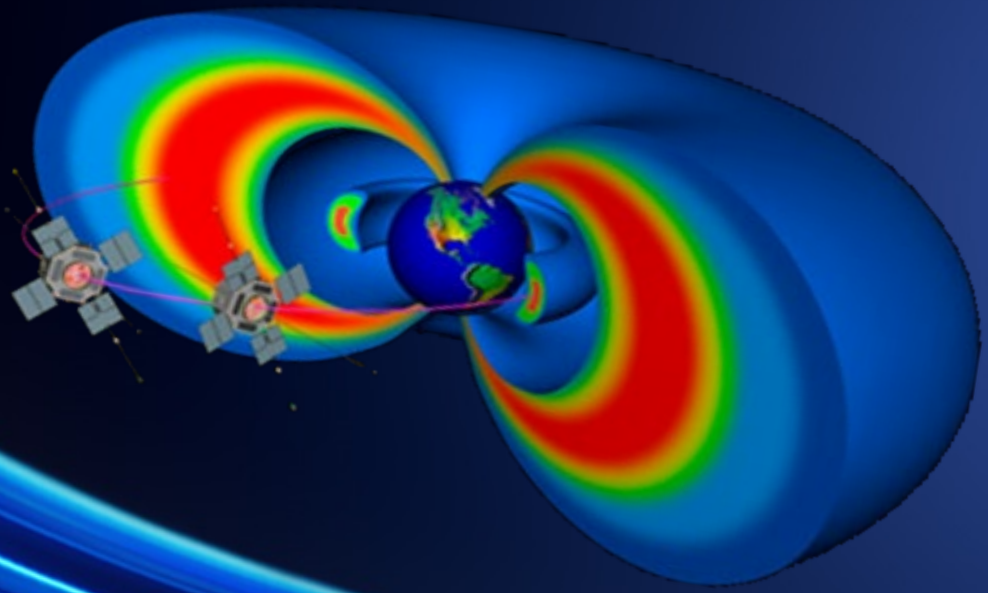
Unlocking the Secrets of Van Allen Radiation Belts



Dr. Weichao Tu
Associate Professor
West Virginia University

PPPL 2022 Intro Course
06/16/2022

About Me

- 2006: B.S. degree from Peking University, China
- 2011: Ph.D. degree from the Laboratory for Atmospheric and Space Physics of University of Colorado at Boulder
- 2012-2015: Postdoc at the Los Alamos National Laboratory
- 2015-present: Department of Physics and Astronomy, West Virginia University

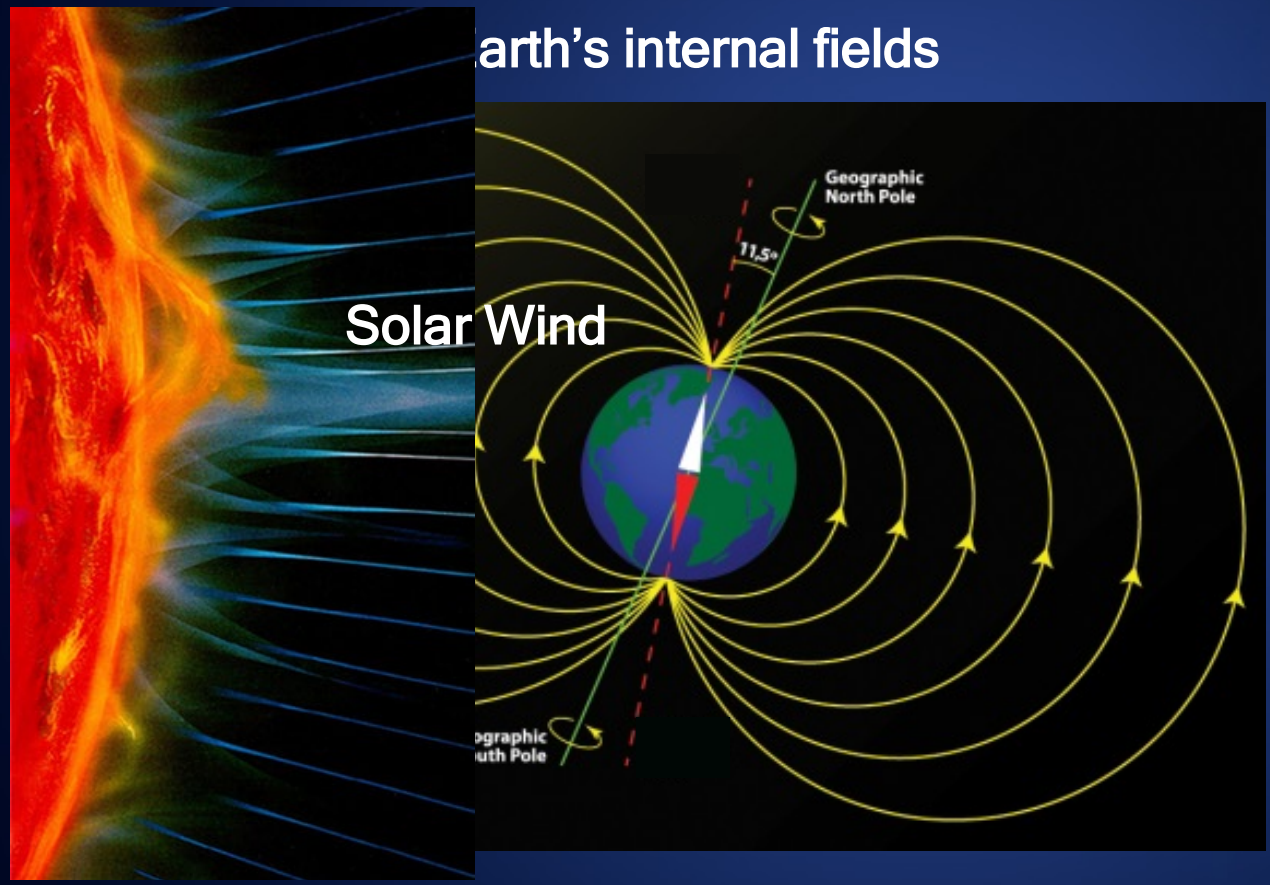
➢ From Rocky Mountains to Appalachian Mountains

➢ Hobbies: Karaoke, baking

Outline

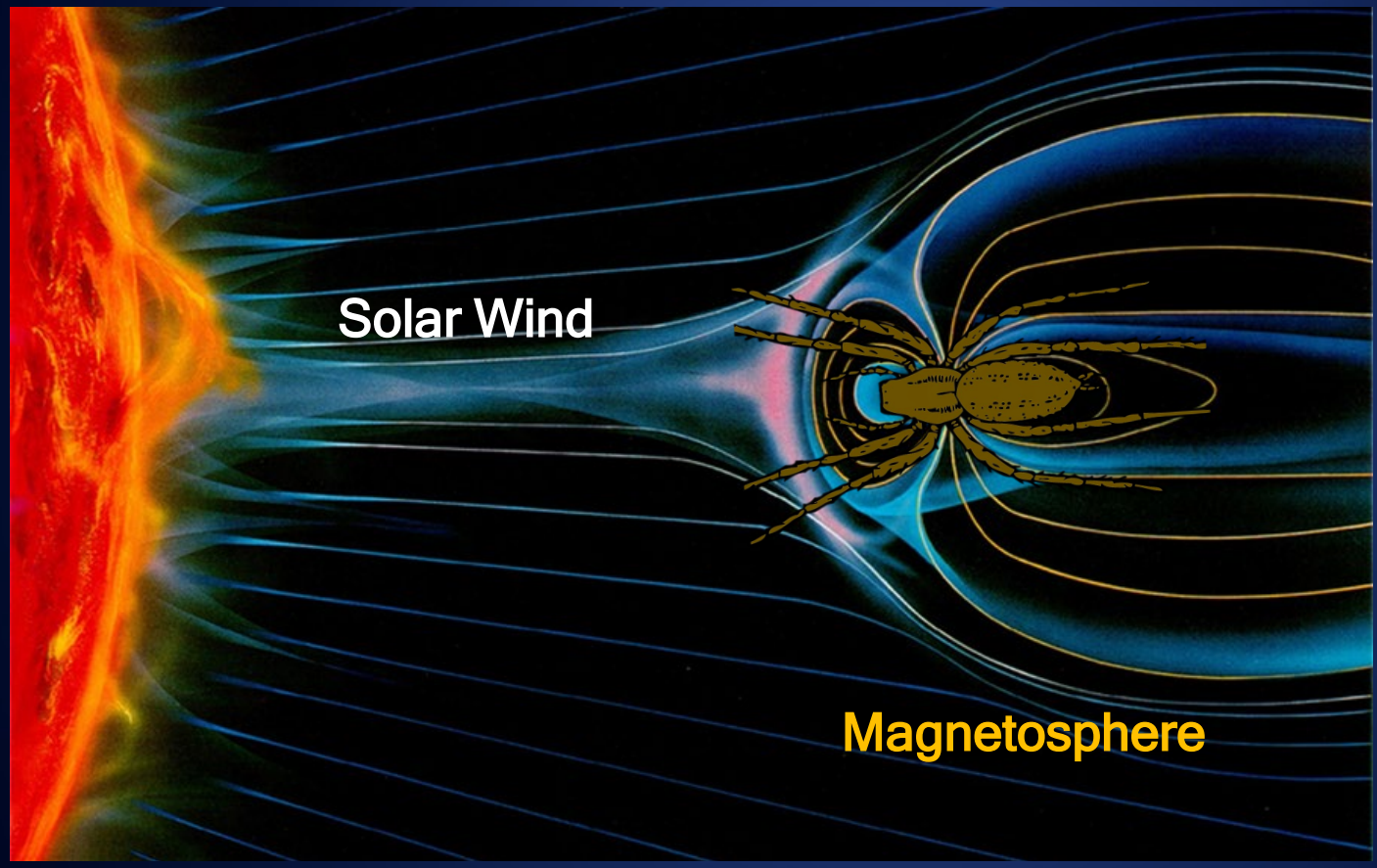
- Introduction: Earth's Magnetosphere
- Introduction: Van Allen Radiation Belts
- Why do we care? – Space Weather
- How do we study them? – Research Approaches

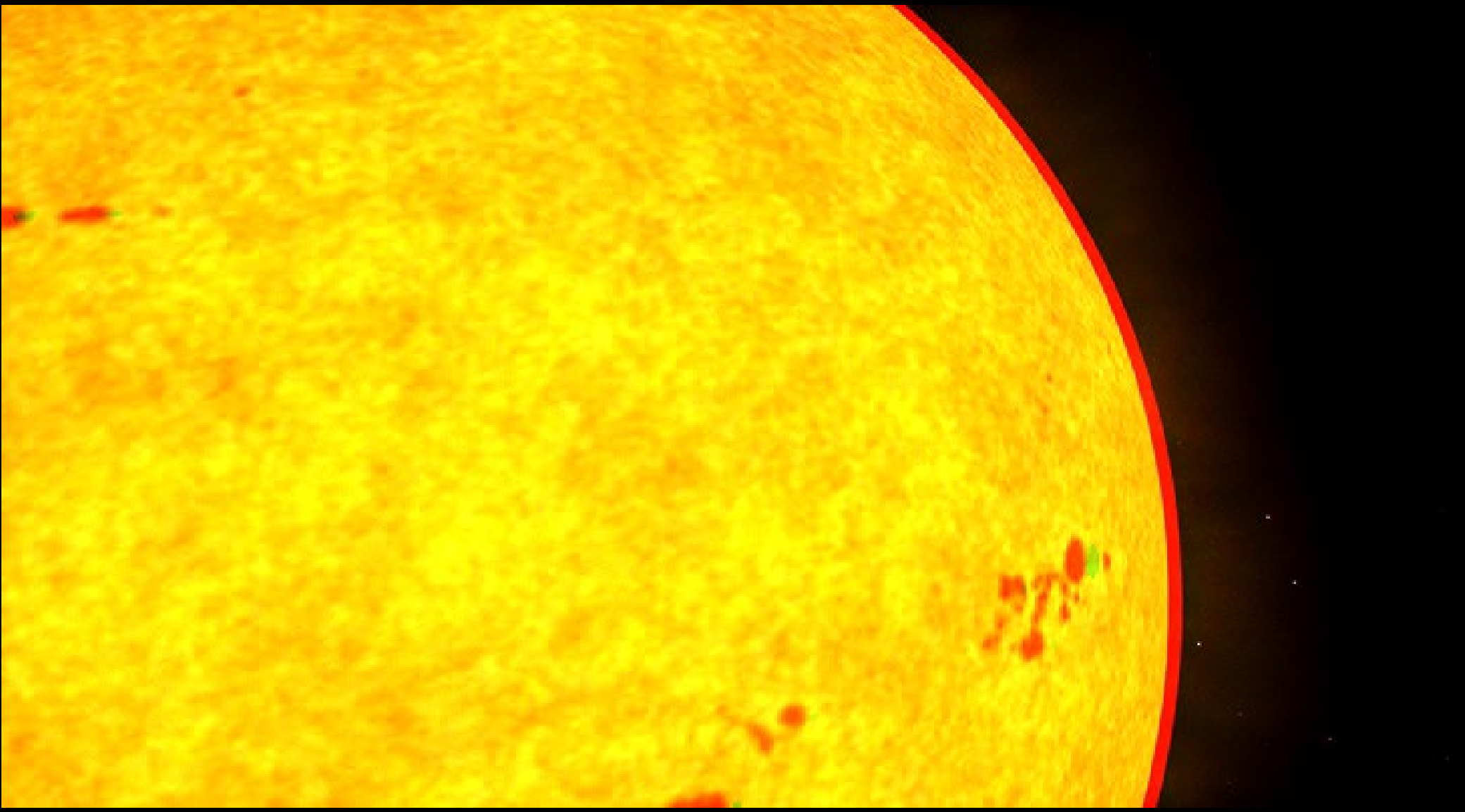
Earth’s Magnetosphere



Earth's Magnetosphere

- Charged particles in solar wind are swept by Earth's magnetic fields, creating a cavity called the Magnetosphere.





