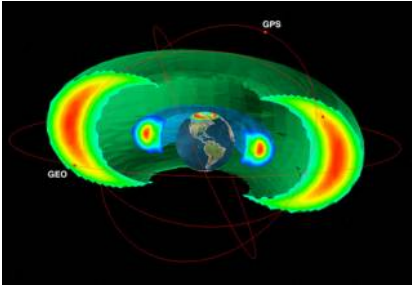
# Space Weather
# Lecture 8: Radiation Belts

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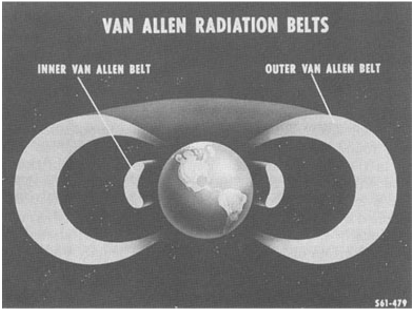
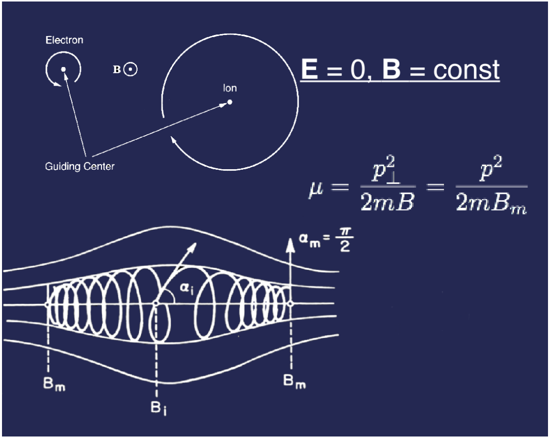
# History

- The first US spacecraft, Explorer 1, in 1958 detected intense charged particle radiation trapped by the geomagnetic field in what are now known as the Van Allen radiation belts.

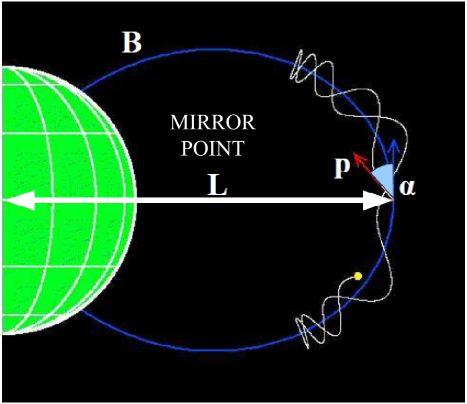
# Charged particle motions: gyration and bouncing




Courtesy: A. Ukhorskiy

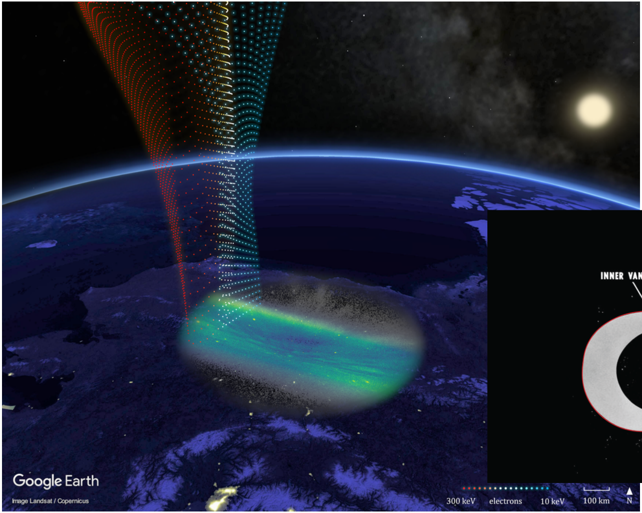
- Uniform rotation around a field line at cyclotron gyrofrequency
- Bounce motion in the magnetic bottle between two mirror points
- Pitch-angle, $\alpha$, of the particle changes from the maximum value at the equator to 90$^\circ$ at the mirror point
- $F_\parallel = -\mu \nabla_\parallel B$ is the mirror force

# Charged particle motions: bouncing



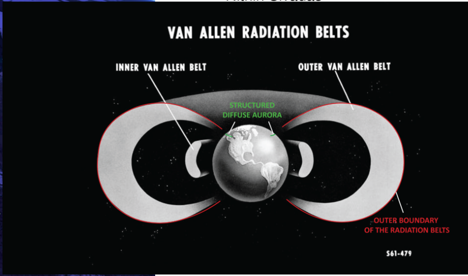

- Pitch-angle, $\alpha$, – the angle between the magnetic field and particle's velocity
- 90° particles will stay in the equatorial plane
- Small pitch-angle particles will be lost to the atmosphere in to the so-called loss cone

