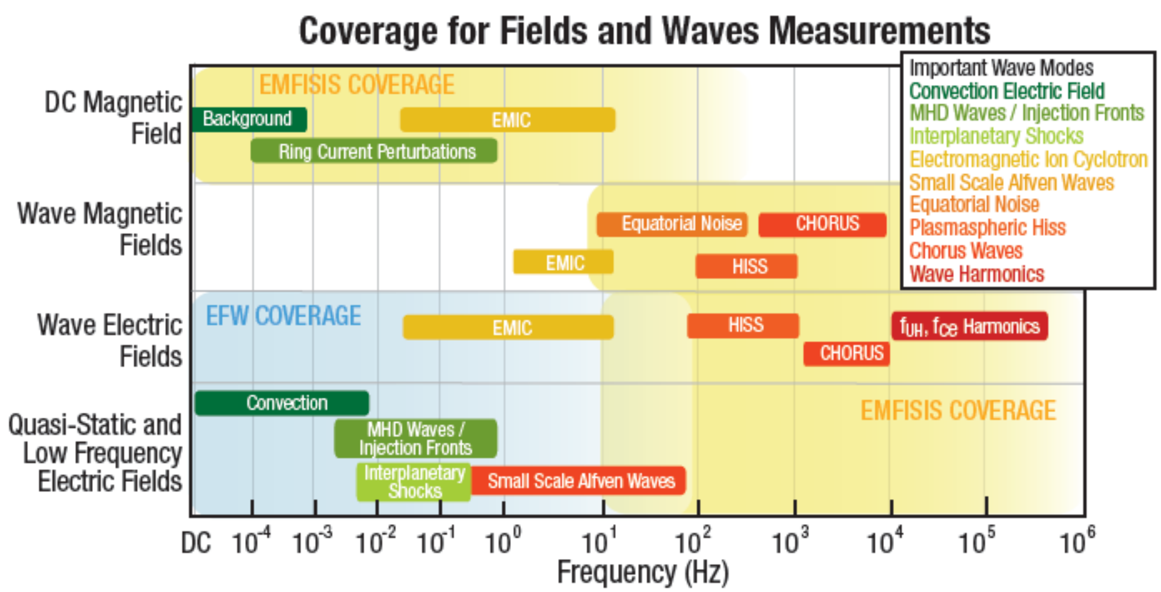


Two spacecraft with variable separations are essential to:

- Separate spatial and temporal effects
- Determine spatial extent of phenomena
- Simultaneously observe source and energized particle populations
- Quantify instantaneous radial gradients in particle phase space density

Fully-Instrumented Spacecraft





Energetic Particle, Composition, and Thermal Plasma (ECT) Suite:

HOPE: Helium Oxygen Proton Electron top-hat analyzer and coincidence detector

MagEIS: Magnetic Electron Ion Spectrometer

REPT: Relativistic Electron Proton Telescope

Radiation Belt Storm Probes Ion Composition Experiment (RBSPICE):

PUCK: Ring current ion composition, energy, and pitch-angle sensor

Proton Spectrometer Belt Research (PSBR):

RPS: Relativistic Proton Spectrometer

Electric and Magnetic Field Instrument Suite and Integrated Science (EMFISIS) Suite:

MAG: Triaxial fluxgate Magneto-meter

WAVES: Triaxial Search Coil and Waveform Receivers

Electric Field and Waves Instrument (EFW):

Spin Plane Double Probes

Axial Stacer Booms

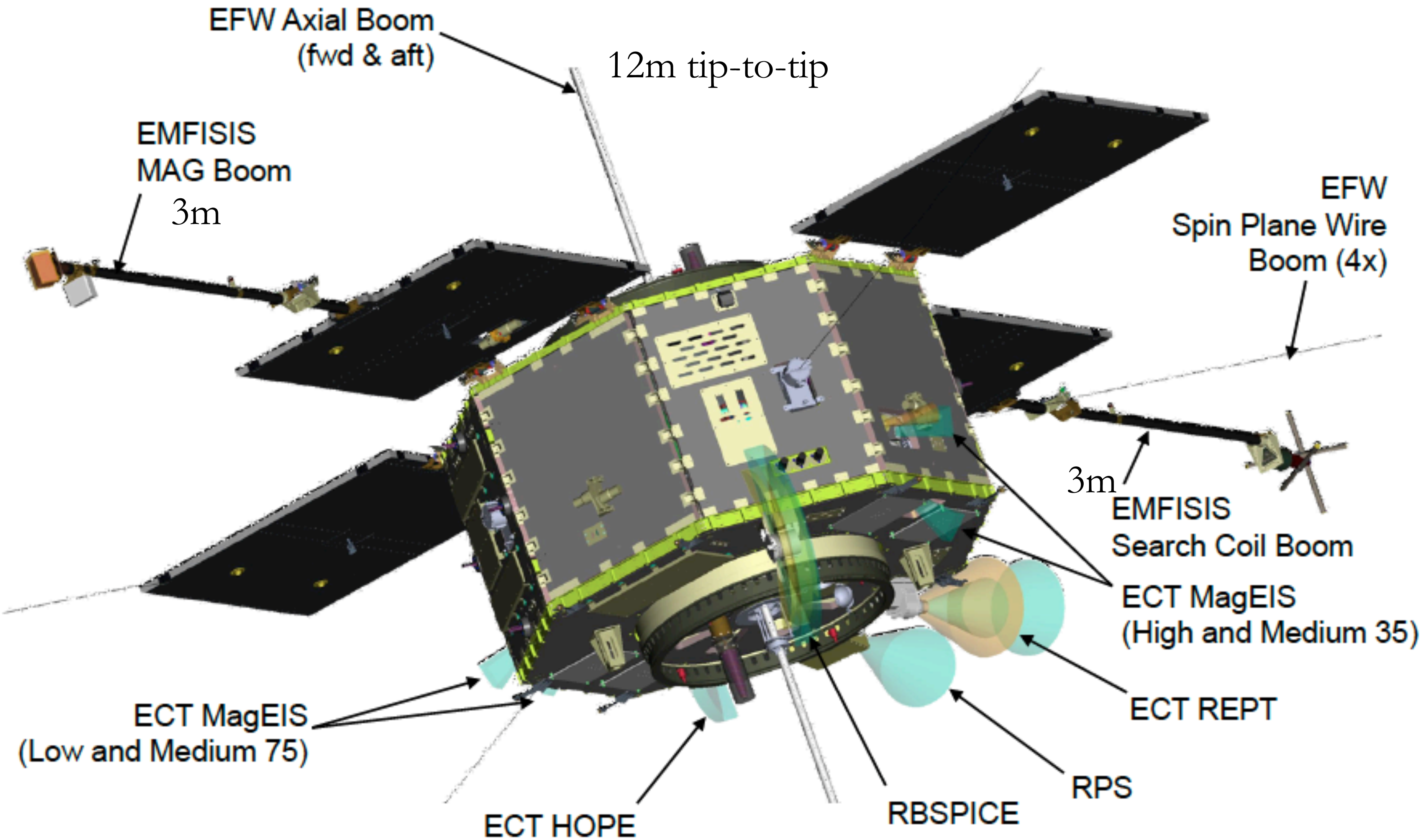
Science Investigations

Science Teams	Science Investigation	Instruments/Suites
Dr. Harlan Spence, PI Boston University,	Measure near-Earth space radiation belt particles to determine the physical processes that produce enhancements and loss	***ECT***: **E**nergetic Particle, **C**omposition and **T**hermal Plasma Suite
Dr. Craig Kletzing, PI University of Iowa,	Understand plasma waves that energize charged particles to very high energies; measure distortions to Earth's magnetic field that control the structure of the radiation belts	***EMFISIS***: **E**lectric and **M**agnetic **F**ield **I**nstrument **S**uite and **I**ntegrated **S**cience Suite
Dr. John Wygant, PI University of Minnesota,	Study electric fields that energize charged particles and modify inner magnetosphere	***EFW***: **E**lectric **F**ield and **W**aves Instrument
Dr. Louis Lanzerotti, PI New Jersey Institute of Technology	Understand the creation of the "storm time ring current" and the role of the ring current in the creation of radiation-belt populations	***RBSPICE***: **R**adiation **B**elt **S**torm **P**robes **I**on **C**omposition **E**xperiment
Dr. Joseph Mazur Aerospace Corporation	Specification models of the high-energy particles in the inner-most Van Allen radiation belt	***RPS***: **R**elativistic **P**roton **S**pectrometer