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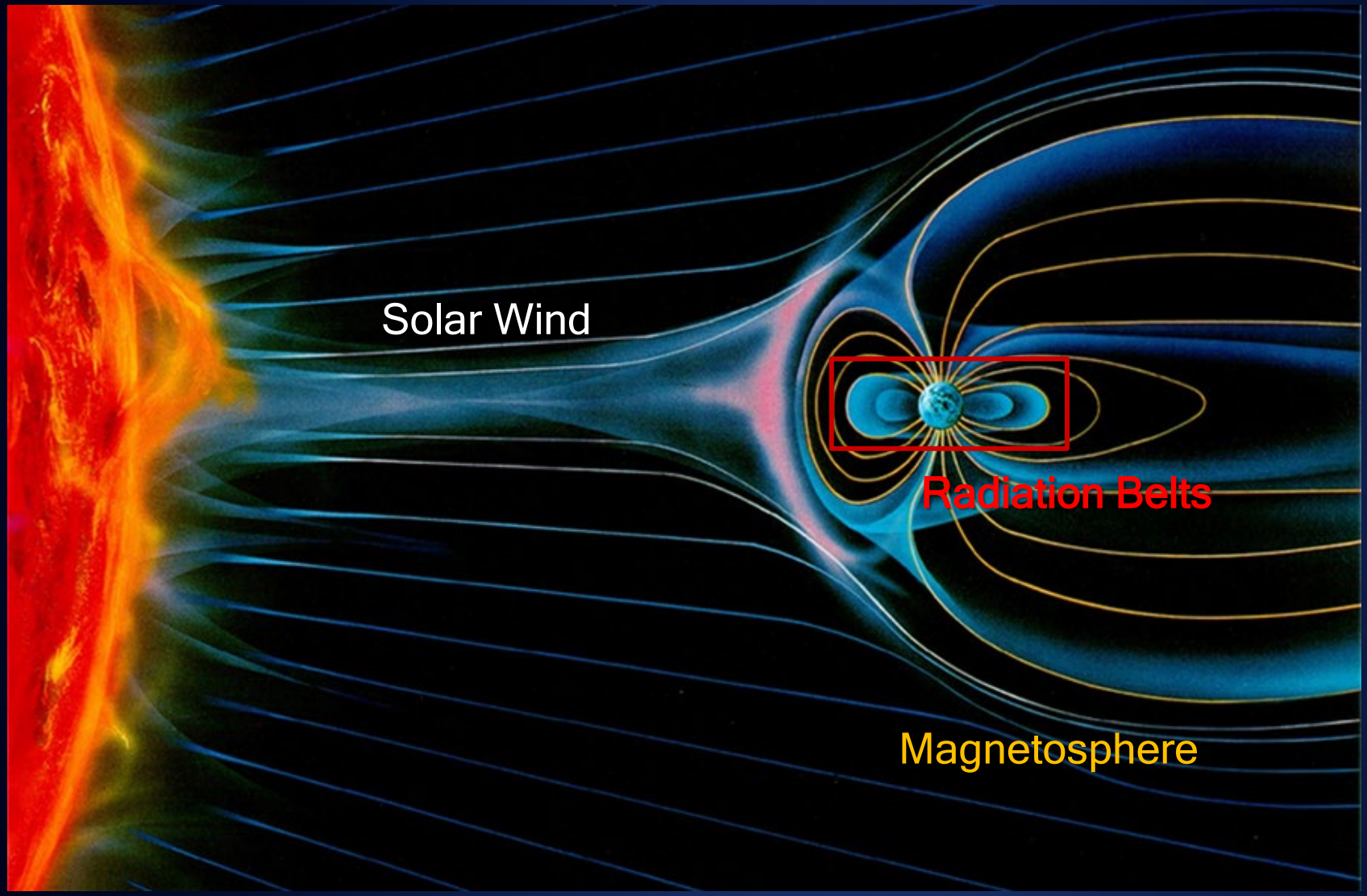
Radiation Belt in Magnetosphere

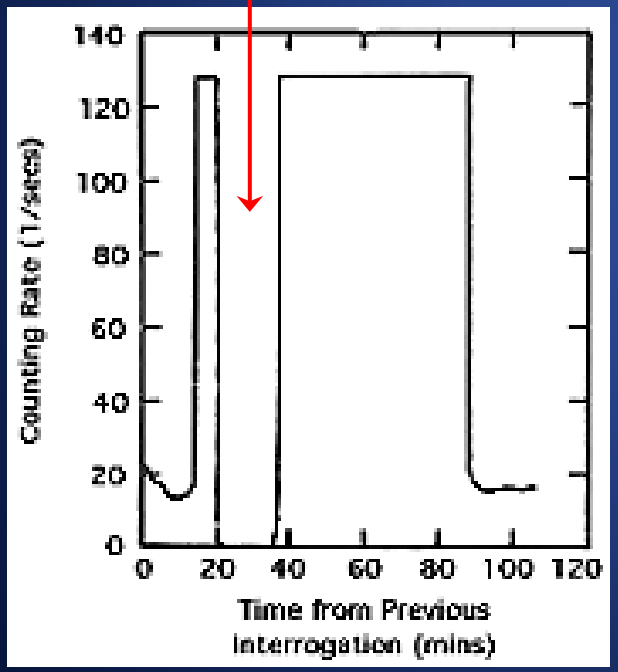


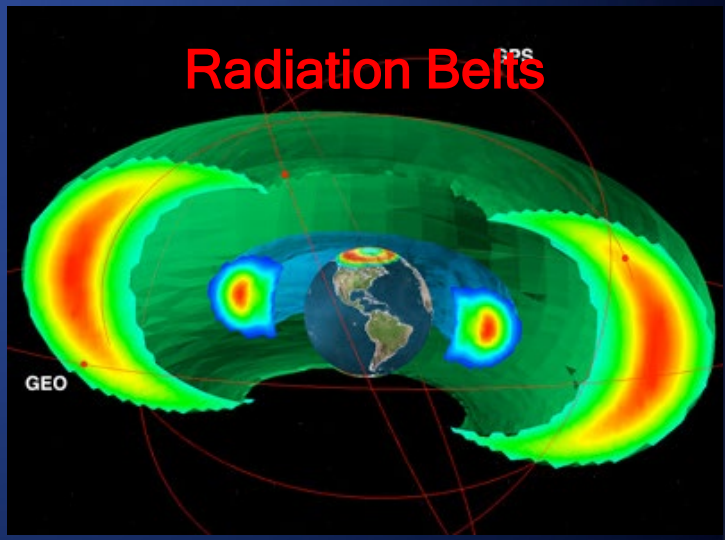
Van Allen Radiation Belts

- **Discovery!** In 1958 by Explorer 1 under Dr. James Van Allen.

Explorer 1 launch: 1958

"My God, space is radioactive!"



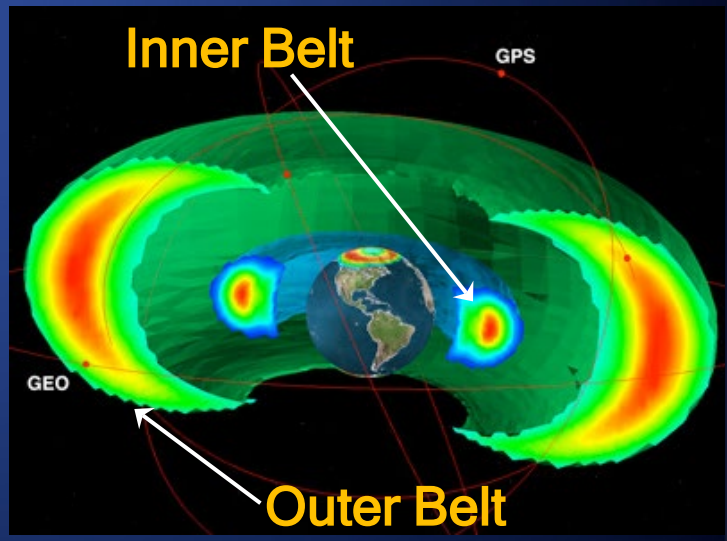


Van Allen Radiation Belts

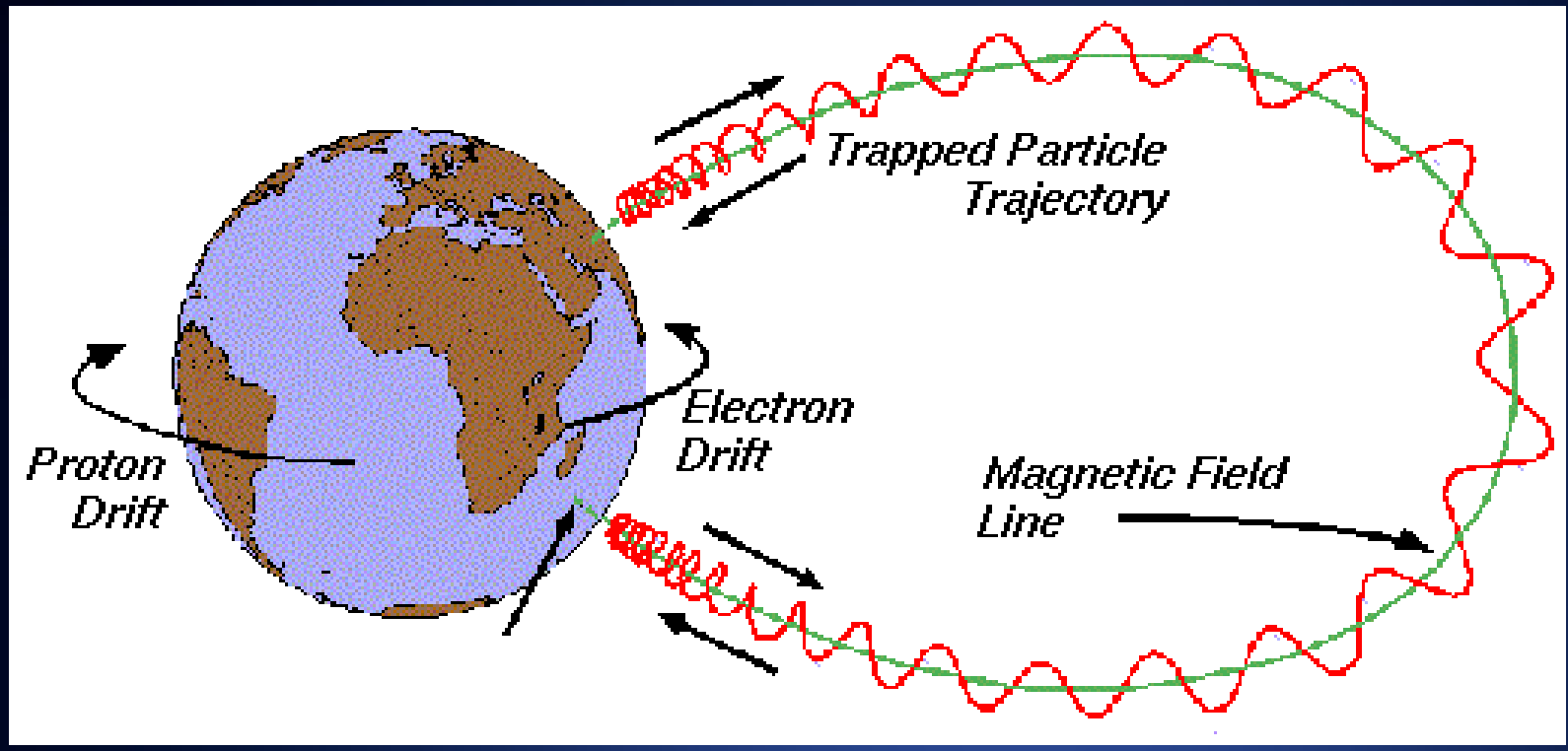
- Discovery! In 1958 by Explorer 1 and 3 under Dr. James Van Allen.