Courtesy: Y. Shprits

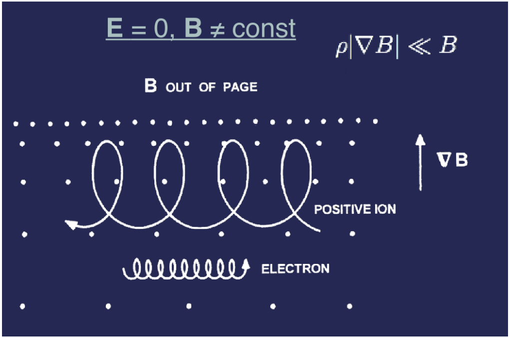



*Credits: NASA/Google Earth/Nithin Sivadas*

*Credits: NASA's GSFC/ Historic image of Van Allen Belts courtesy of NASA's Langley Research Center/ Nithin Sivadas*



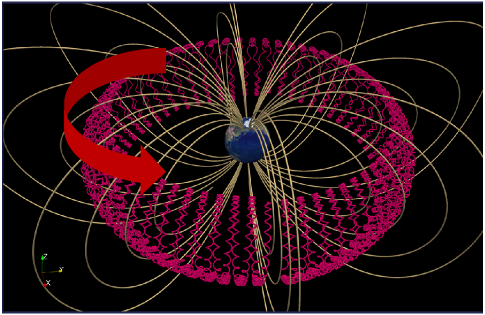
# Charged particle motions: drift




- Gradient of the magnetic field intensity causes drift of the guiding center
- $\rho$ is the particle gyroradius

Courtesy: Y. Shprits

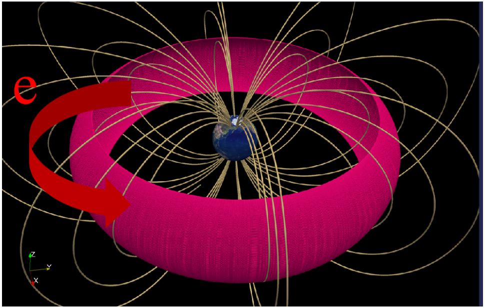
# Simulations of the drift: 1 MeV negative charge, $m = 20m_e$



- Gyro motion around the field line
- Bounce motion between the mirror points
- Slow drift around the Earth
- Each type of periodic motion can be associated with an adiabatic invariant

Courtesy: A. Ukhorskiy/Y. Shprits

# Simulations of the drift: 1 MeV electron




- Gyro motion around the field line
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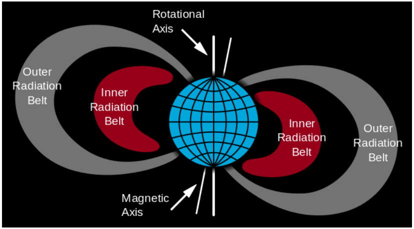
- Each type of periodic motion can be associated with an adiabatic invariant

Courtesy: A. Ukhorskiy/Y. Shprits

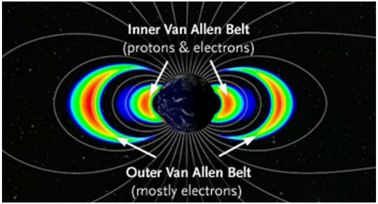
# Structure and location

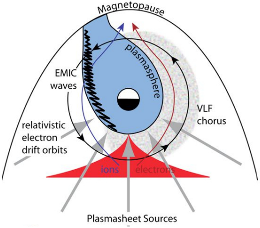
- There are “inner” and “outer” radiation belts.
- The inner edge of the inner zone is defined by the upper atmosphere of the Earth. It extends down to 300–1000 km near the South Atlantic anomaly. Many satellites, including ISS, fly at this height (Low Earth Orbit).
- The outer part of the outer zone does not extend beyond 8 $R_E$ *(Walt05).*
- The void between these places is called the slot region, sometimes referred to as the ”safe zone” (Weintraub04).