Selected

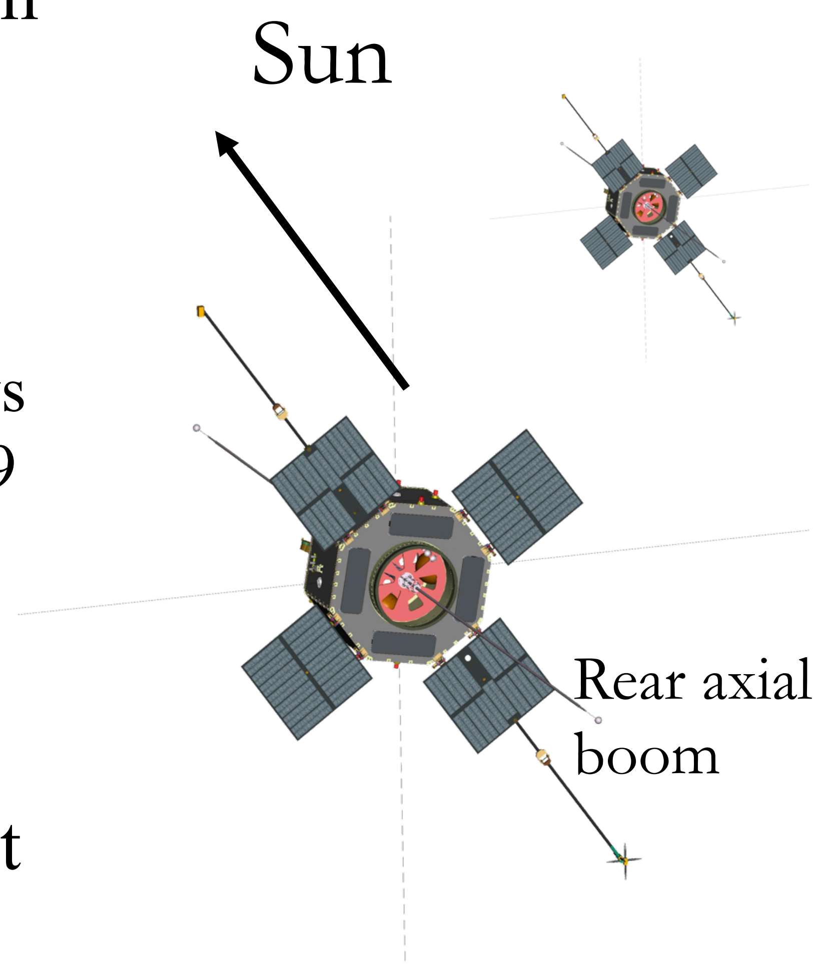
GFE

Two Identical Spacecraft



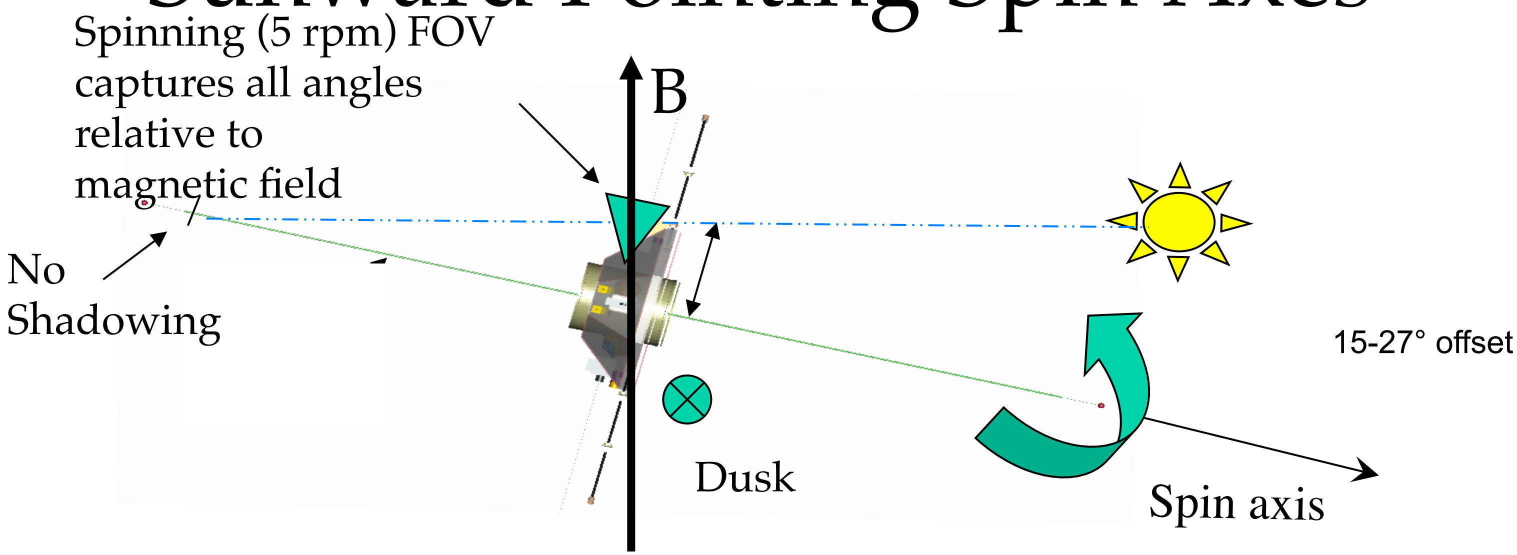
Spacecraft

- Size: stacked spacecraft ~ 2.5m
- Wet Mass (for two) < 1600 kg
- Sun-sensor
- 16 Gbit solid state recorder > 2 days data storage (inst. 100kbps, data 5.9 Gbits, downlink ~8.6 Gbits/day)
- Radiation hardness- must operate through worst known storms, e.g. March 2001 event
- 4 deployed solar panels



4 Deployed Solar Panels

Sunward Pointing Spin Axes



<u>Nearly sunward-pointing spin axes</u>:

• Enable particle instruments to capture the full range of look directions relative to the magnetic field once each spin

and

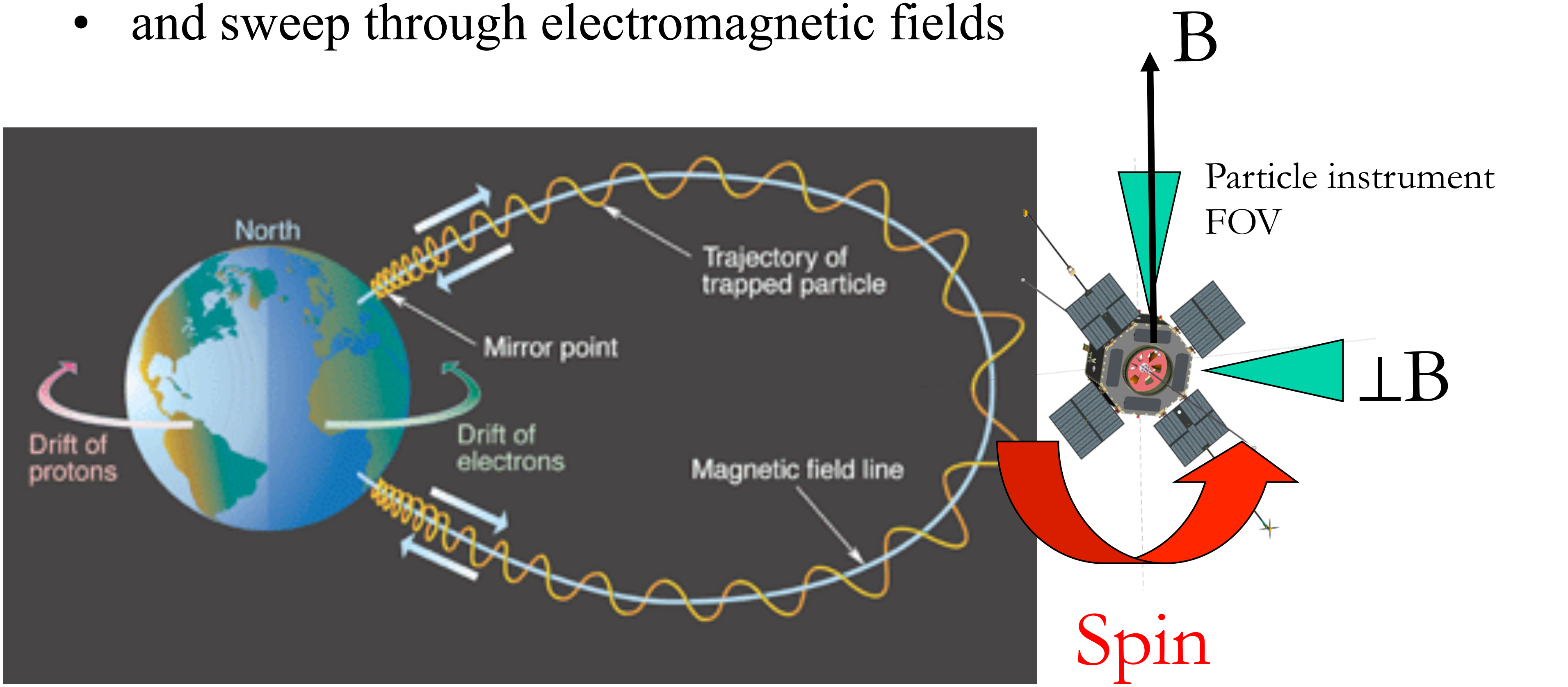
•Enable the spin plane booms of the electric field instrument to capture the dominant dawn-dusk component of the electric field once each spin.

•Slight off-pointing from the Sun prevents shadowing of rear boom.

E Field Stacer Booms Deploy

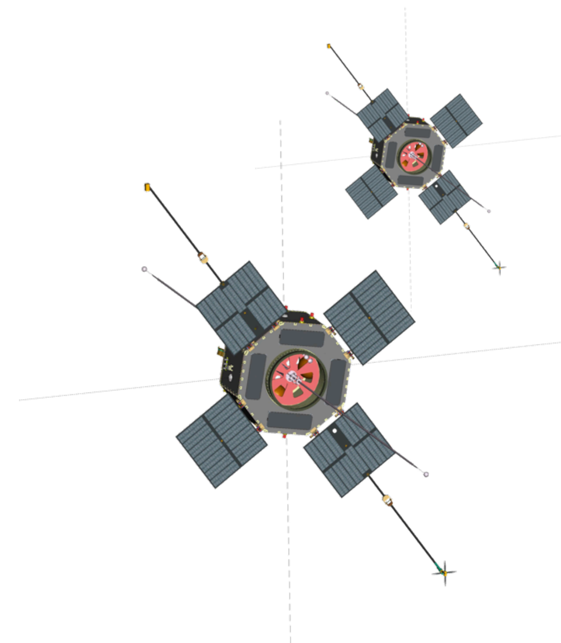
Spacecraft Spin

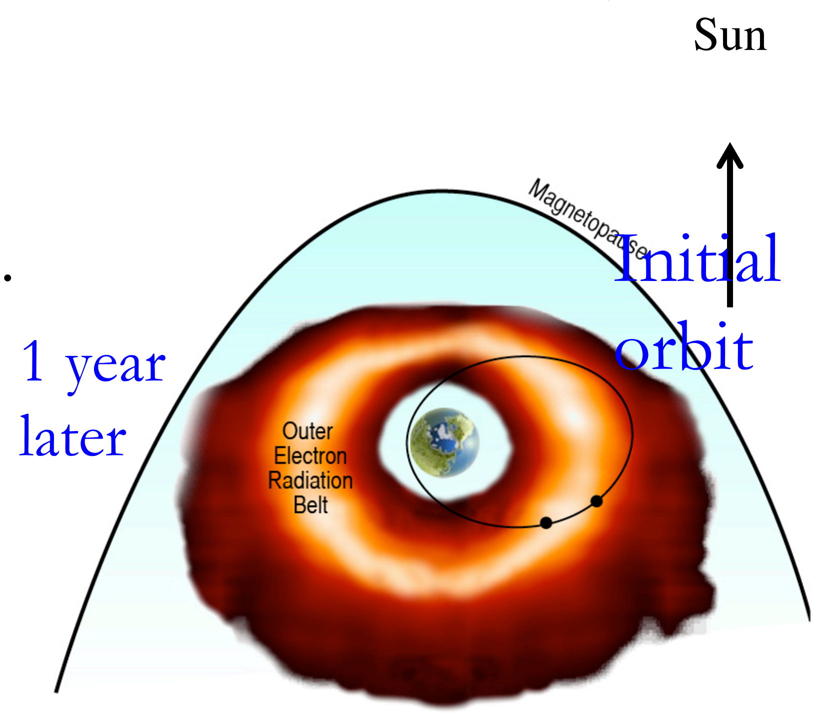
- 10.9s spin period enables
- accurate spin plane sampling of particle pitch angles (velocities)
- and sweep through electromagnetic fields