Explorer 1 launch: 1958

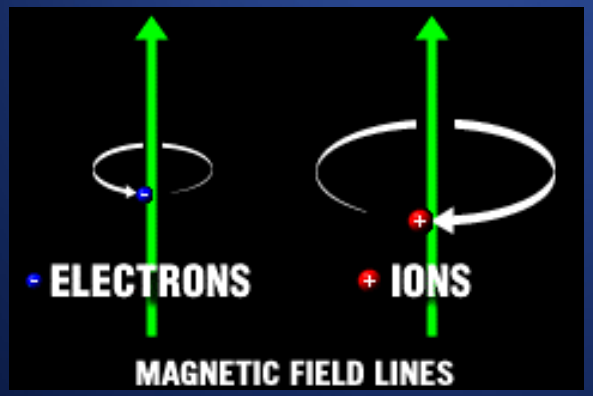
- Belts of energetic charged particles trapped by Earth's magnetic fields.
- Inner belt
  - 1,000-6,000 km altitude
  - Protons (10s-100s MeV)
    Electrons (10s-100s KeV)
- Outer belt
  - 13,000-60,000 km altitude
  - Electrons (0.5-10 MeV)



Charged Particle Motions



- Gyromotion:



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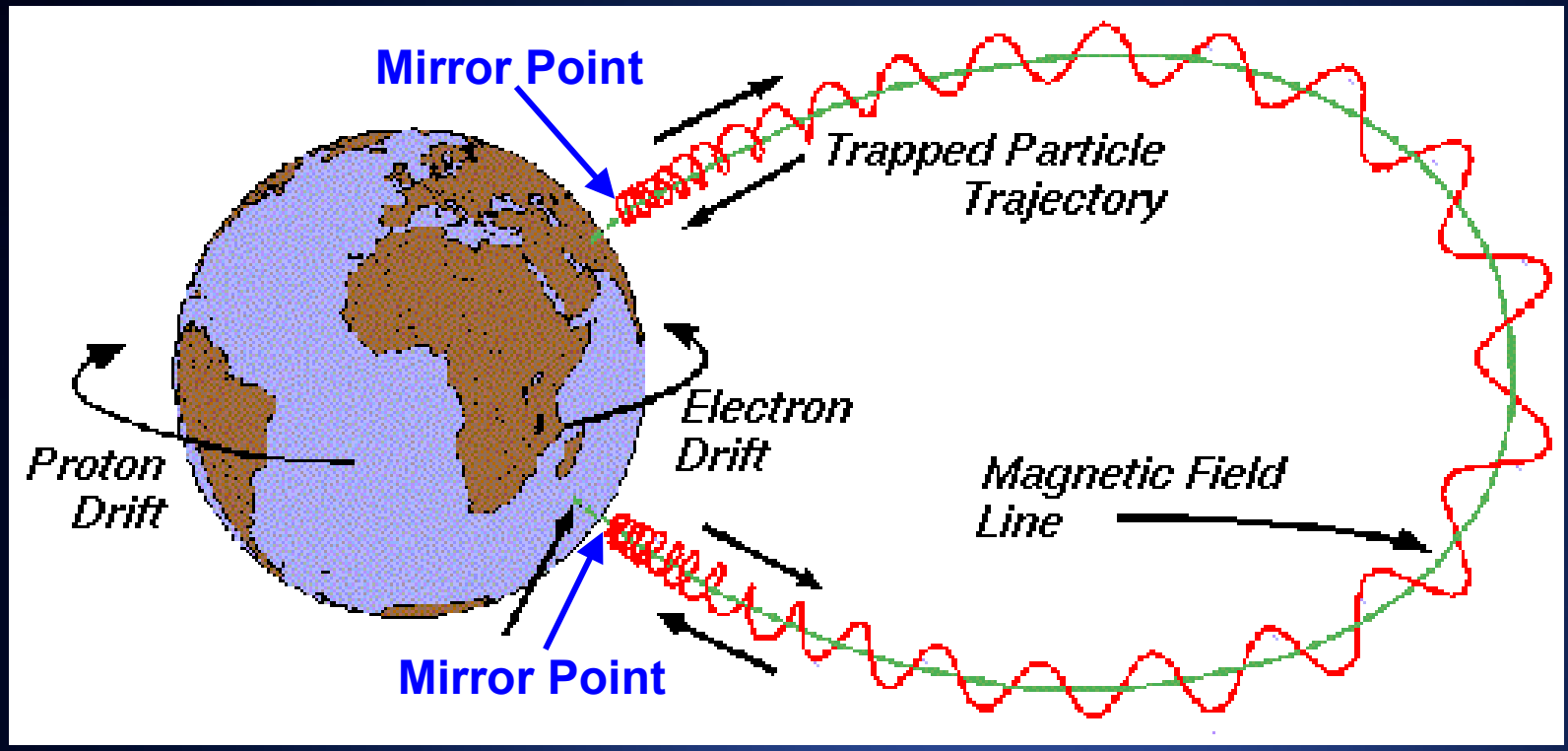
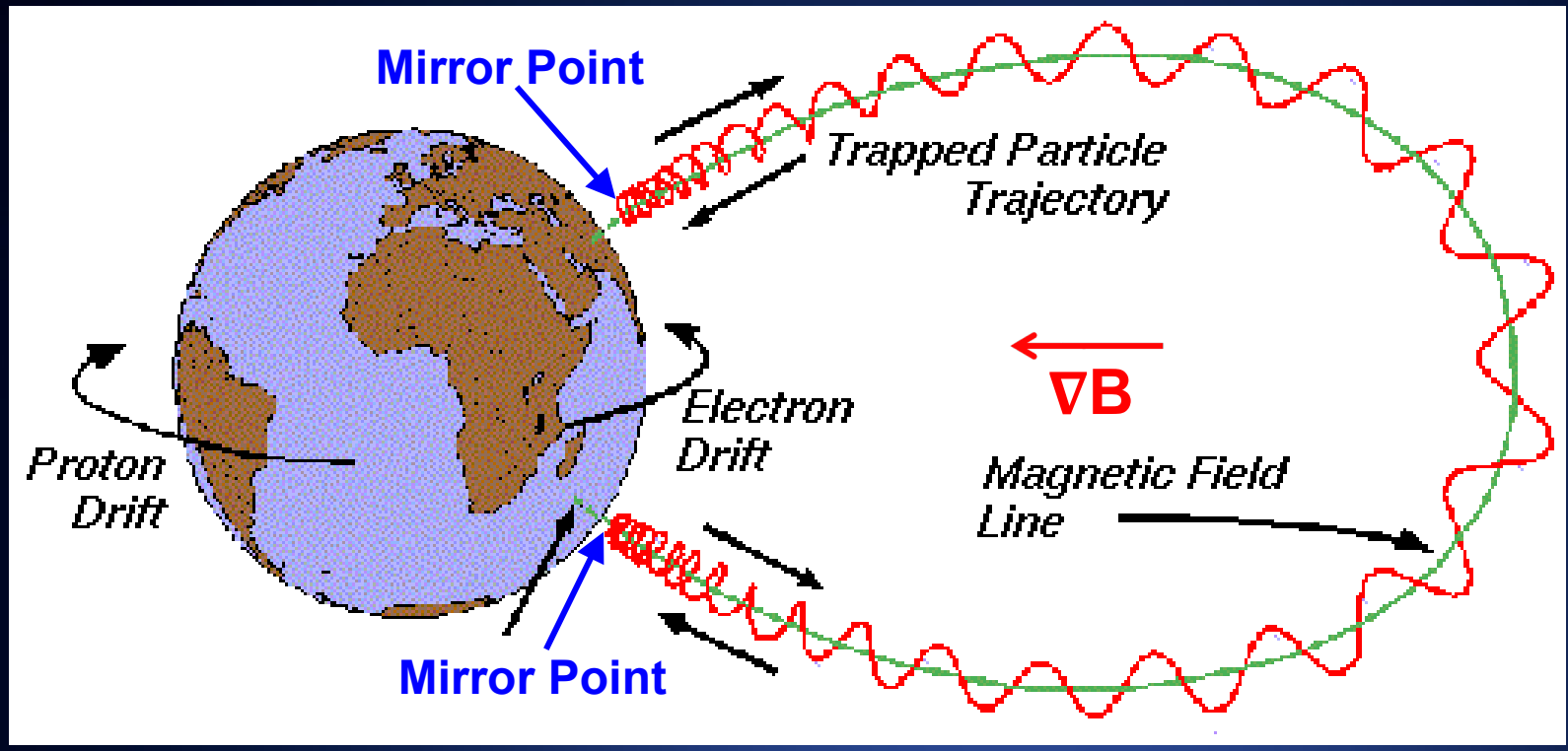
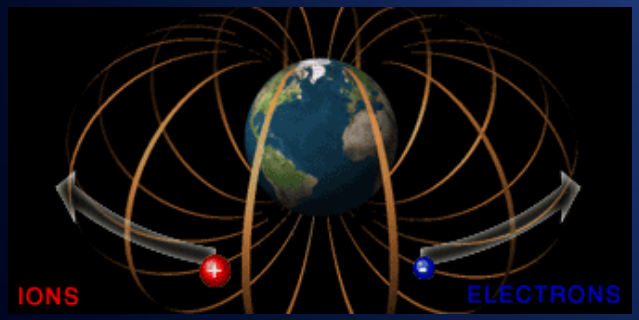


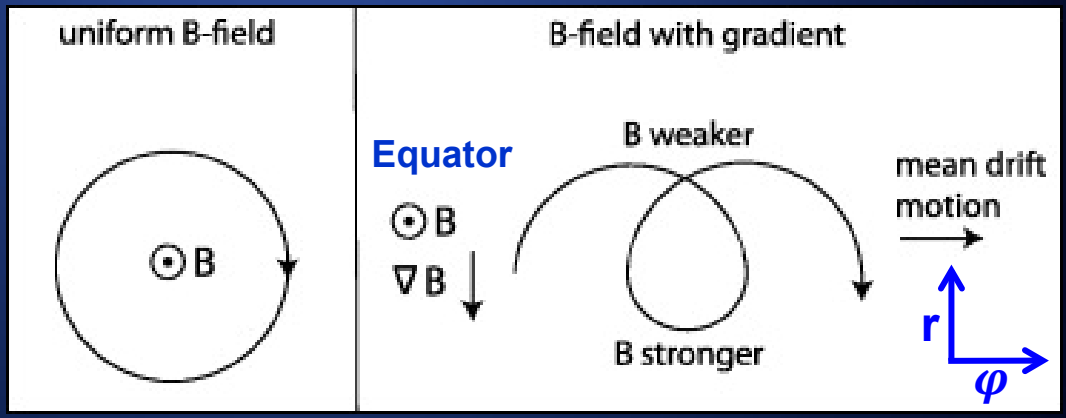
- Bounce motion:

Charged Particle Motions



- Drift motion:





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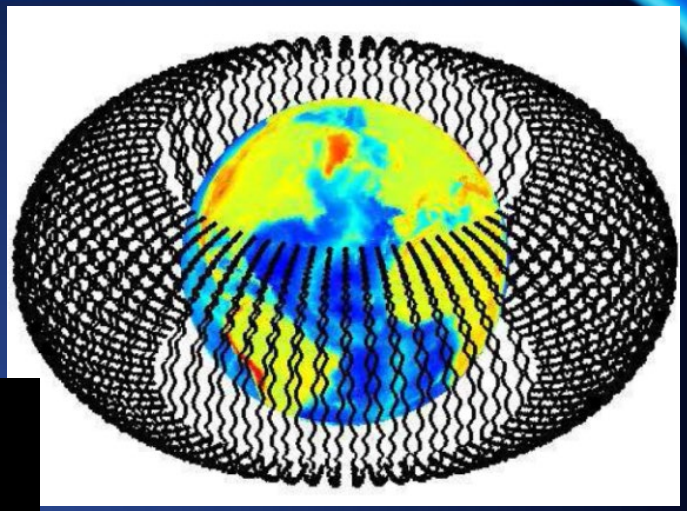


Van Allen Belts Dance

Are Radiation Belts Static?