# Structure of the radiation belts: composition

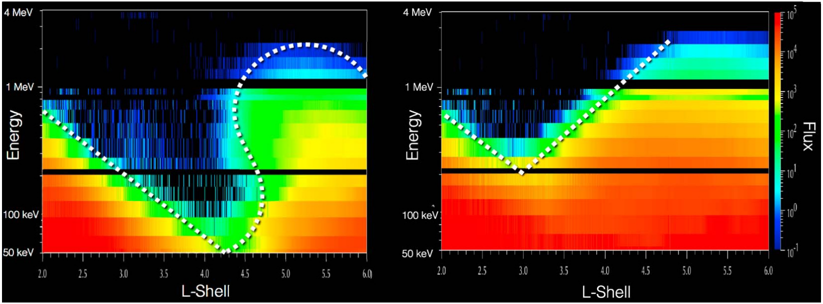
- Typical energies range from about 50 keV to $\sim$4 MeV for electrons and exceed 400 MeV for protons.
- The outer belt consists mainly of electrons. They are injected from the geomagnetic tail following geomagnetic storms/substorms, and are subsequently energized through wave-particle interactions.
- The inner belt usually comprises
  (1) energetic protons resulting from the interaction of cosmic ray ions with atoms of the atmosphere
  (2) electrons penetrating from outer radiation belts to the slot region.



# Structure of the radiation belts: energy, distance & activity dependence

- Electrons with energy $> 50$ keV can penetrate metallic spacecraft surfaces and cause internal discharge *(Robinson&Coakley92).*

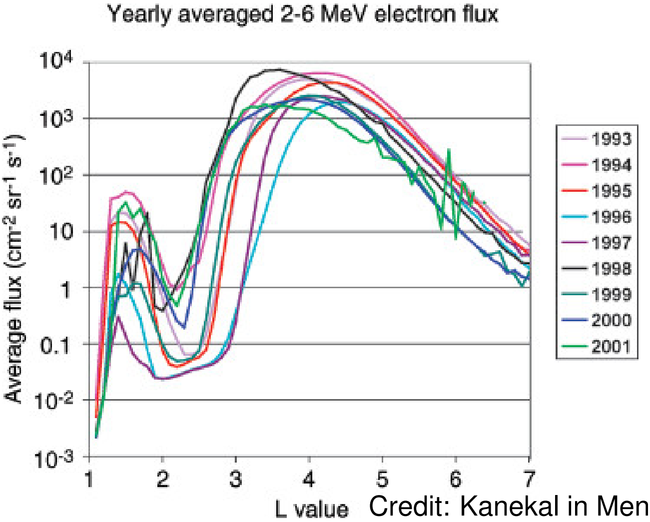



Quiet Active

Credit: Reeves+15

# Intensity variation over years vs distance

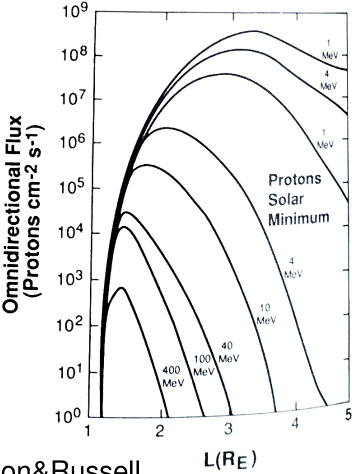
Radiation belts are highly variable in shape and density.




Credit: Kanekal in Menk&Waters

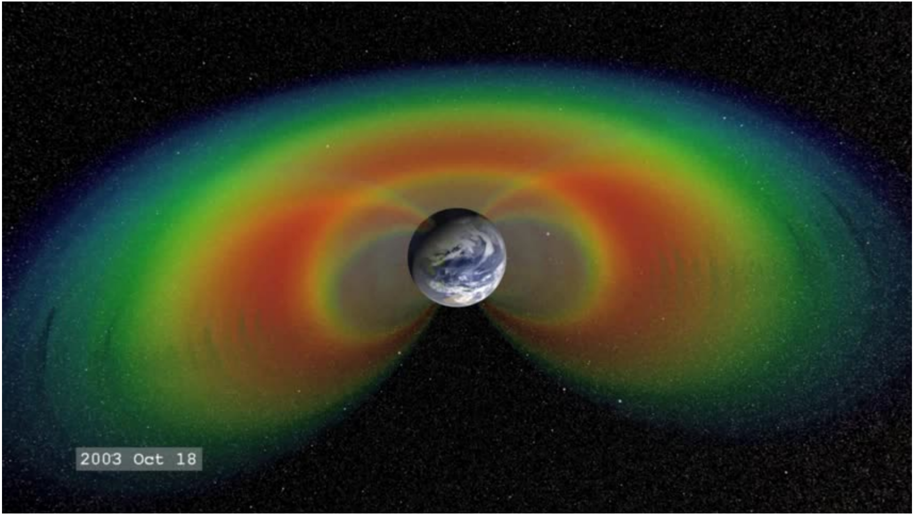
# Intensity variation energies vs distance

Protons with *kinetic energies at about 100 keV* can penetrate 0.6 $\mu$m of lead and those at 400 MeV can penetrate 143 mm of lead.



