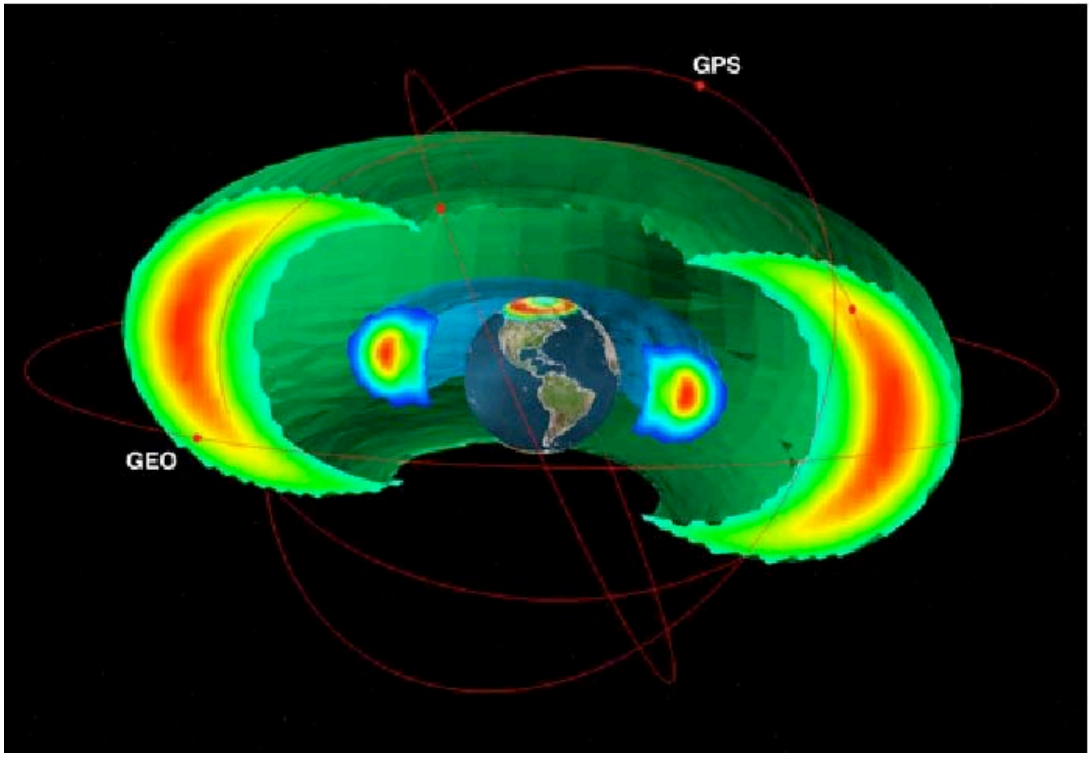
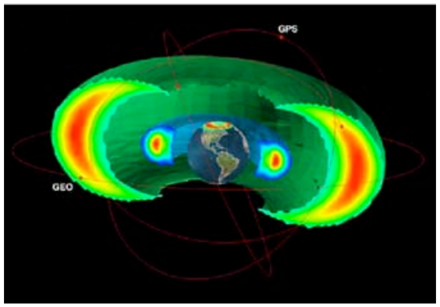
Introduction to the Radiation Belts