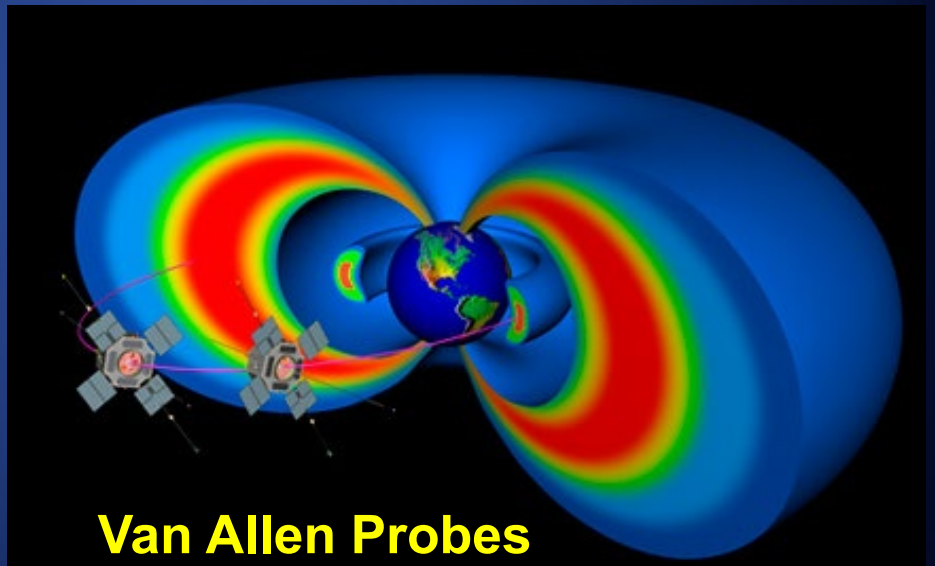
- After the discovery of Van Allen Belts, the radiation belts were thought to be static through the 1960's.

"The problem has been solved"

"The radiation belts are unchanging"

"The textbooks are being written"

- New missions in the 1990's and 2000's showed that the electrons in the outer radiation belt are highly dynamics!
- Understanding the dynamics is the No.1 goal of the NASA Van Allen Probes Mission.



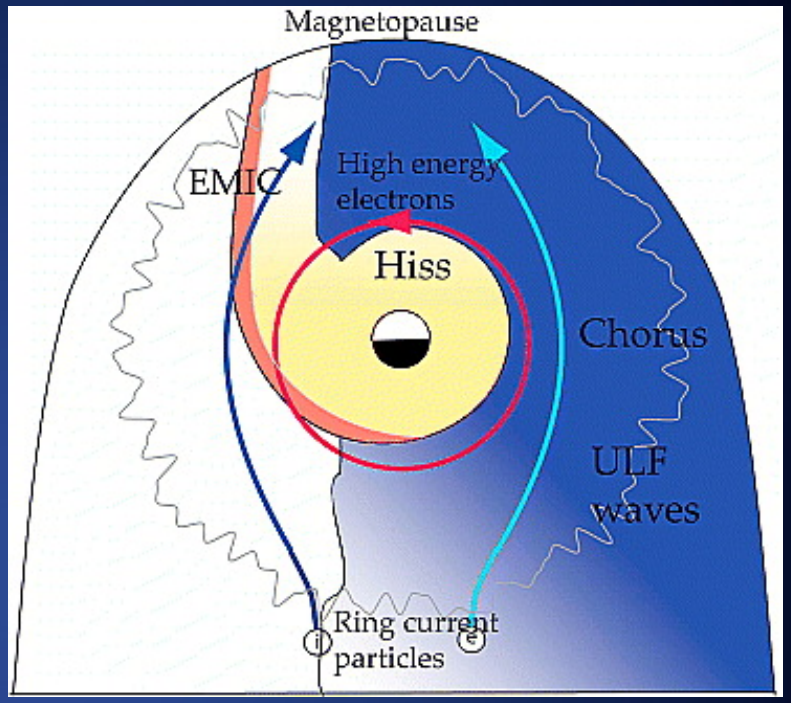
Van Allen Probes
(Aug 2012 – Oct 2019)

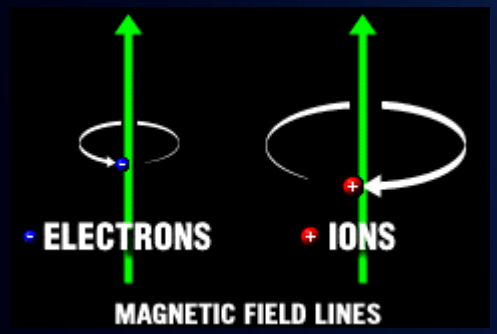
Radiation belts are highly dynamic!

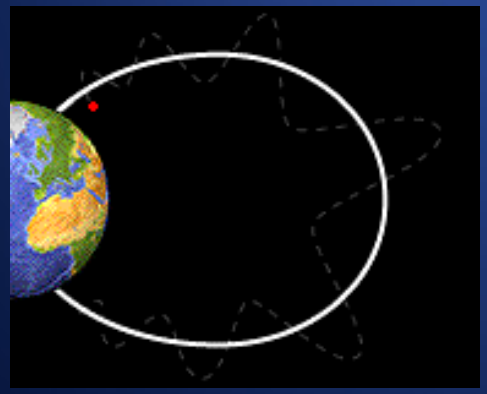
- The observed dynamics is a complicated balance between various source and loss processes.

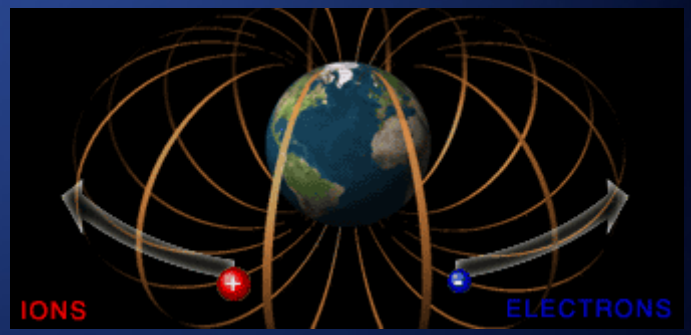
Wave-Particle Interactions

- A variety of electromagnetic waves exist in near-Earth space environment.
  - ULF waves, Chorus, Hiss, EMIC, etc.
- These waves have different frequencies that can resonate with the characteristic motions of radiation belt electrons.
  - Drift resonance, bounce resonance, gyro-resonance



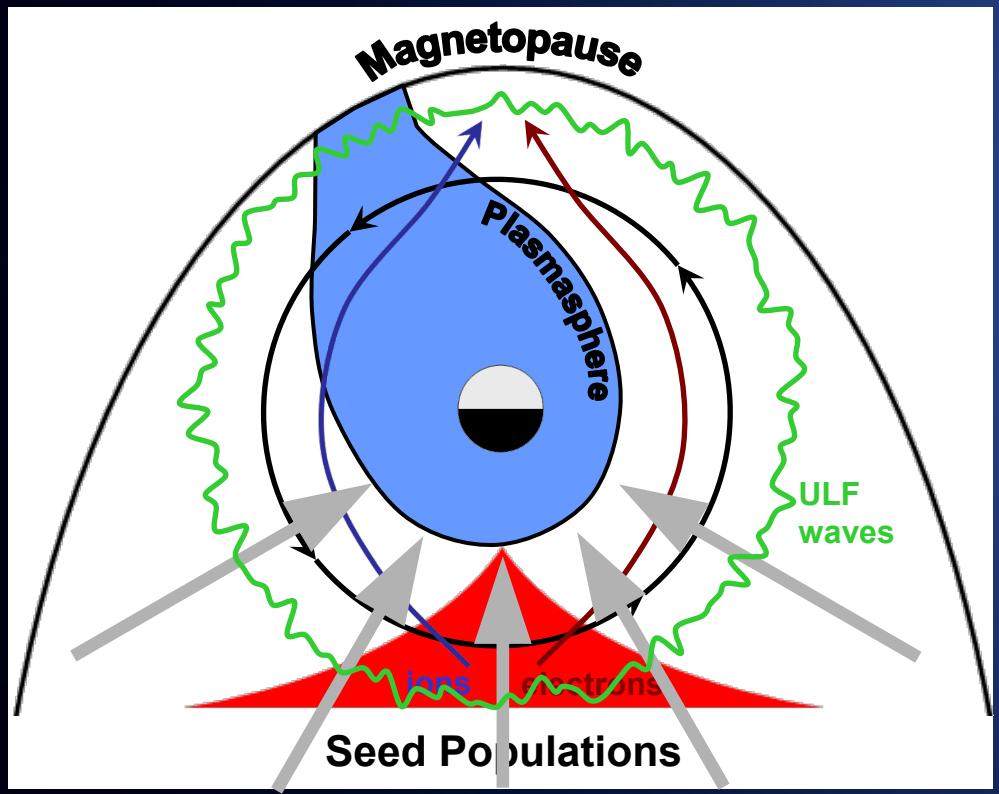


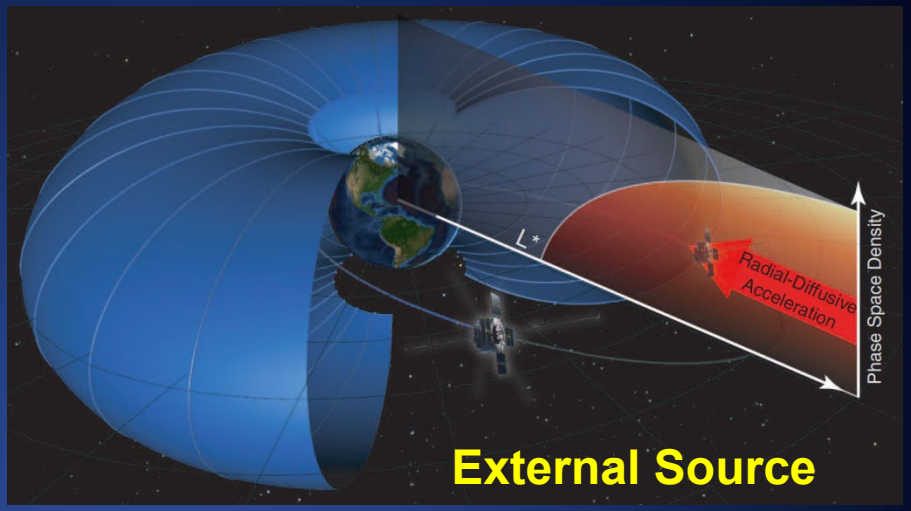


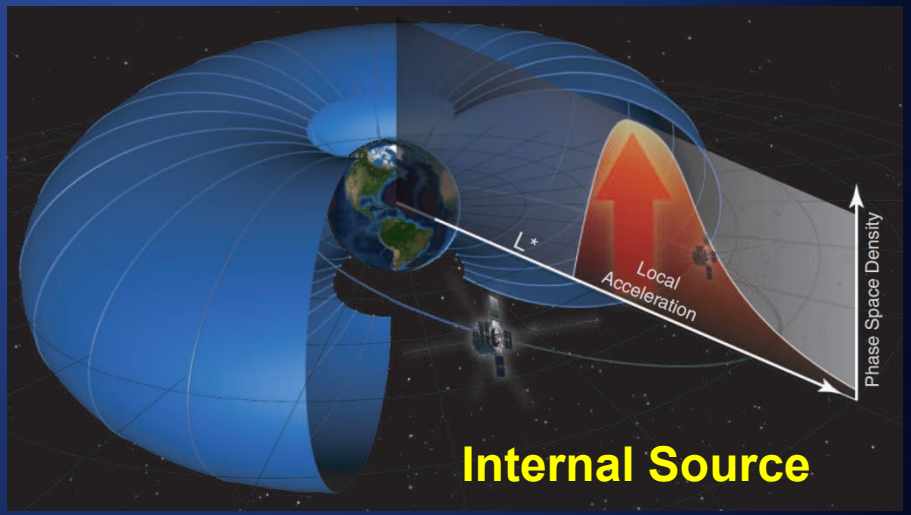


Radiation Belt Dynamics: Sources

- External source: Inward radial transport due to interaction with ULF waves.