Orbit

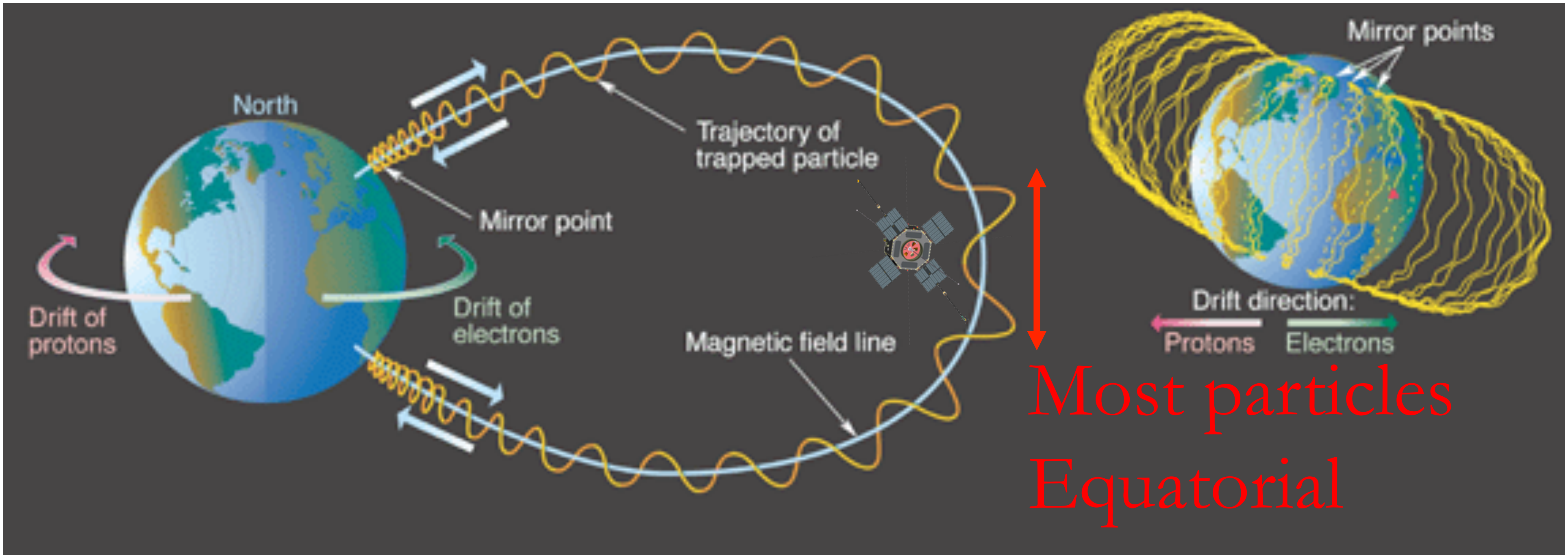
- Launch vehicle - Atlas V 401
- Launch date: August 30, 2012
- Initial apogee at 0900 LT
- 60 day commissioning
- Precession to dusk within 1 year
- Precession to dawn within 2 years.
- --> enables coverage of nightside during 1st year, all local times within 2 years.



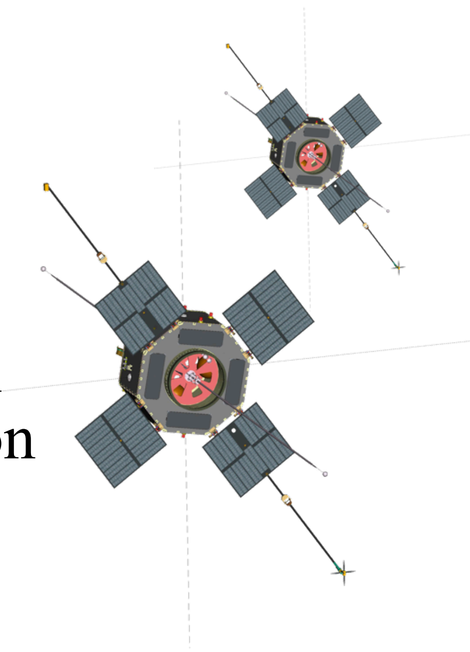


Orbit

- 10° inclination provides access to (almost) all magnetically trapped particles and most (but not all) relevant waves

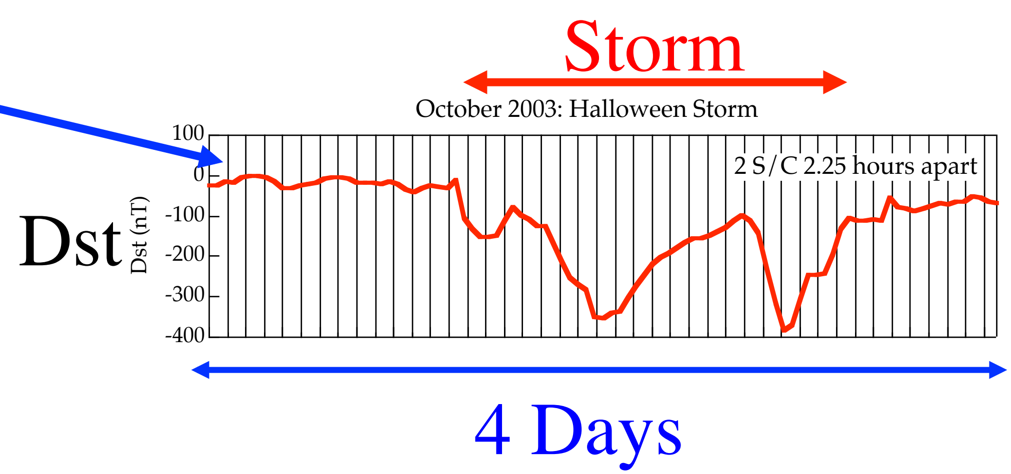


Orbit



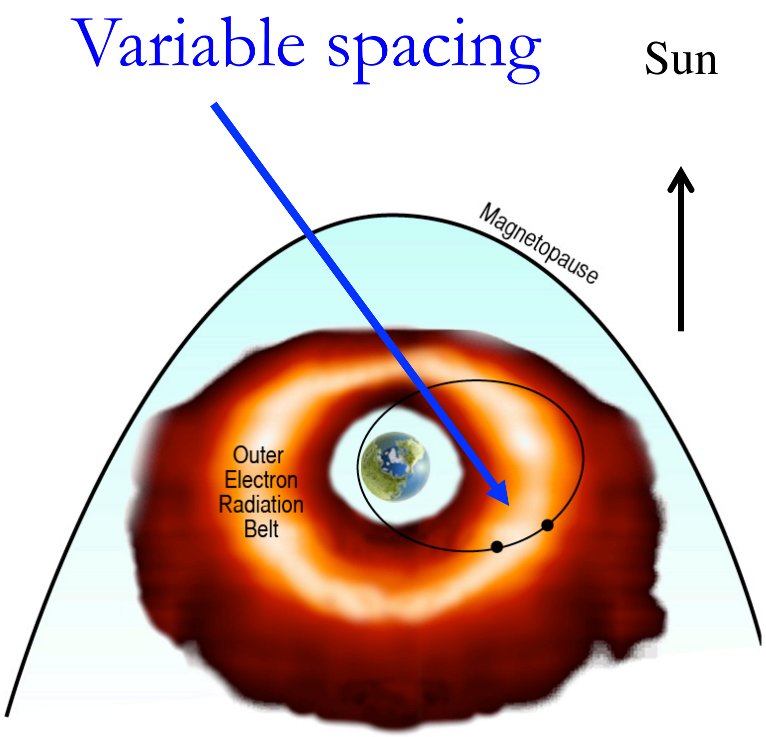
- 600 km altitude perigee (avoid monatomic oxygen harmful to EFW sensors but observe inner radiation belt)
- 5.8 R_E geocentric apogee (for full radiation belt sampling)
- --> Results in 9 hour orbital period << relevant storm time scales

Vertical bars indicate cadence of radial cuts through the radiation belts during storm measured by geomagnetic Dst index



Lapping Spacecraft

- 4 laps/year for simultaneous observations over a range of separations in each quadrant