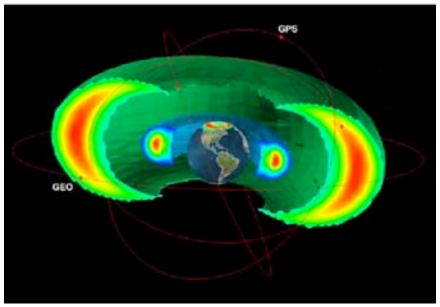
Wm. Robert Johnston

GEM Workshop - Midway, UT - 17 June 2007



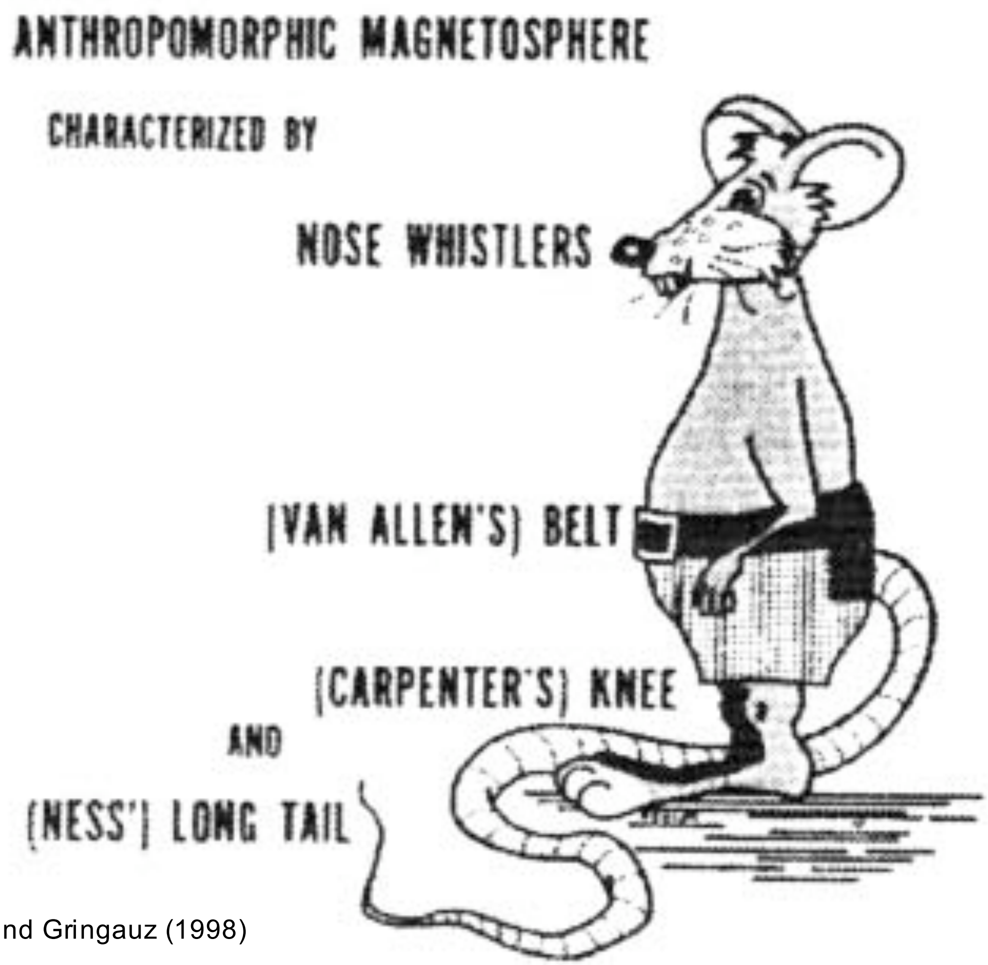
Outline

- Introduction to radiation belts
- Trapped particle motions and adiabatic invariants
- Pitch angle
- Wave-particle interactions and the plasmasphere
- Source, loss, and diffusion mechanisms
- Observation platforms
- Conclusion

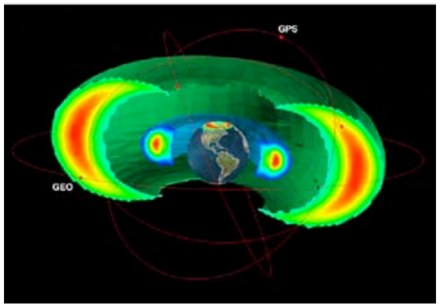


How far we've come...

- The magnetosphere in 1965:

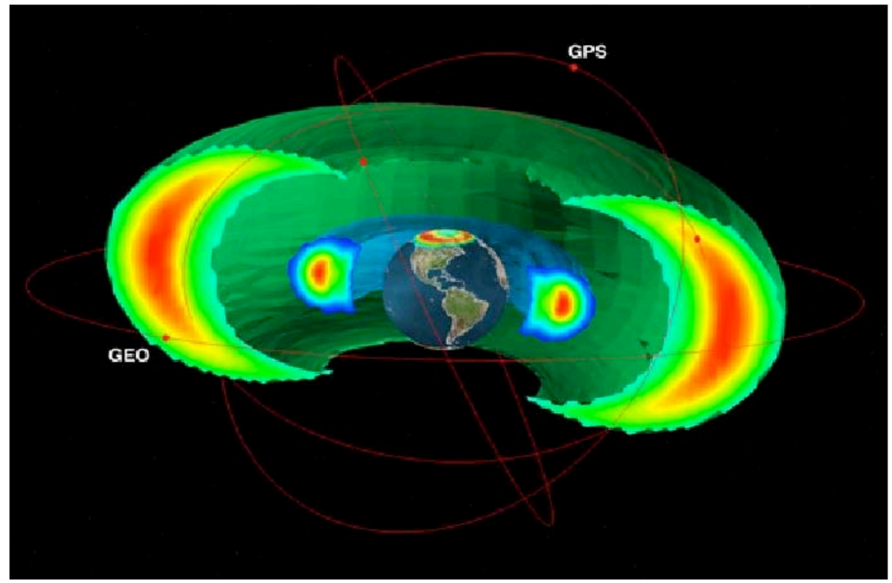


O'Brien, in Lemaire and Gringauz (1998)