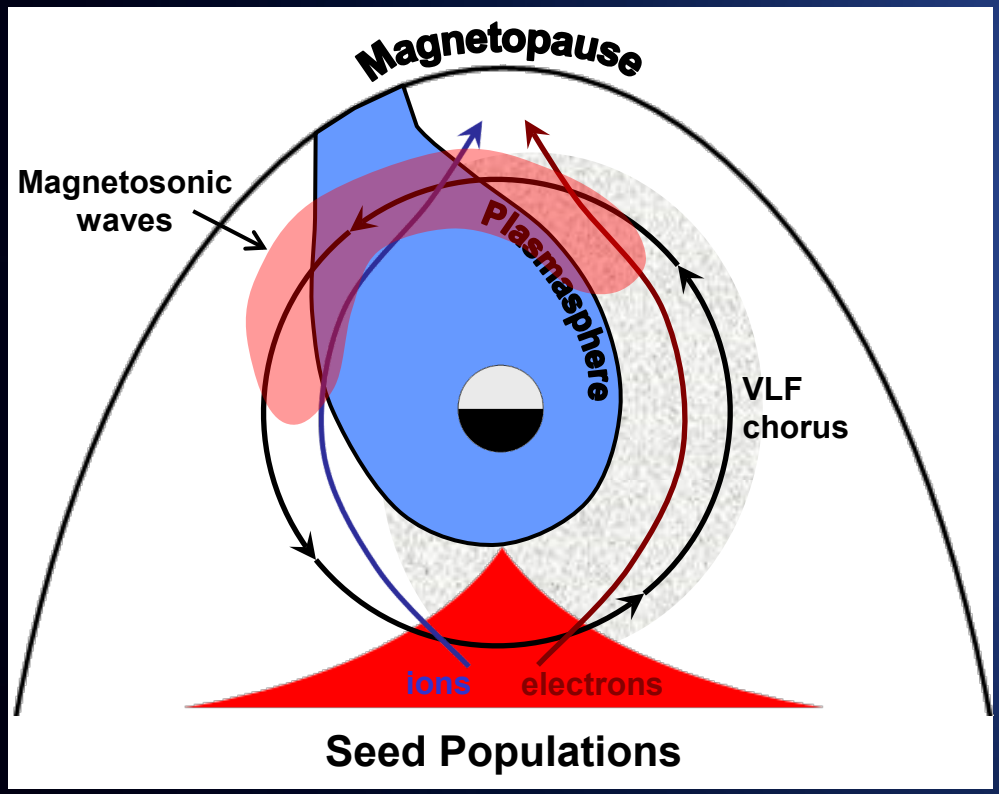


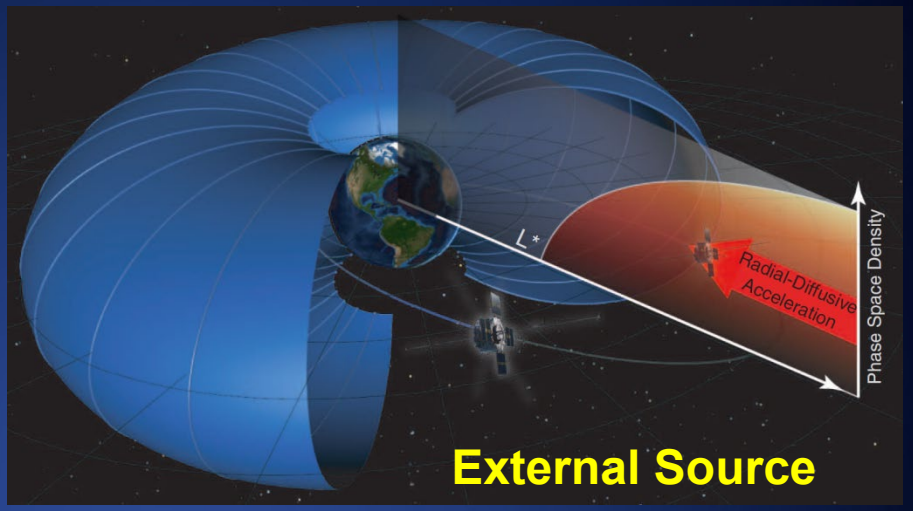


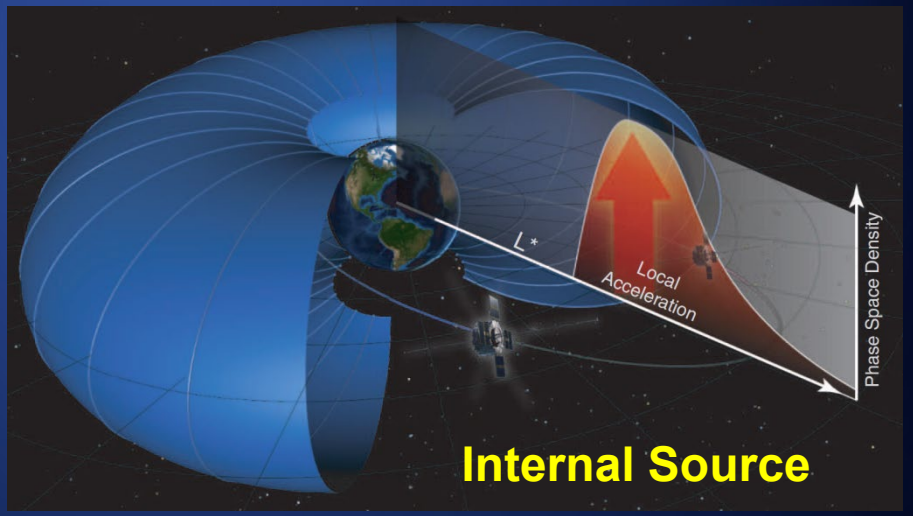
[Reeves et al., Science 2013]

Radiation Belt Dynamics: Sources

- External source: Inward radial transport due to interaction with ULF waves.
- Internal source: Local acceleration due to interaction with VLF waves.







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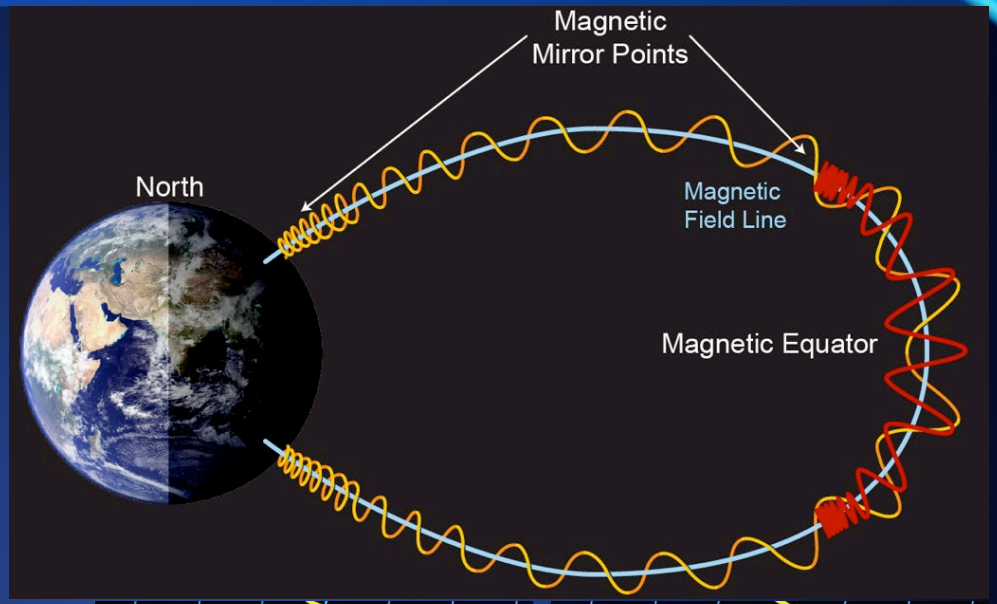
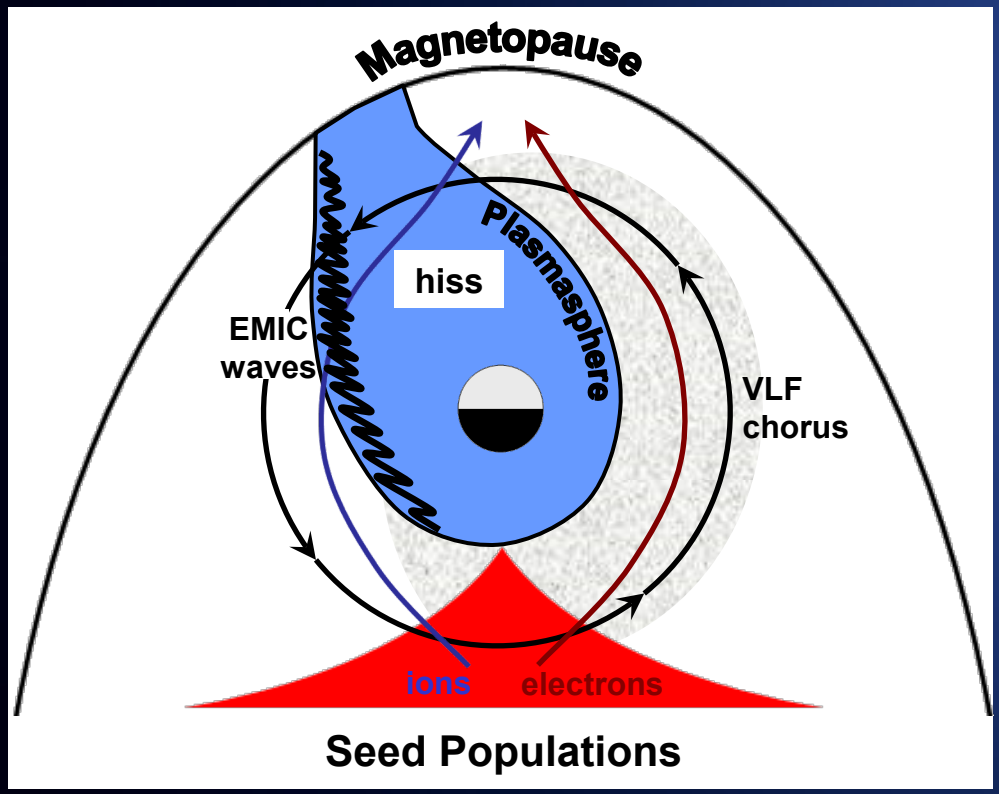
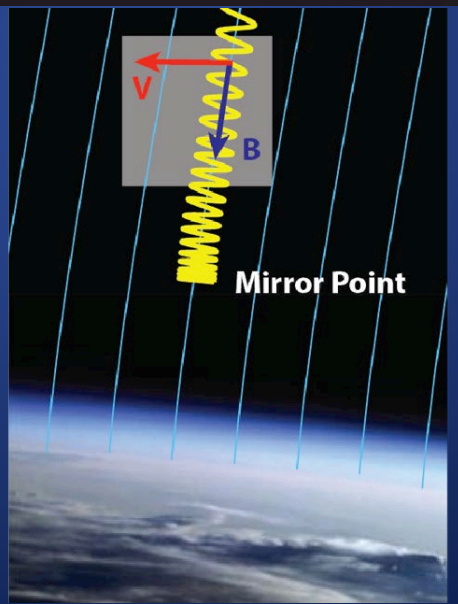
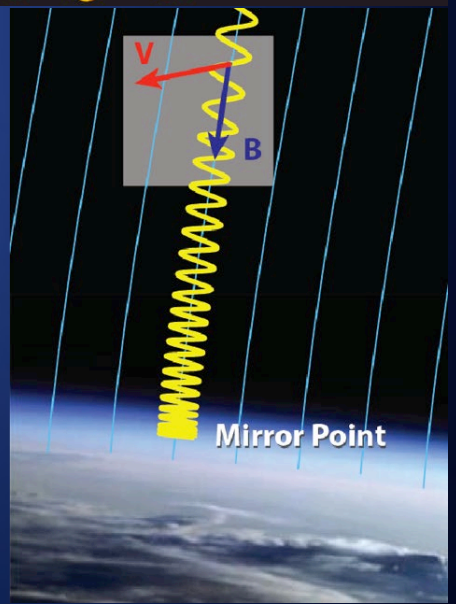
Radiation Belt Dynamics: Losses

- **Precipitation loss:** pitch angle scattering by, e.g., VLF, EMIC waves.