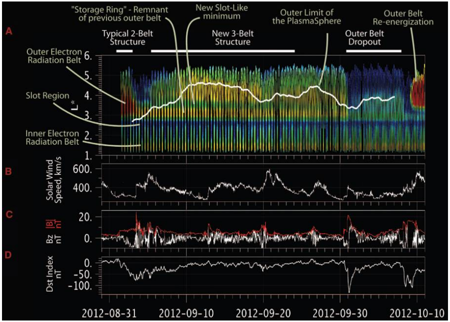

Credit:Hess+68 in Kivelson&Russell

# Variation of radiation belts from Oct 18 2003 to Jan 1 2004

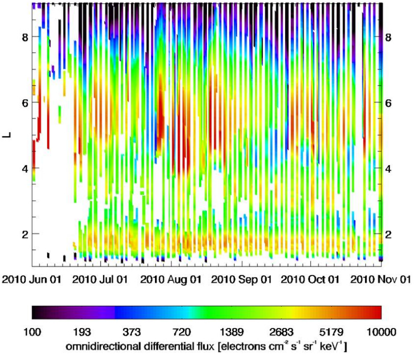



Computer generated Imagery video from NASA/Goddard Space Flight Center

# 3rd Radiation Belt

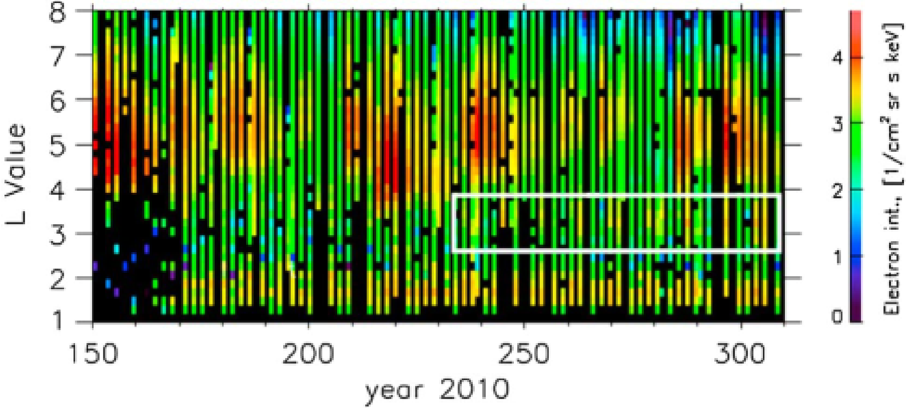



*Baker+12*



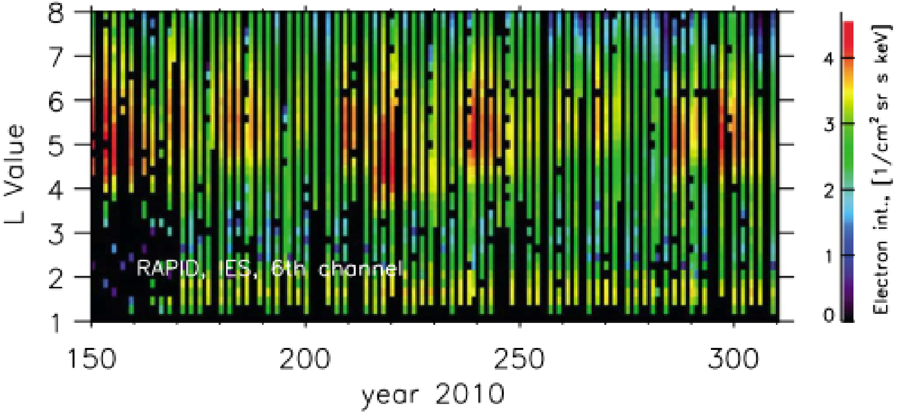

*Unpublished in Nature result*

# 3rd radiation belt: data without correction




*Kronberg+16*

# 3rd radiation belt: with correction from Geant4 (for GEometry ANd Tracking) is a CERN toolkit for the simulation of the passage of particles through matter using Monte Carlo methods)




*Kronberg+16*

# Question: What is the difference between the ring current and radiation belts?

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# The difference between the ring current and radiation belts

- The ring current particles contribute substantially to the plasma pressure in the inner magnetosphere (typically protons of 10 to 100 keV).