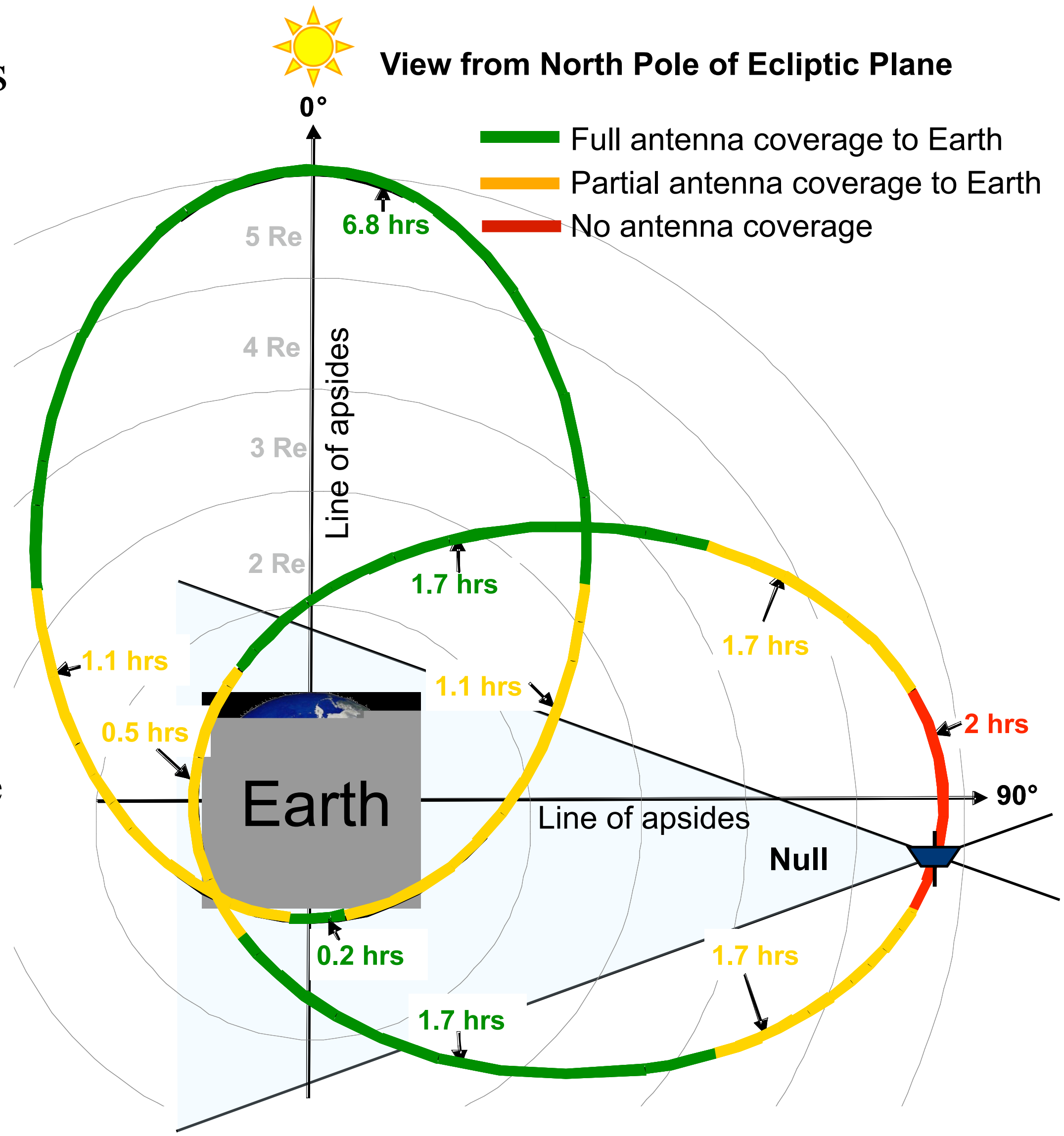


Telecommunications

- Average daily telemetry: 5.9 Gbits
- Uplink and downlink
  - Uplink in S-band <2200 MHz
  - Downlink in S-Band >2200 MHz
  - Primary…18.3-m dish at APL
- Space weather broadcast (1 kbps, 8 W, two antennas on front/rear faces, S-Band)
  - subset of data
  - Agreements with Argentina, Brazil, Czech Republic, South Korea

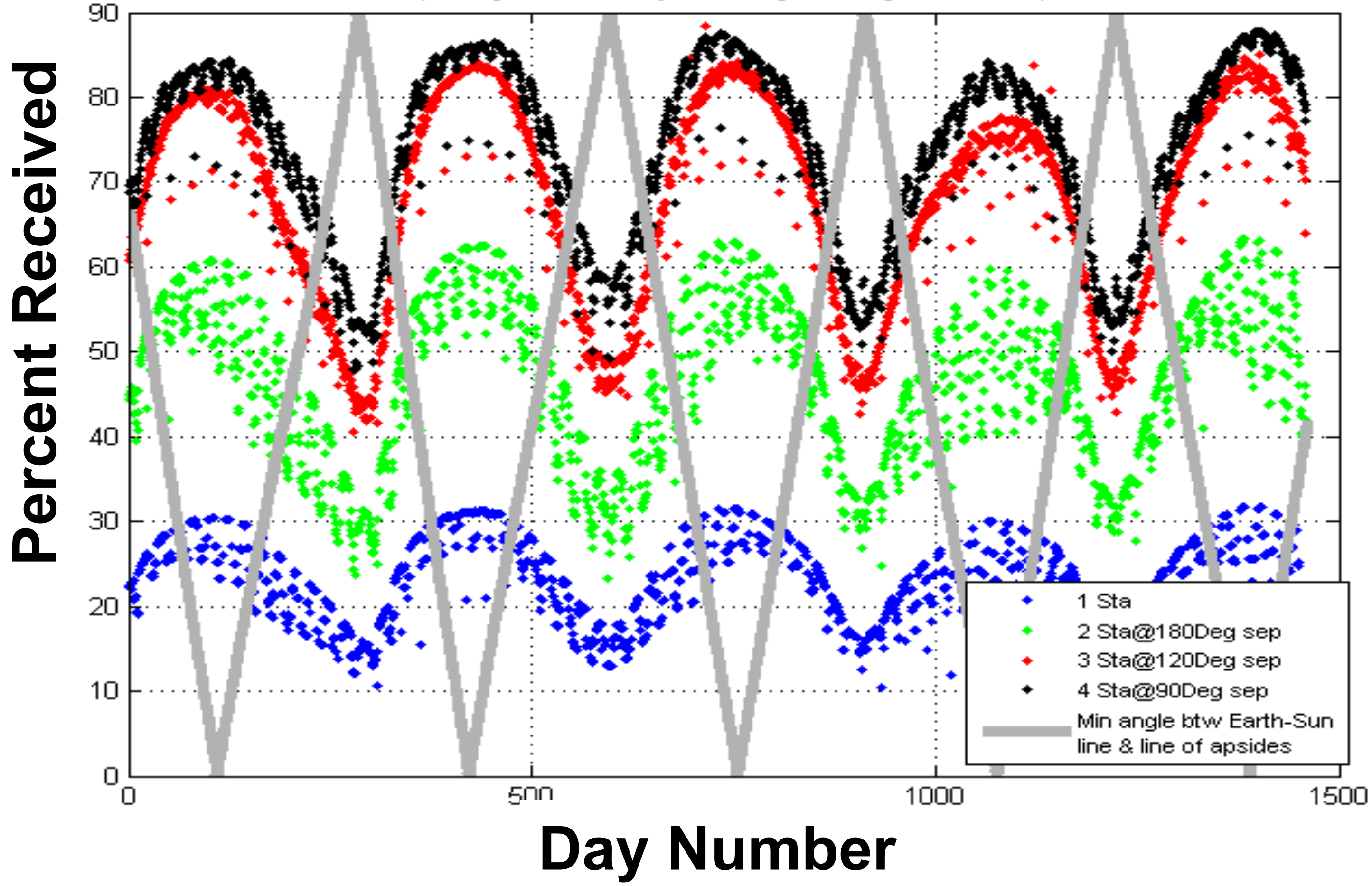
Seasonal Variations in Space Weather Coverage Due to Antenna Coverage Limits

- Antenna coverage to Earth depends on orbit geometry that seasonally varies
  - Although antenna coverage is large, there are times when the antenna patterns are not aligned with the Earth
  - There is excellent coverage when the line of apsides (major axis of orbit ellipse) is along or near the Earth-Sun line
  - Coverage is reduced significantly near apogee when the line of apsides is near perpendicular to the Earth-Sun line



Note – Graphic coverage transition points and times are approximate and are for illustrative purposes only.

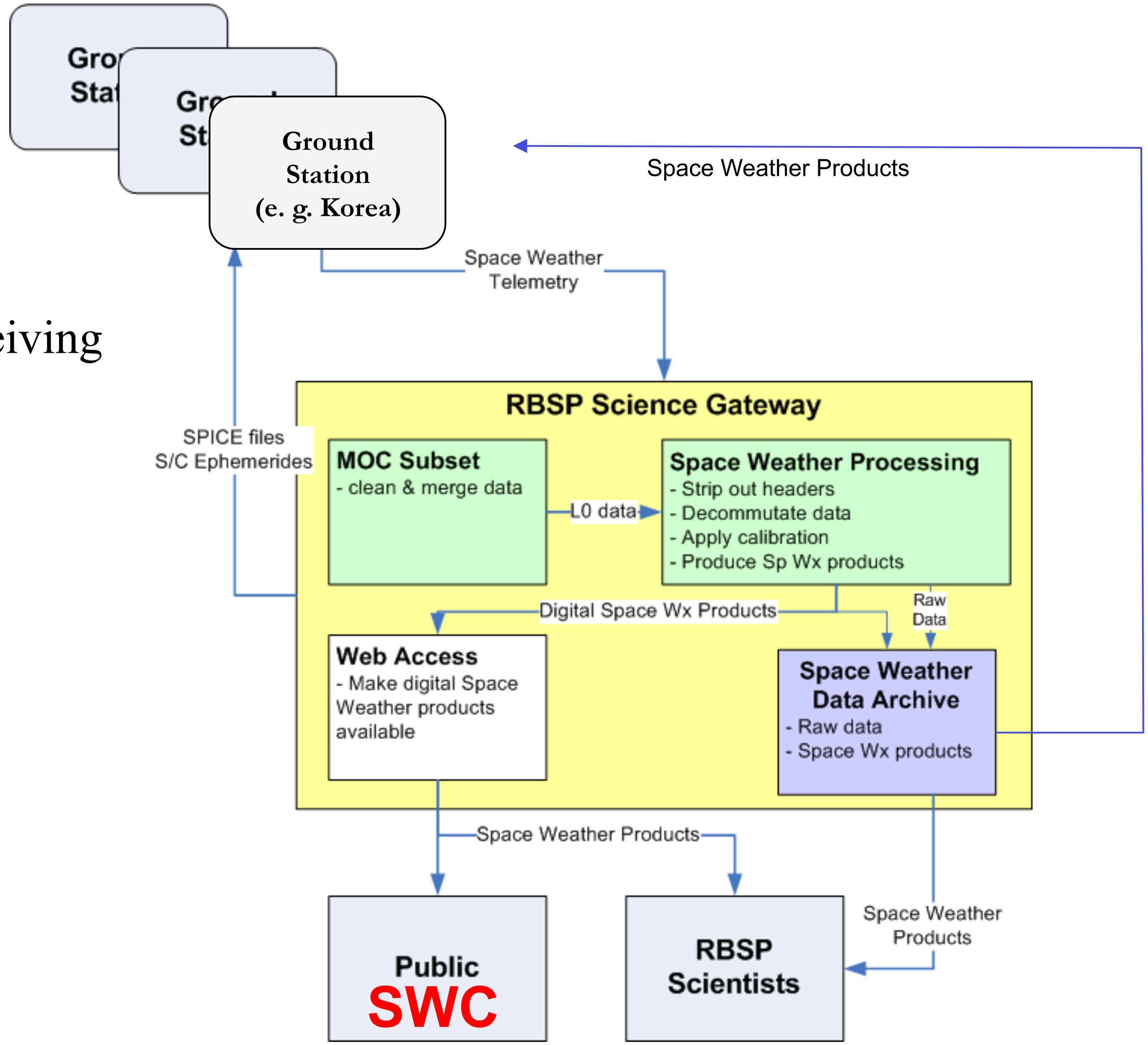
Optimization of Van Allen Probes SW data reception requires > 3 stations distributed around Earth