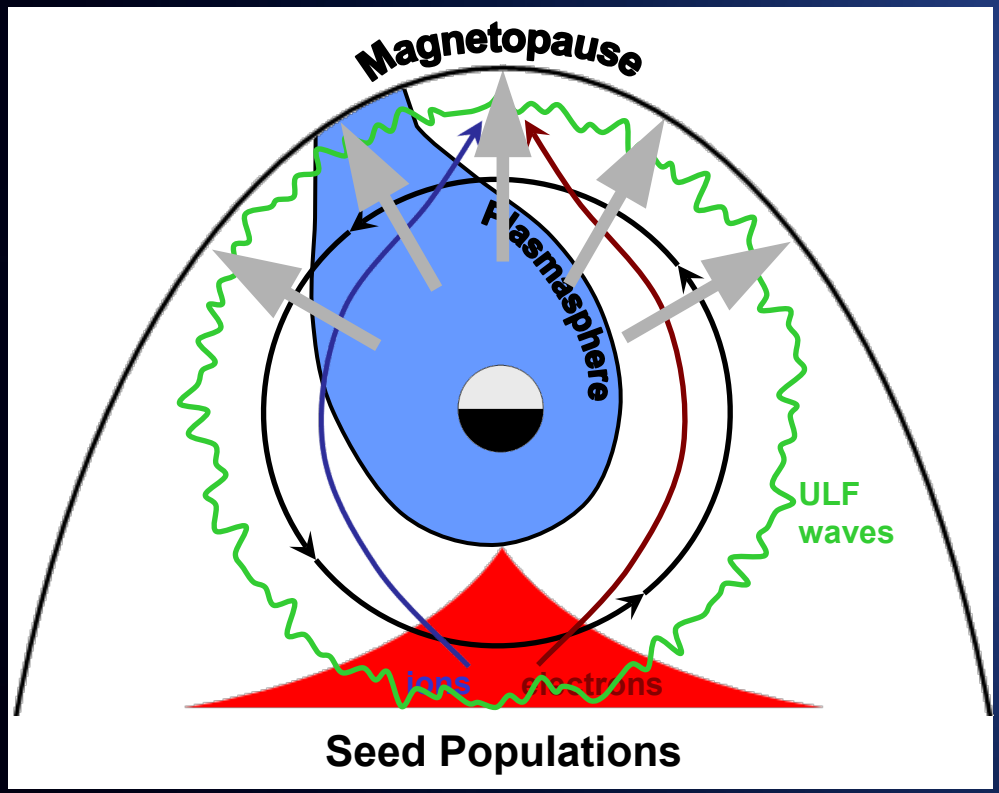


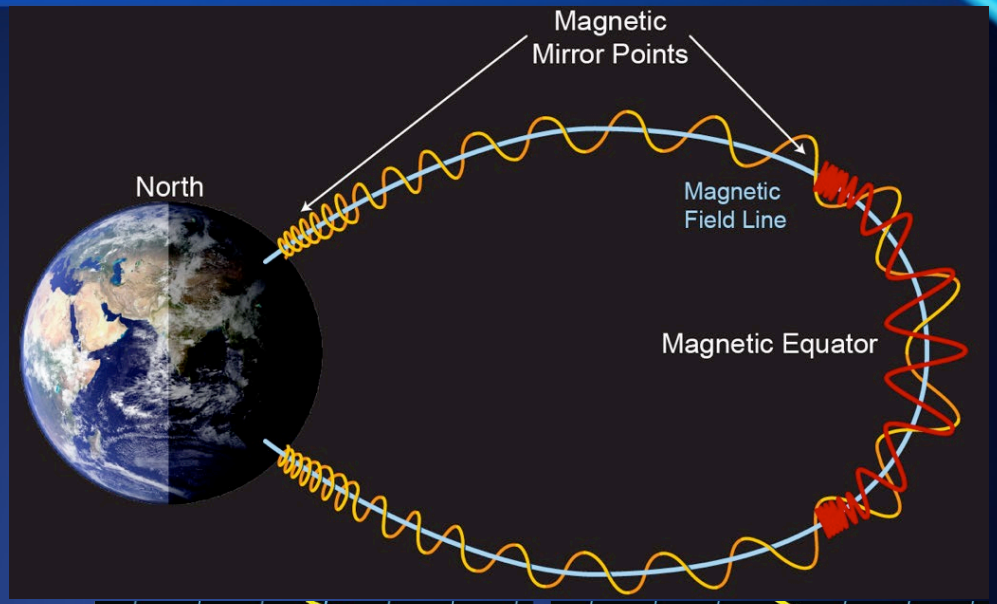


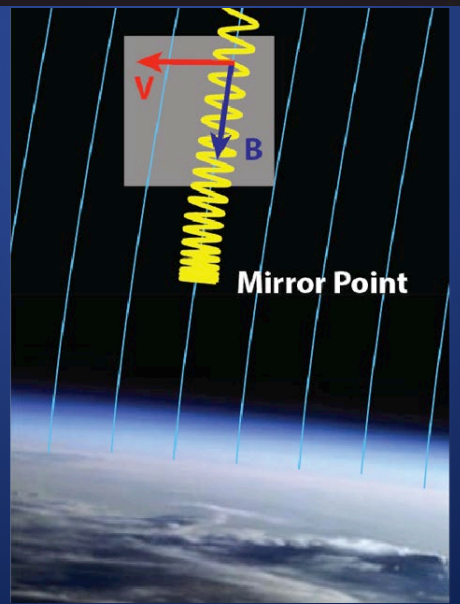


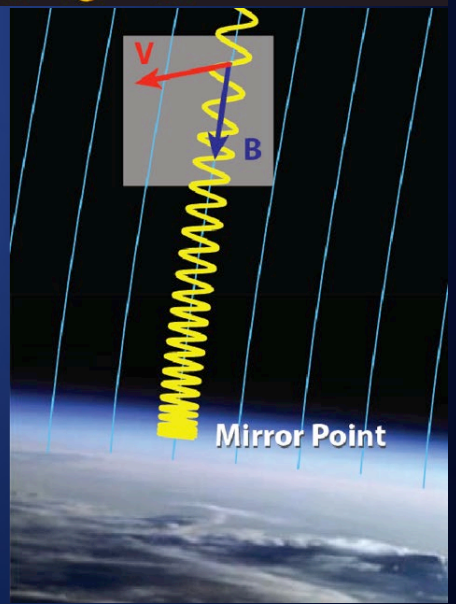
Radiation Belt Dynamics: Losses

- **Precipitation loss:** pitch angle scattering by, e.g., VLF, EMIC waves.
- **Magnetopause shadowing:** outward radial transport (ULF waves) or magnetopause compression.









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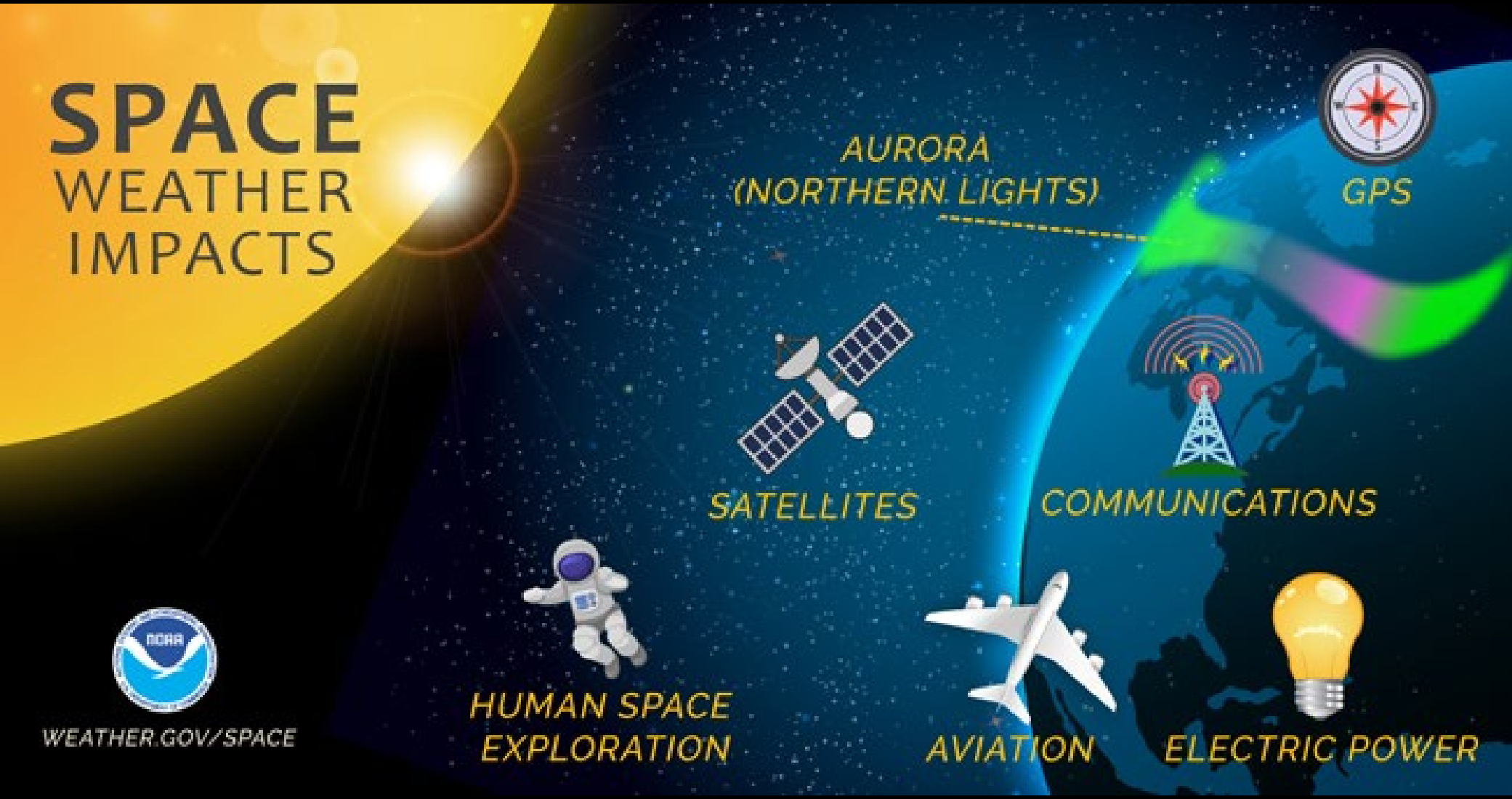
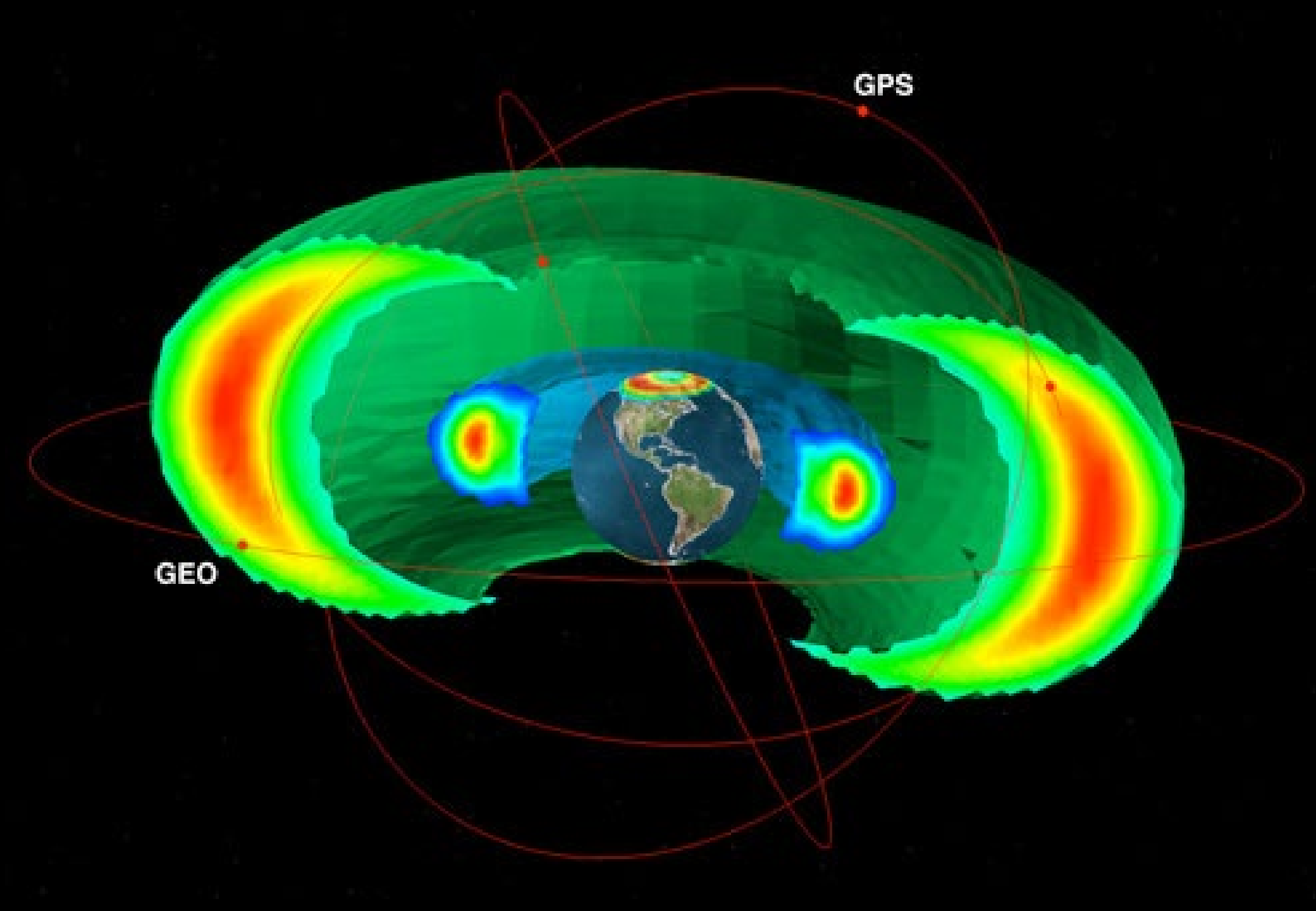
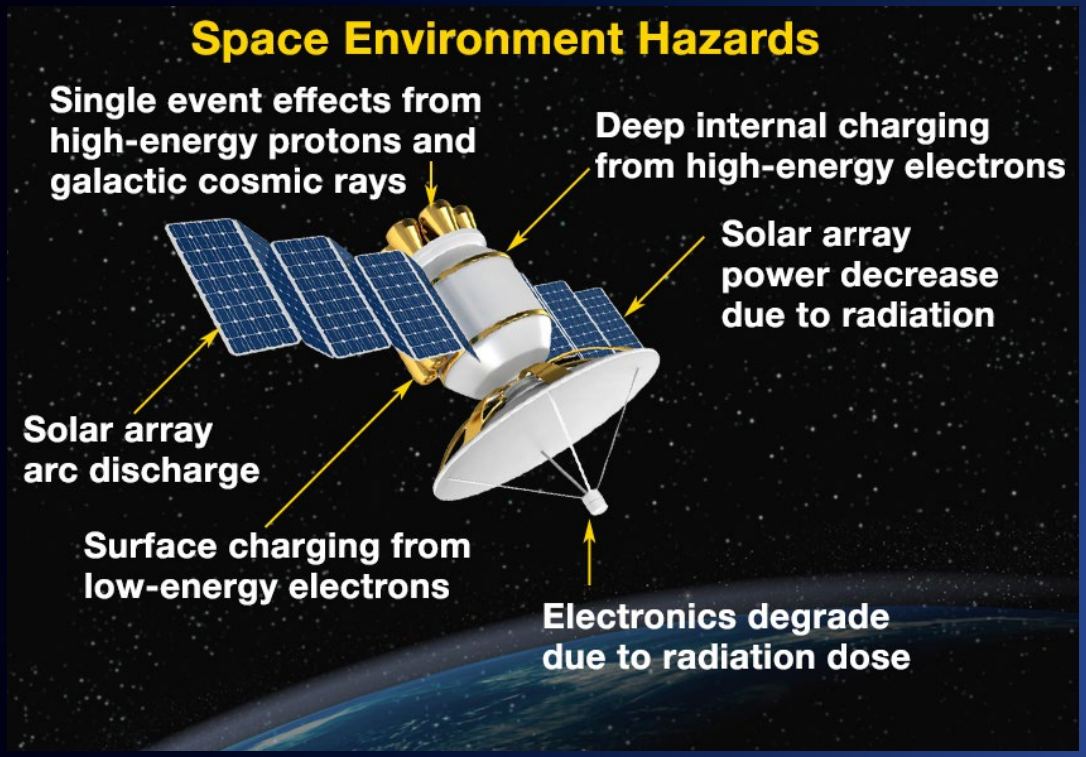
- Introduction: Van Allen Radiation Belts
- Why do we care? – Space Weather
- How do we study them? – Research Approaches