# Observations

Current missions:

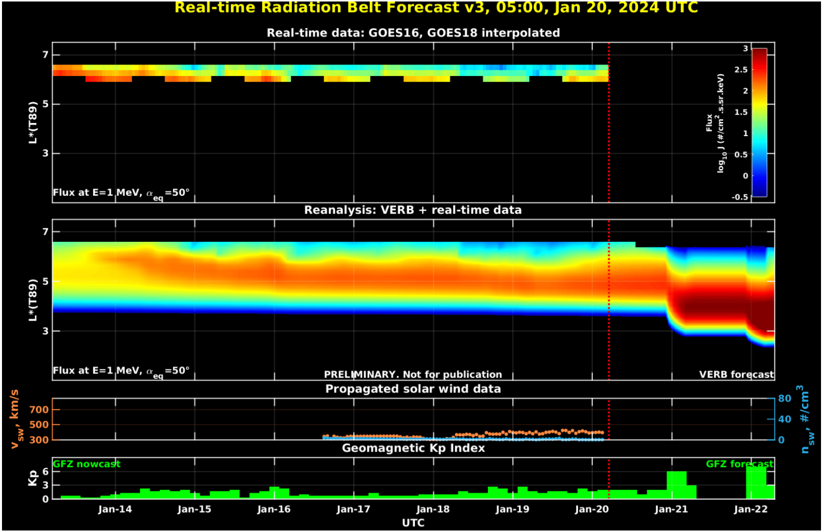
- ERG 2017–. . .
- THEMIS 2007–. . .
- LANL
- GEOS 1975–. . .

Ex-missions:

- Van Allen Probes 2012–2019
- Cluster 2001–2016
- Polar 1996–2008
- SAMPEX (1992–2012)
- CRRES– gold standard – 1990–1991

# Prediction of radiation belts at GFZ in Potsdam

https://isdc.gfz-potsdam.de/data-assimilative-radiation-belt-forecast/



# Radiation belt effects on instrumentation in space

- Solar cells (electrons or protons introduce imperfections in the crystal structure of the silicon), integrated circuits, electronic components and sensors can be damaged by radiation.
- Miniaturization and digitization of electronics and logic circuits have made satellites more vulnerable to radiation, as the total electric charge in these circuits is now small enough so as to be comparable with the charge of incoming ions. Electronics on satellites must be hardened against radiation to operate reliably.

Credit: Wikipedia

## Question: How the astronauts managed to fly to the Moon through the hazardous radiation belts?

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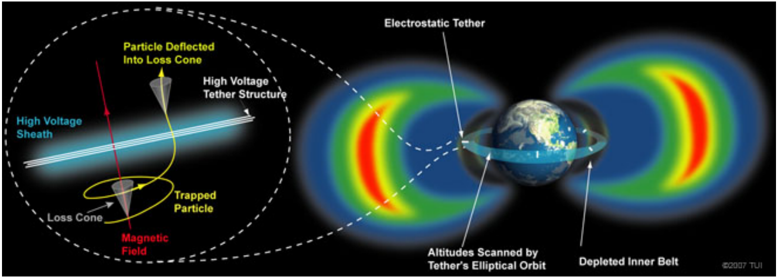
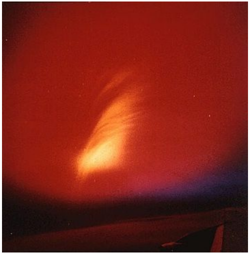
# Proposed removal

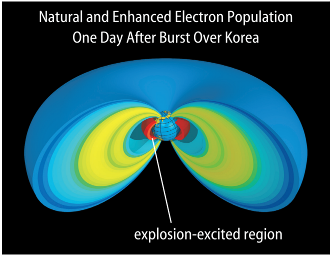
- High-Voltage Orbiting Long Tether (HiVOLT):
  A System for Remediation of the Van Allen Radiation Belts



# Artificial Radiation Belts

Credit: Reeves et al., 2005






- Between 1958-1962 a series of High Altitude Nuclear Explosion (HANE) tests were completed by the USA and USSR.
- The largest successful HANE was Starfish Prime (1962) Launched from Johnston Island in the North Pacific detonated at 400 km
- Results:
  1. Caused aurora visible from the Samoan Islands and power outages
  2. Created long lasting artificial radiation belts
  3. Damaged 1/3 of all satellites in Low Earth Orbit!

# Summary

- Radiation belts is a key region of a space weather as it contains high particle intensities which are dangerous for the satellites.
- The intensity of radiation belts is highly variable and still needs to be studied.

# Literature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