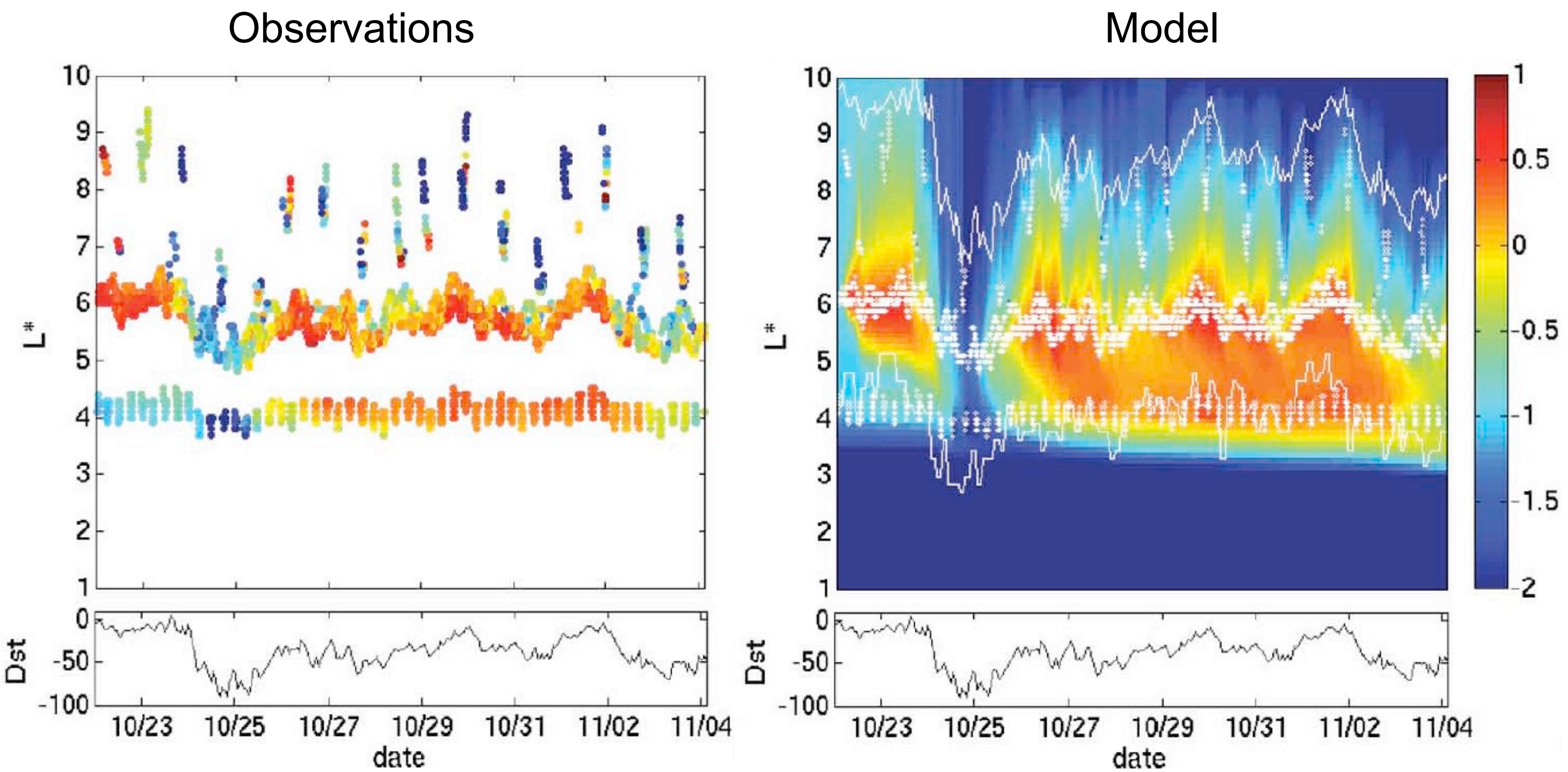
SW Broadcast data is processed centrally and available globally within 15 minutes of real time

International Partnerships

- Ground stations receiving SW Broadcasts:
  - Argentina
  - Brazil
  - Czech Republic
  - Korea



LANL DREAM models fills in the gaps between spacecraft observations and turns localized and limited sampling into predictions