SPACE
WEATHER
IMPACTS
AURORA
(NORTHERN LIGHTS)
GPS
SATELLITES
COMMUNICATIONS
HUMAN SPACE
EXPLORATION
AVIATION
ELECTRIC POWER
WEATHER.GOV/SPACE


GPS
GEO

“Killer” Particles in Radiation Belts

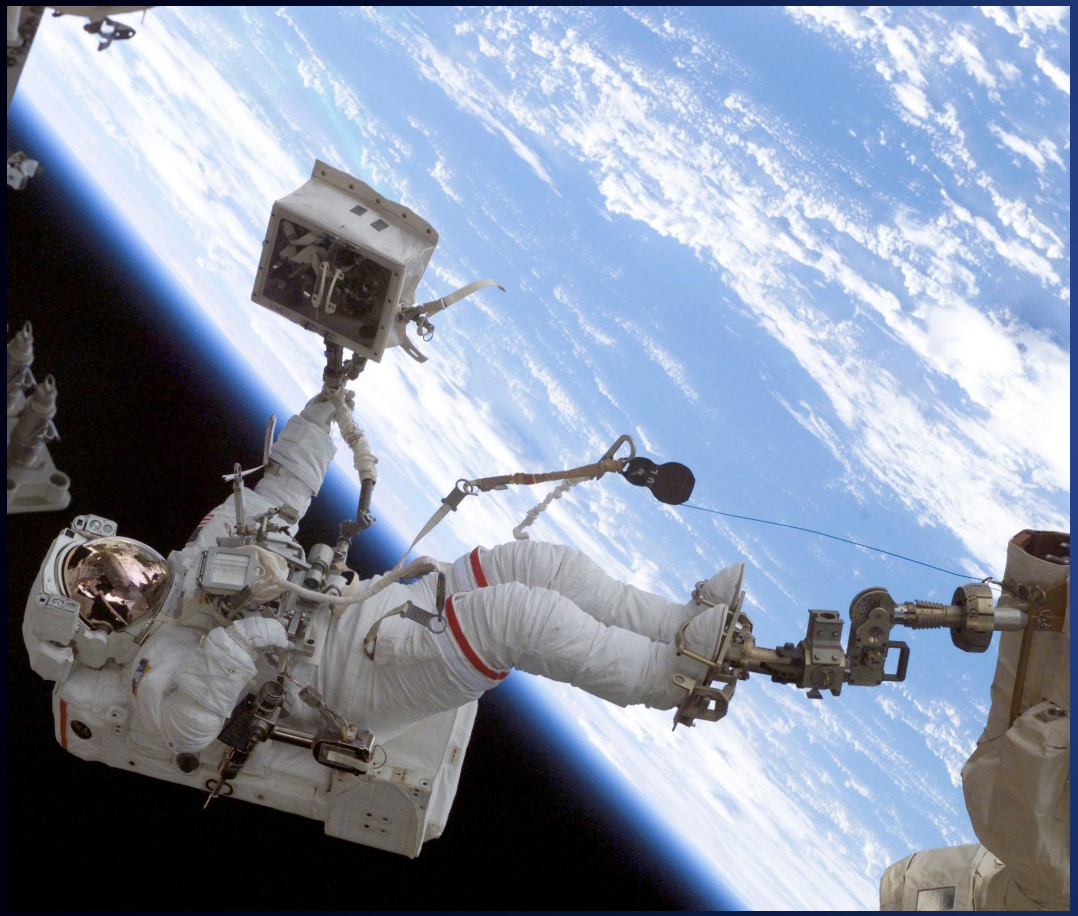


- Near-Earth radiation environment causes significant threats to spacecraft electronics.

- Several satellite ‘anomalies’ have been associated with variations in the energetic particle environment.

Elevated Radiation on Astronauts

- Astronauts are also at risk during space weather storms. If the radiation from highly energetic protons hits a person's body, it's like getting 40 chest X-rays at once!

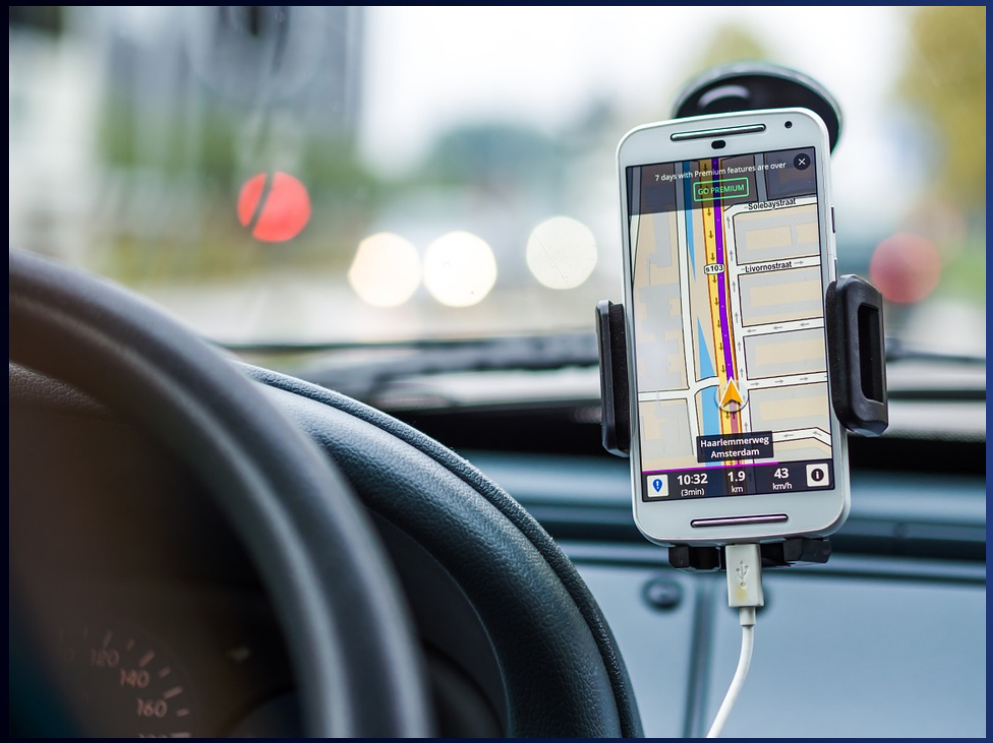


E.g., during the Halloween Storm of 2003:

- Astronauts inside the International Space Station retreated to the Station's shielded core to wait out the space-weather storm.
- Even there, the astronauts received elevated doses of radiation.

Effects on GPS Navigation

- The energetic particles in RB can directly threat the electronics of GPS satellites.



- Also, energetic particles can reach the Earth's ionosphere, 100 to 1000 km above the Earth, leading to increased ionization in the ionosphere.
- Increased ionization will affect the radio waves used for satellite communications or GPS navigation, leading to disruption of the communication or navigation systems.

Geomagnetically Induced Currents

- Energetic particles can interact with the Earth's magnetic field producing magnetic disturbances.
- Magnetic disturbances also induce electric currents in long conductors such as power lines and pipelines causing power system outages or pipeline corrosion.

- August 1989 storm: affected microchips, leading to a halt of all trading on Toronto's stock market as computers crash.
- Halloween Storm of 2003: induced electric current overloaded a high-voltage transformer and blacked out the city of Malmo in Sweden for almost an hour.