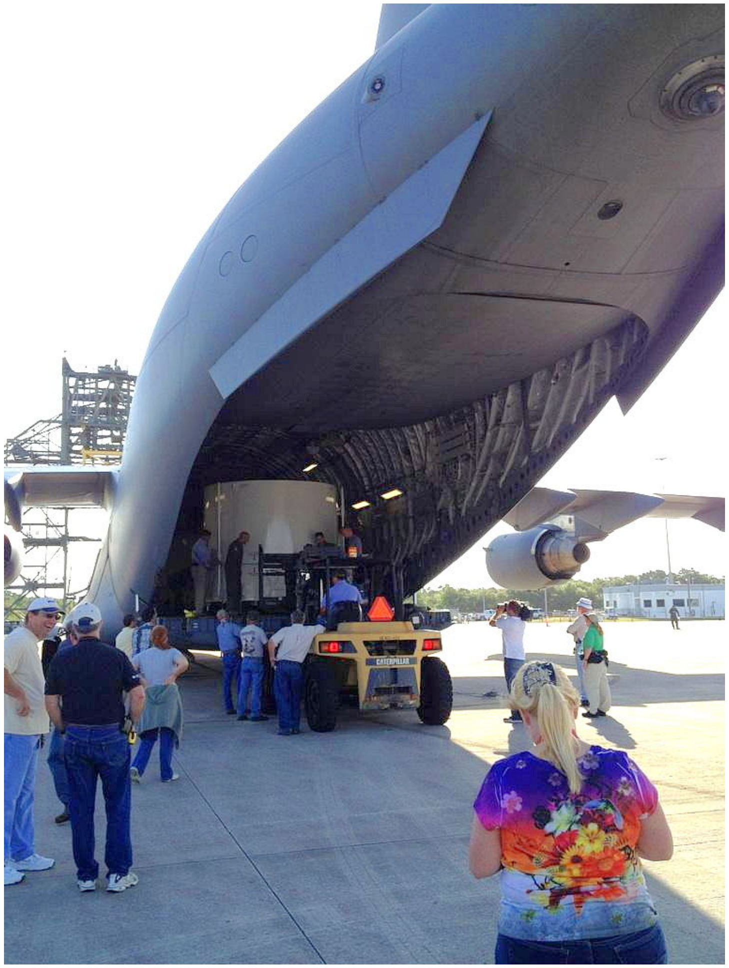


Reeves et al., Space Weather, In Press, 2012

Input Probe Space Weather Data → Output Radiation Belt forecast

The Countdown to launch

- Unloading from the C-17 airplane



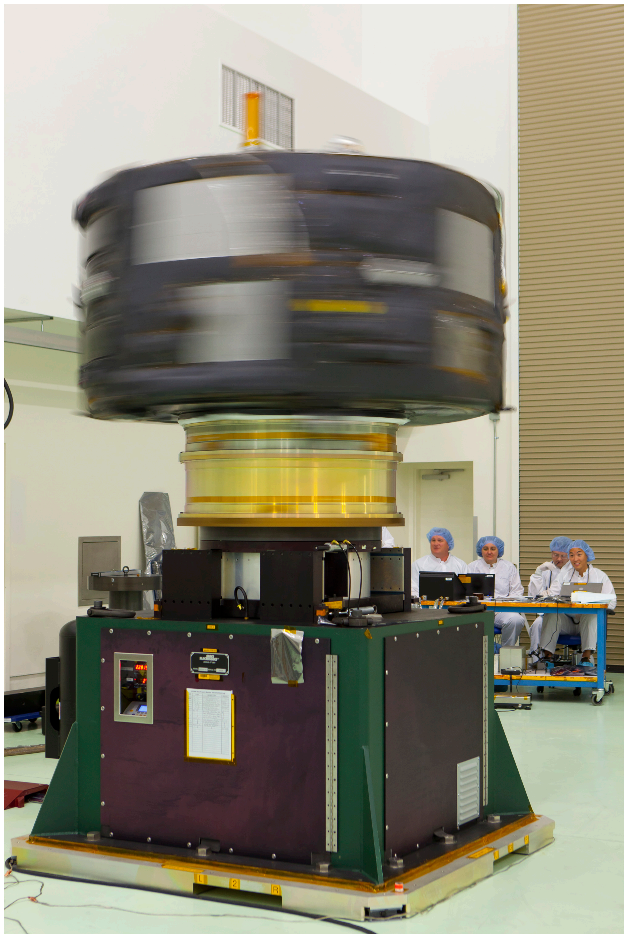
The Road to Launch

- Fairing

closing panels

The Road to Launch

- Spin test



The Road to Launch

- Solar array and boom deploy

The Road to Launch

- Loading Propellant

The Road to Launch

The Road to Launch

The Road to Launch

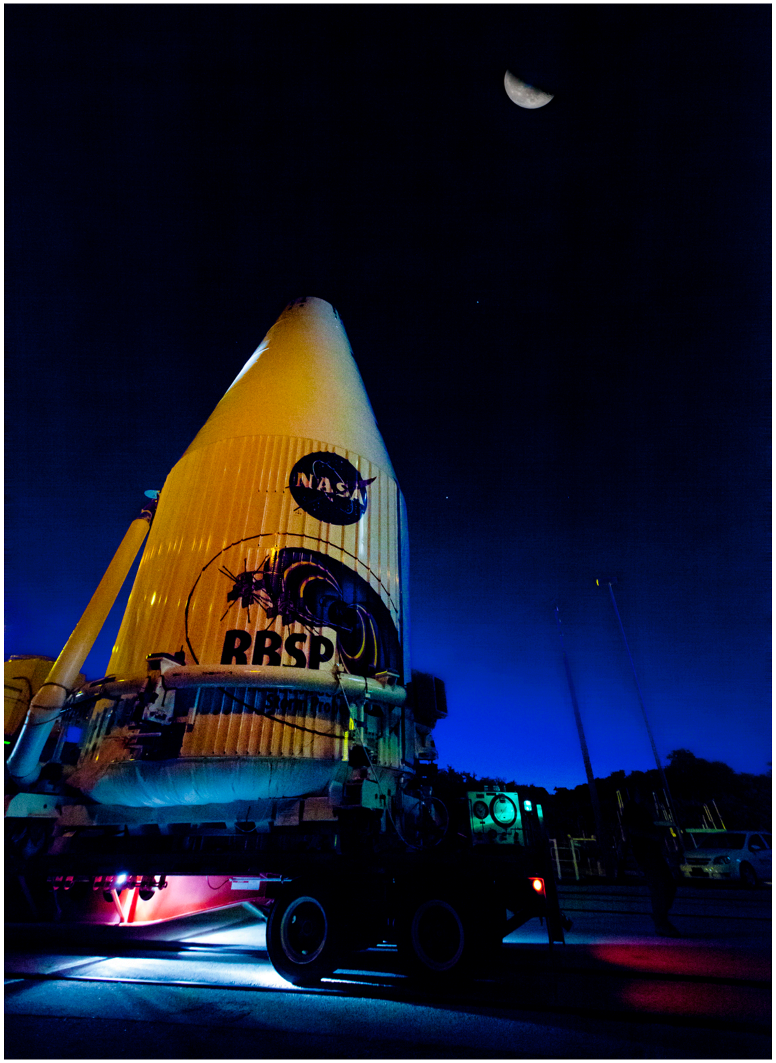
- Payload in Fairing

The Road to Launch

- Payload on the move…

The Road to Launch

- Payload on the move…



The Road to Launch

- Payload to Atlas-5 rocket

The Road to Launch

- Final closeout

The Road to Launch

Roll out

The Road to Launch

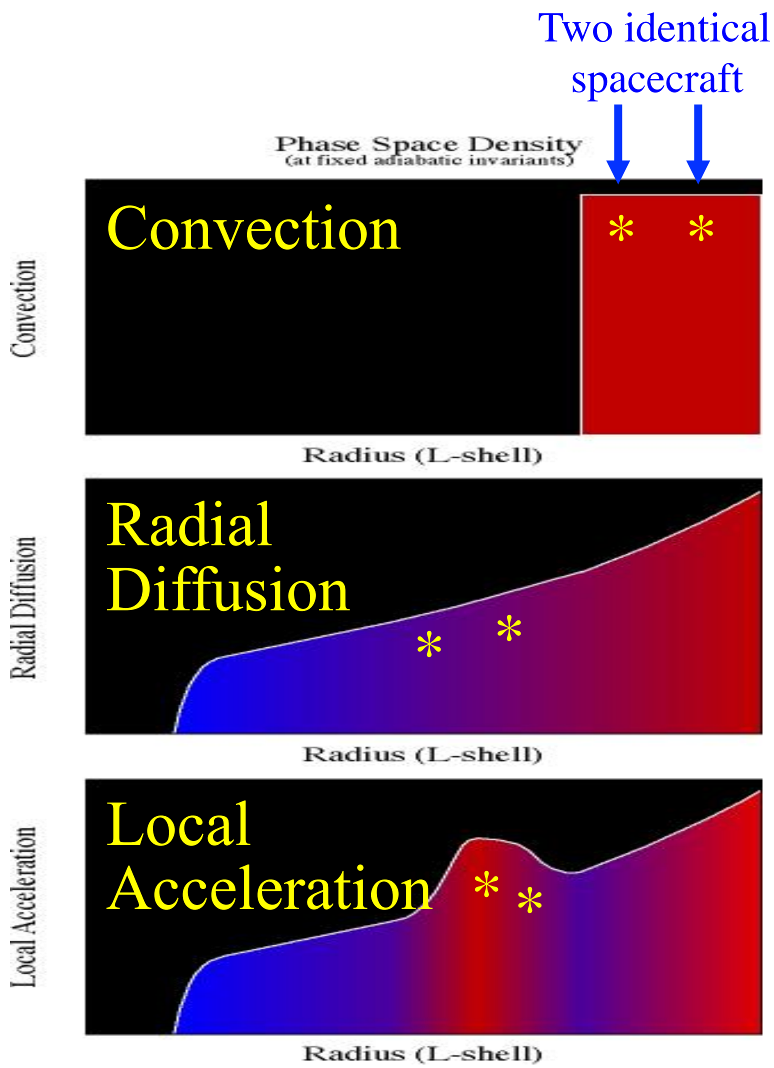
Launch

Launch
August 30, 2012
4:05 EDST

Early Results from Van Allen Probes

- 1. Where do the particles come from?
- 2. How are they energized and lost?
- 3. How do they interact with waves?
- 4. How do they interact with shocks?

Two Spacecraft

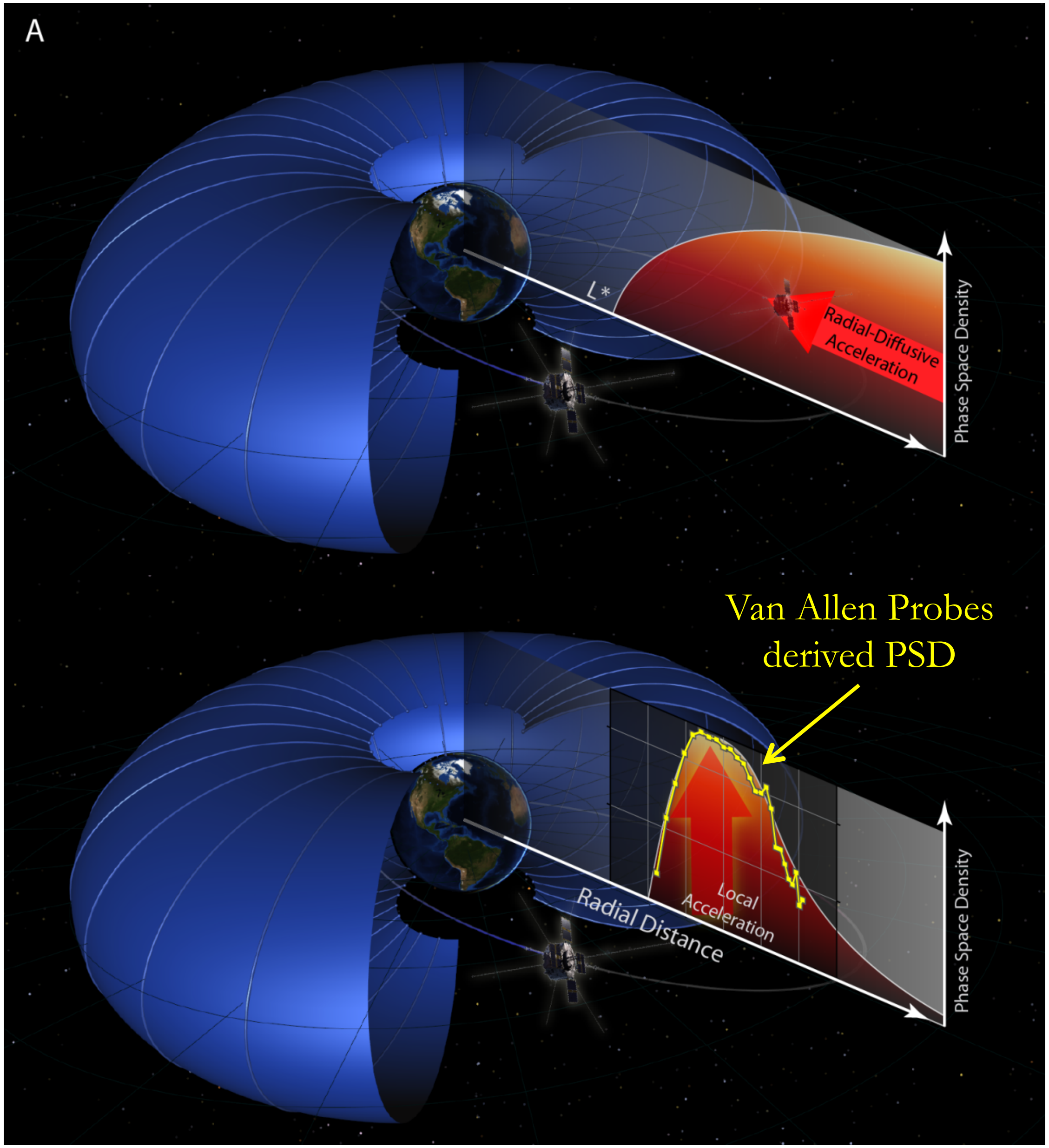


<u>Two spacecraft with variable separations are essential to</u>:

- Separate spatial and temporal effects
- Determine spatial extent of phenomena
- Simultaneously observe source and energized particle populations
- Quantify instantaneous radial gradients in particle phase space density

Van Allen Probes confirms that radiation belt electron acceleration occurs locally and not just as a result of transport.

- Reeves et al. (ECT)