Confused Homing Pigeons

- Certain animal species on Earth are able to detect the magnetic field and used it for navigation purposes.

- During space weather disturbances, the intense electric currents flowing in near-Earth space produce non-steady magnetic fields that are felt at the Earth's surface.
- Homing pigeons have been observed to become confused during such disturbances and can even be lost.

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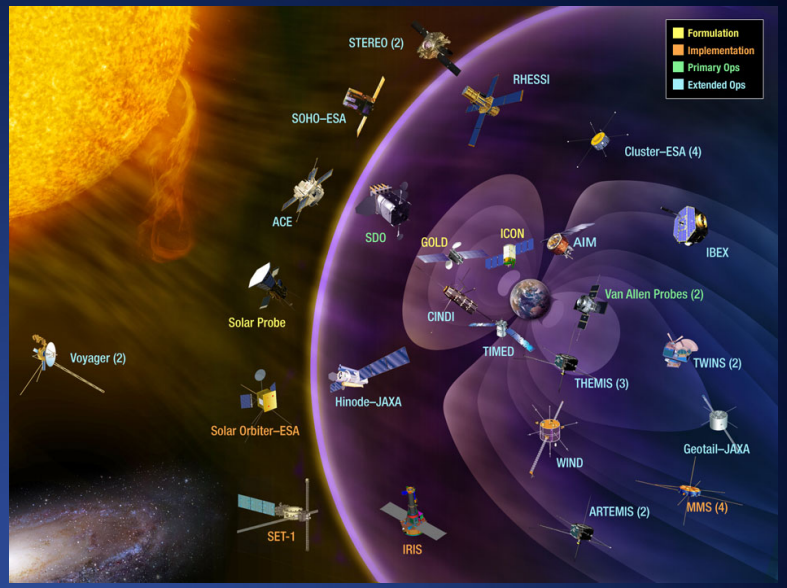
Research Approaches

- Data analysis
  - Wave and particle measurements from multiple space and ground missions
  - Combined with plasma theories to explain the radiation belt dynamics



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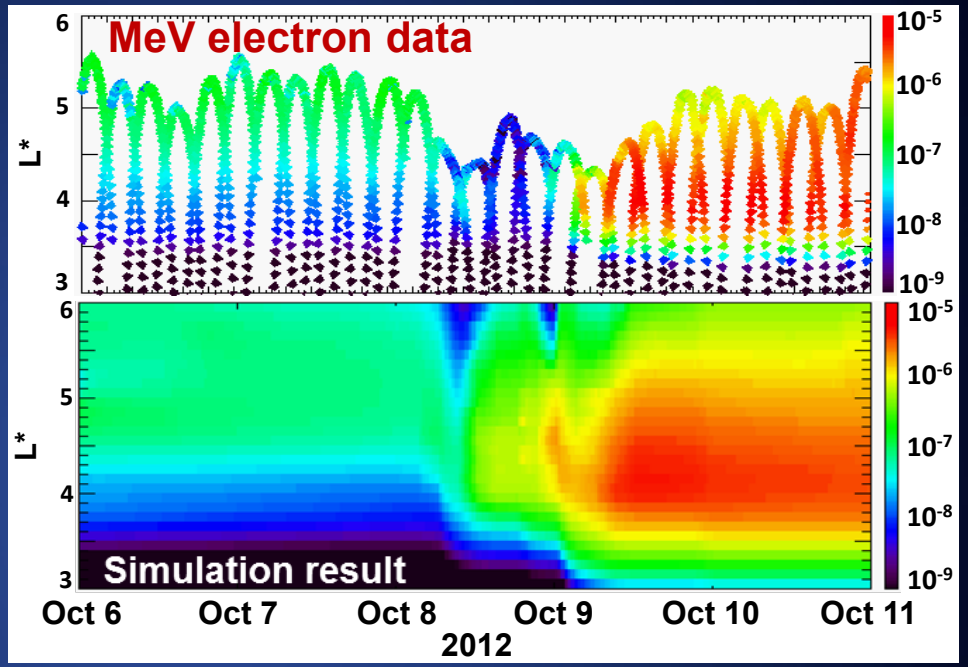
  - Develop analytical models to describe physical problems
  - E.g., DREAM3D diffusion model to simulate the acceleration and loss processes in radiation belt

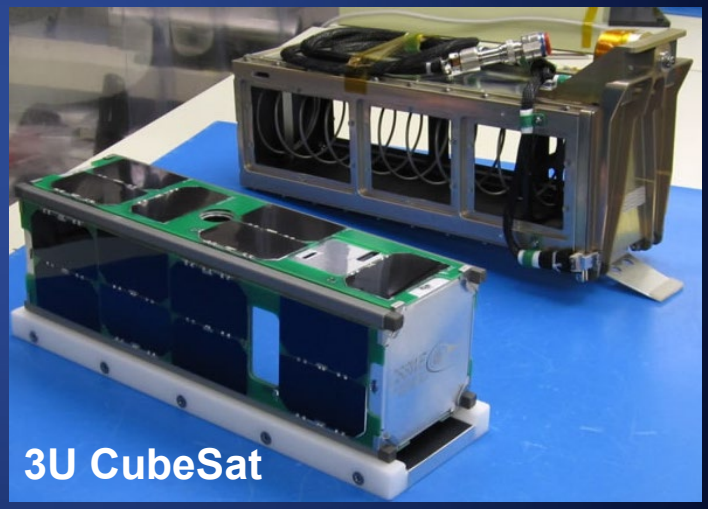


$$\frac{\partial f}{\partial t} = L^2 \frac{\partial}{\partial L}\left(\frac{D_{LL}}{L^2}\frac{\partial f}{\partial L}\right) + \frac{1}{\Gamma}\frac{\partial}{\partial \alpha}\left(\Gamma D_{\alpha\alpha}\frac{\partial f}{\partial \alpha}\right) + \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D_{pp}\frac{\partial f}{\partial p}\right)$$

Research Approaches

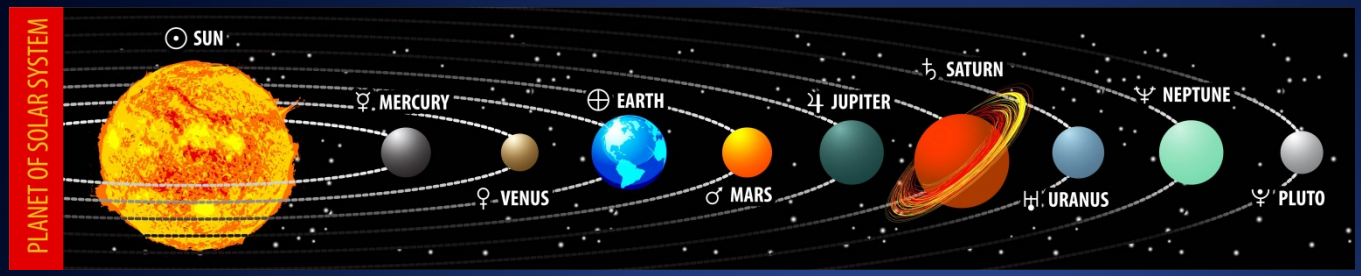
- Data analysis
  - Wave and particle measurements from multiple space and ground missions
  - Combined with plasma theories to explain the radiation belt dynamics
- Numerical modeling
  - Develop analytical models to describe physical problems
  - E.g., DREAM3D diffusion model to simulate the acceleration and loss processes in radiation belt
- Space exploration
  - Design and build an instrument or satellite to directly explore the energetic particle environment in space

Colorado Student CubeSat

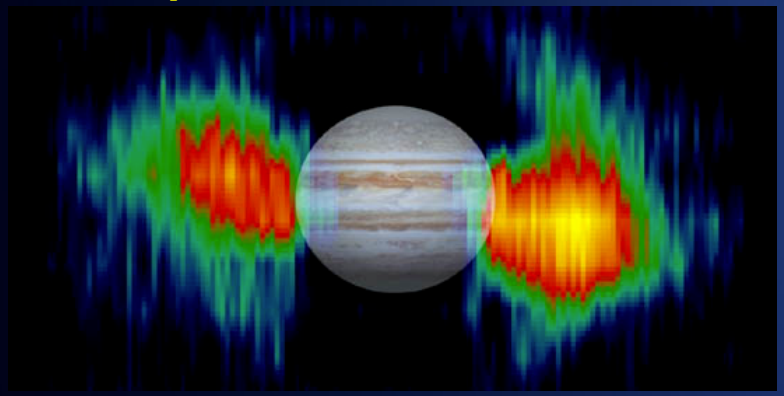


Radiation Belts Beyond Earth

- Radiation belts have also been discovered in other planets.

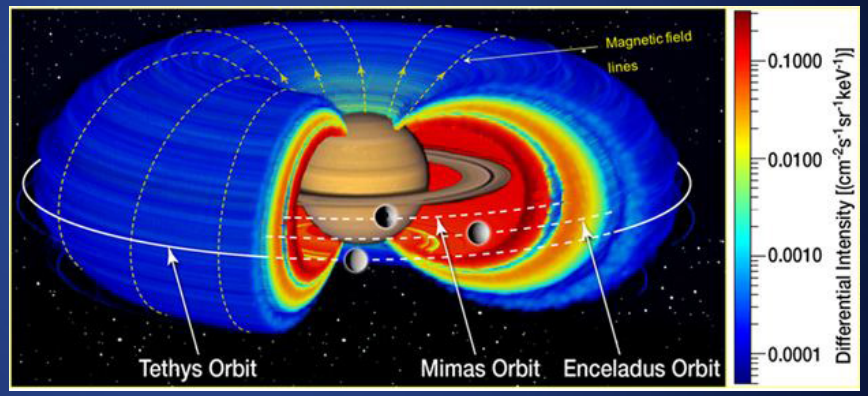


Jupiter's Radiation Belts



NASA

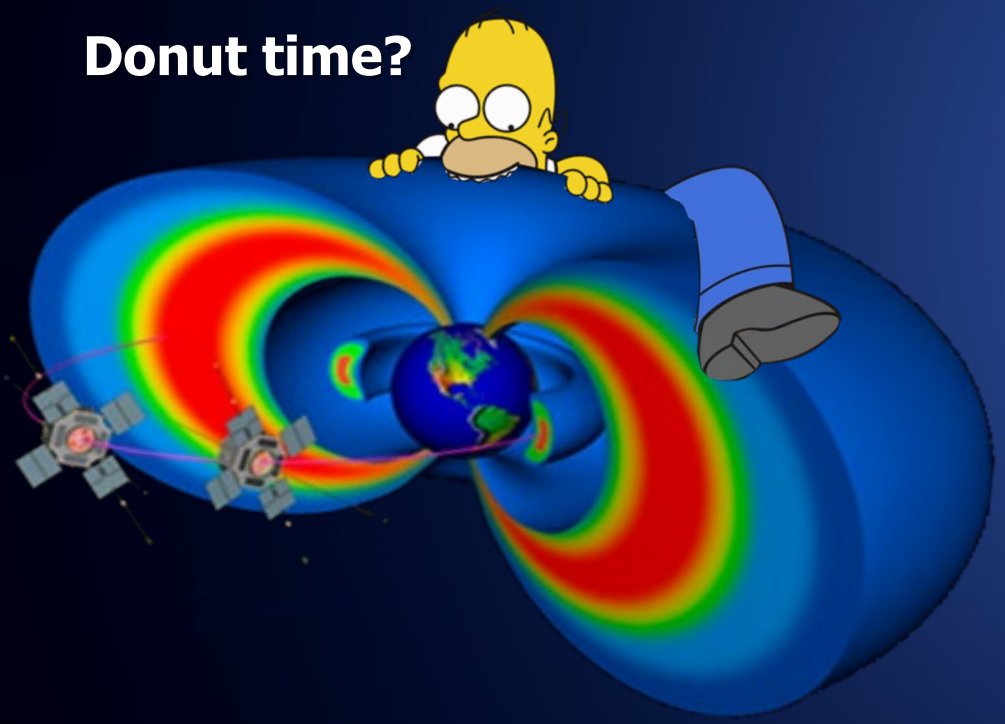
Saturn's Ion Radiation Belts



- Challenge & Opportunities: How do the radiations belts within very different planetary systems compare with each other? Can we extract what we learn between systems?

Take-Home Messages

Thank you!



- Energetic charged particles trapped by Earth's magnetic fields form radiation belts.
- Radiation belt is a highly dynamic system with important space weather applications.
- Active research is being performed to understand and predict this radiation environment!