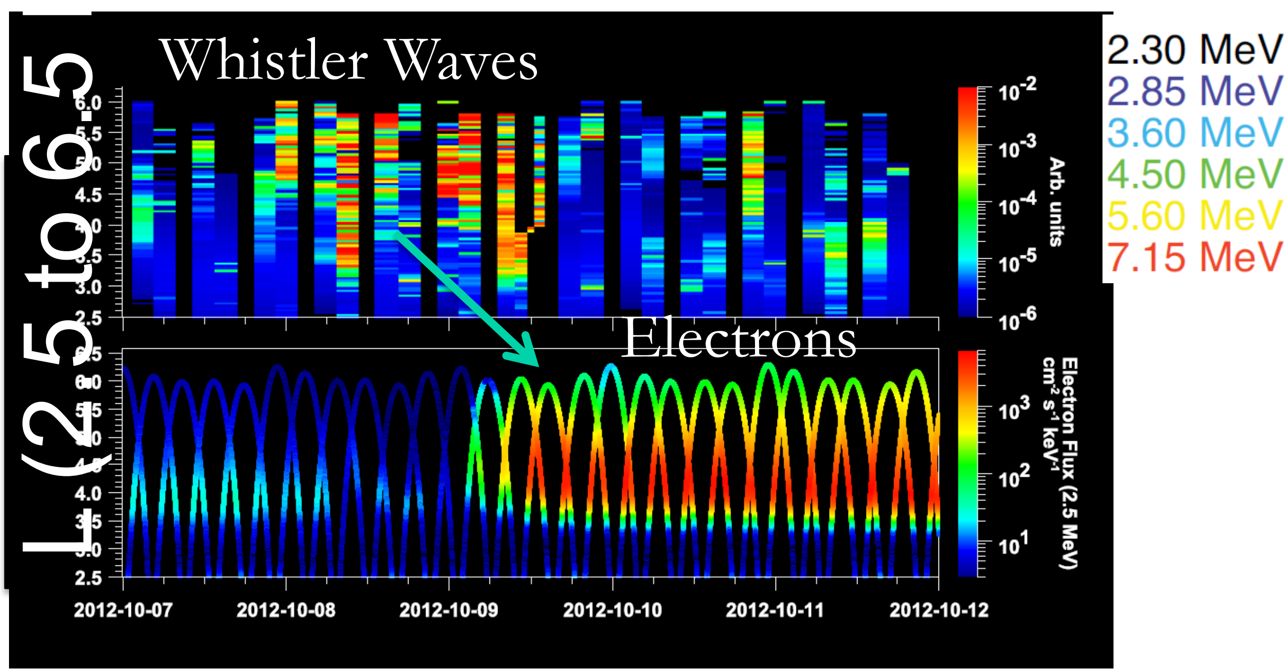


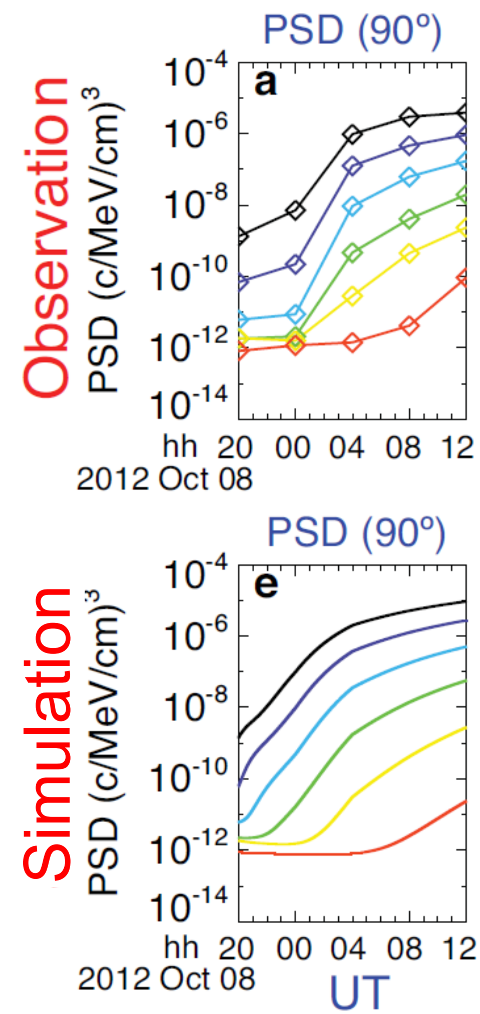
Radiation Belt Electrons are Accelerated Locally by Whistler Waves

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

Thorne et al. 2013; Nature

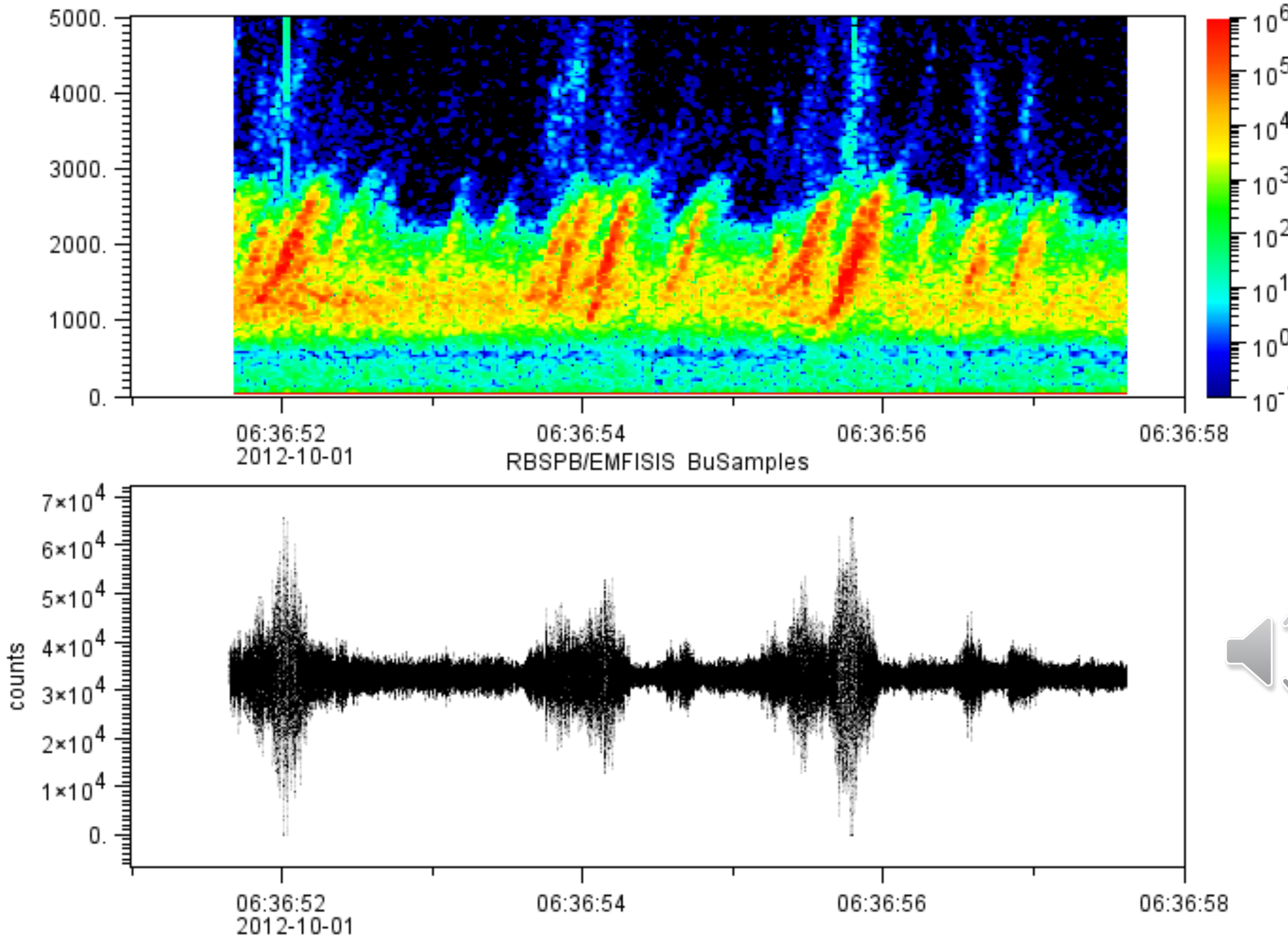




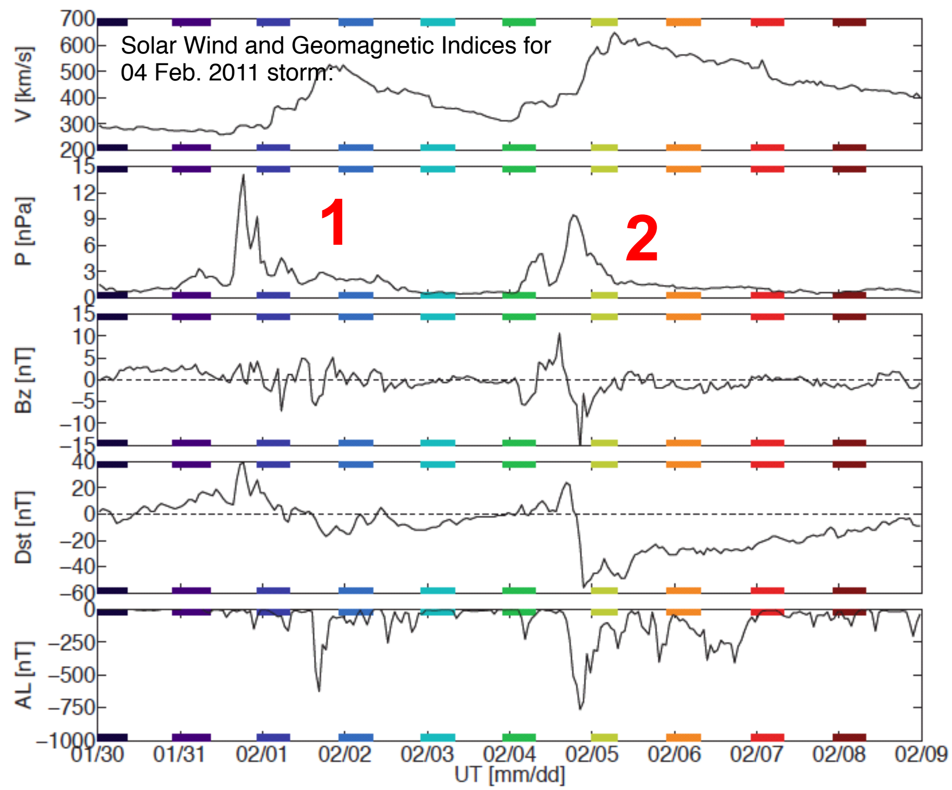
Reeves et al. 2013, Science

Date (5 Days)

Whistler Chorus Waves

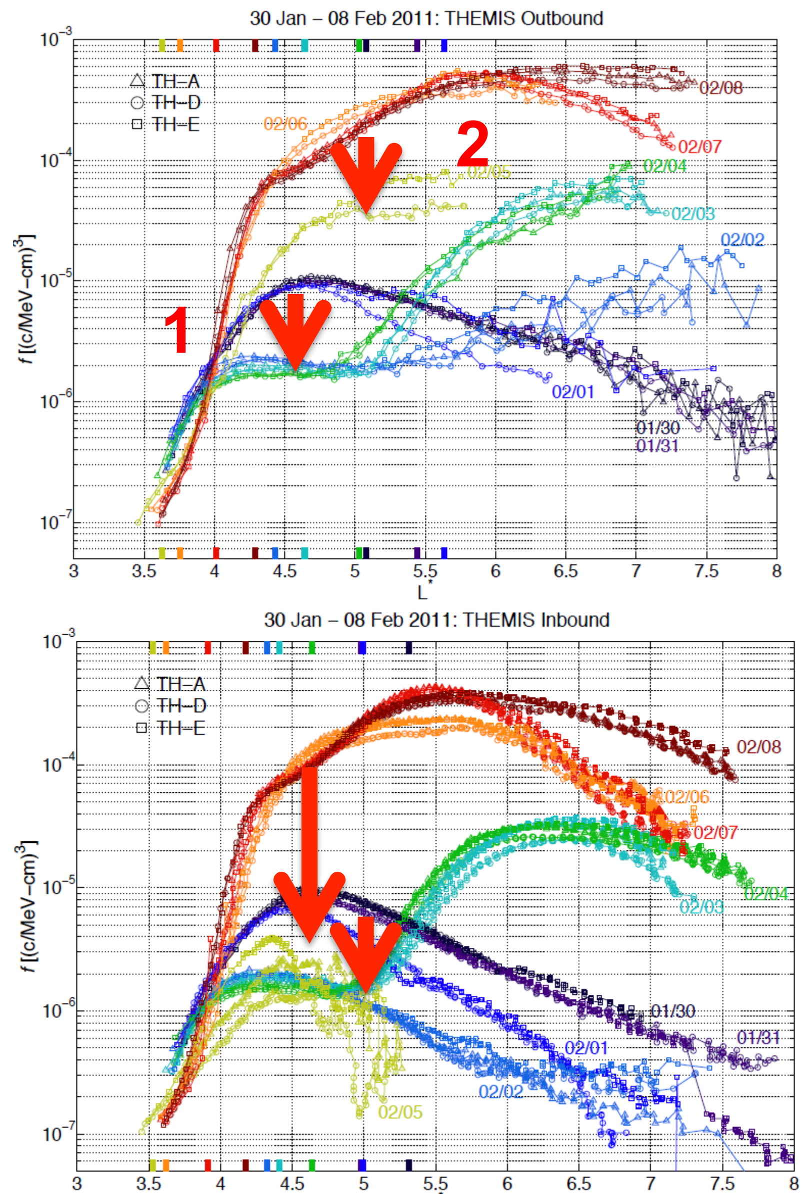


What Causes Sudden Large-Scale Dropouts?



Turner et al. [2012]:

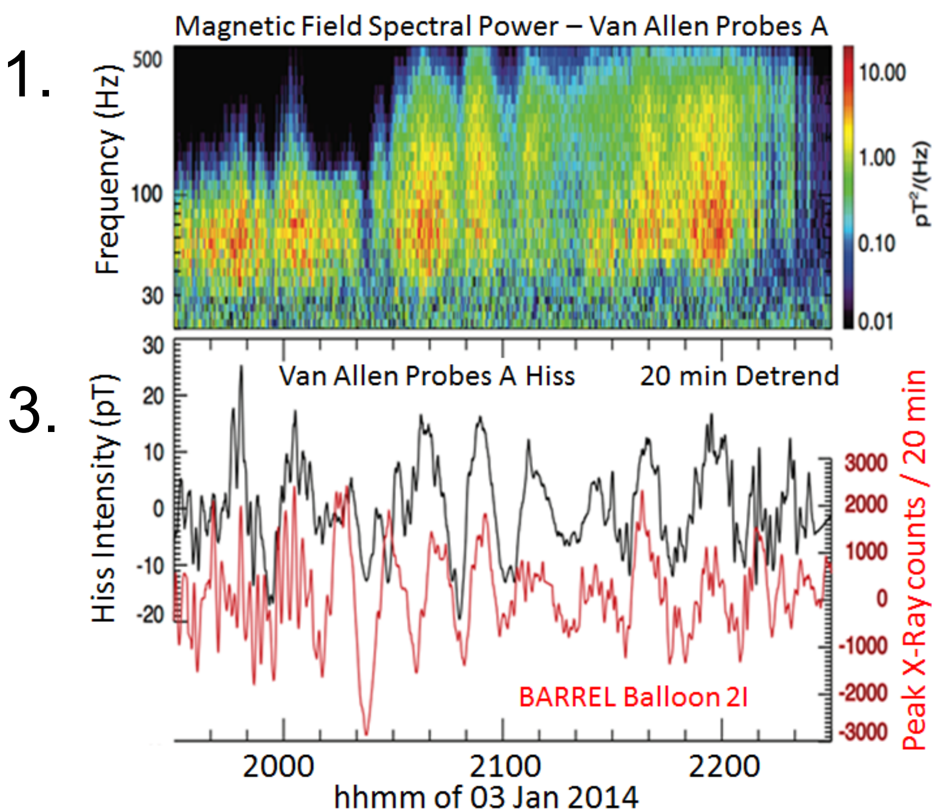
a. Two solar wind pressure increases compress the magnetosphere
b. Radiation belt electrons fluxes drop
c. Low altitude NOAA spacecraft don't see loss to the ionosphere
d. → magnetopause loss

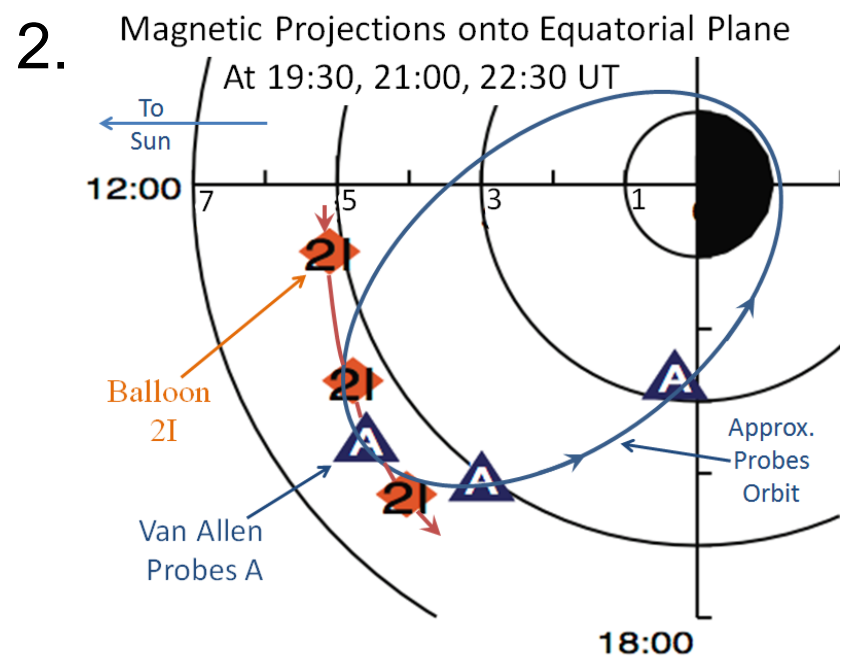


Equatorially mirroring, relativistic electron phase space density profiles, colors correspond to periods of same color shown on the solar wind plot

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.



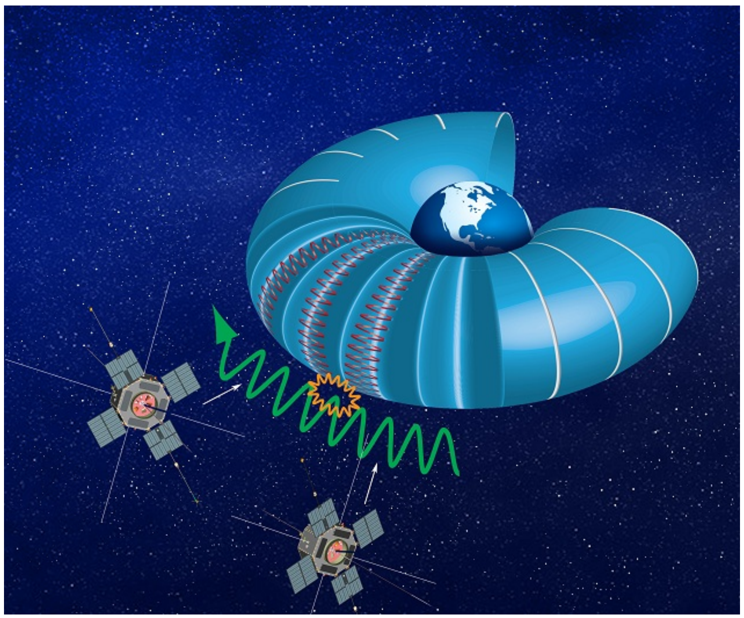


Breneman, Halford, Millan, Wygant et al., in prep

Van Allen Probes uniquely measures "drift resonance" interaction between Energetic Electrons and Ultra Low Frequency (ULF) Waves

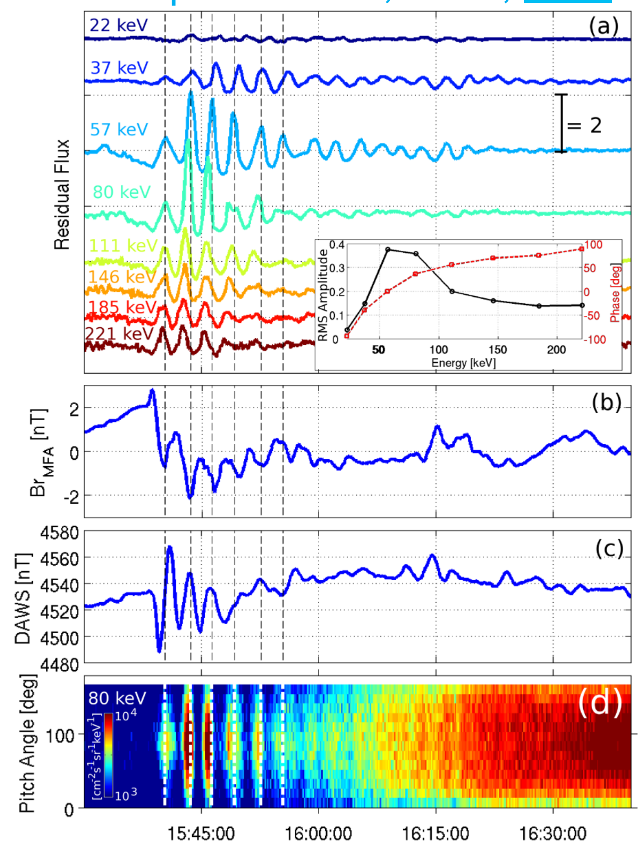
Drift resonance between charged particles and ULF Waves are critical for the radial transport and corresponding energization of charged particles in Earth's radiation belts

Dai et al., 2013 GRL



Unique multi-satellite measurements and the first definitive identification of radial particle gradients as the source of free energy for the growth of the ULF Waves

Claudepierre et al., 2013, GRL



First direct observations of the drift resonance exchange of energy between ULF Waves and electrons

Conclusion

- 1. Both Van Allen Probes are fully functional.
- 2. Sending down real time space weather broadcasts.
- 3. Hard at work making the discoveries for which they were designed.
- 4. That will lead to improved space weather models.