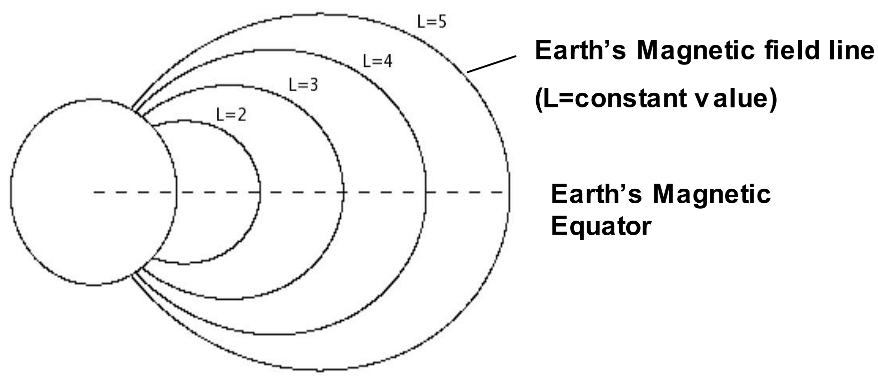


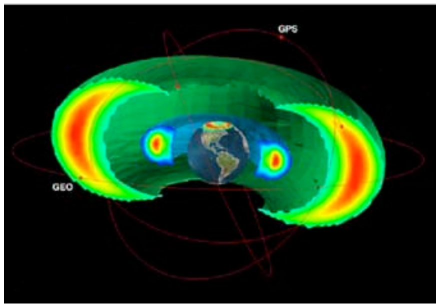
Radiation belt basics

- Radiation belts comprise energetic charged particles trapped by the Earth's magnetic field. (from keV to MeV)
- A given field line is described by its L value *(radial location, in R_E, of its intersection with magnetic equator)*
- Inner belt region:
  - Located at L~1.5-2
  - Contains electrons, protons, and ions.
  - Very stable.
- Outer belt region:
  - Located at L~3-6
  - Contains mostly electrons.
  - Very dynamic.
- Slot region: lower radiation region between the belts

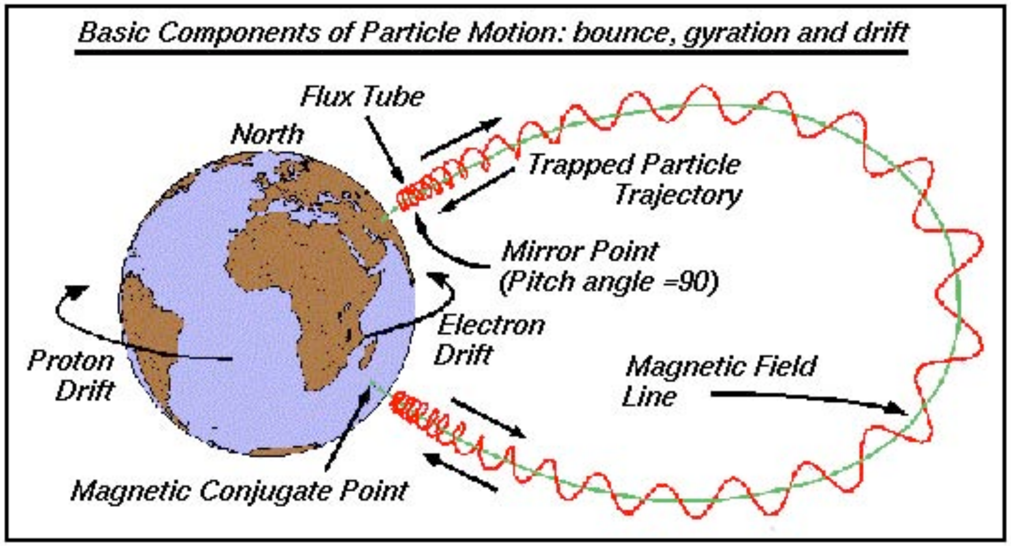


NASA





Periodic motions of trapped particles (1)



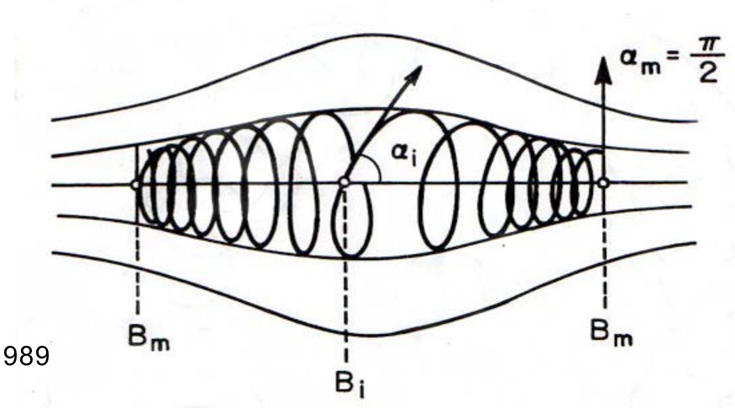
ESA

- Three types of periodic motion of trapped particles
  - gyro motion
  - bounce motion
  - drift motion
- Each motion has an associated adiabatic invariant

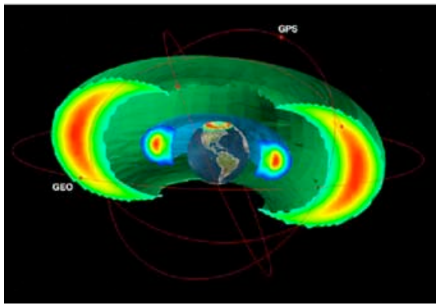
- Gyro motion:
  - V x B acceleration leads to gyro motion about field lines
  - frequencies ~kHz
  - associated 1st invariant μ, relativistic magnetic moment:

$$\mu = \frac{p^2 \sin^2 \alpha}{2m_0 B}$$

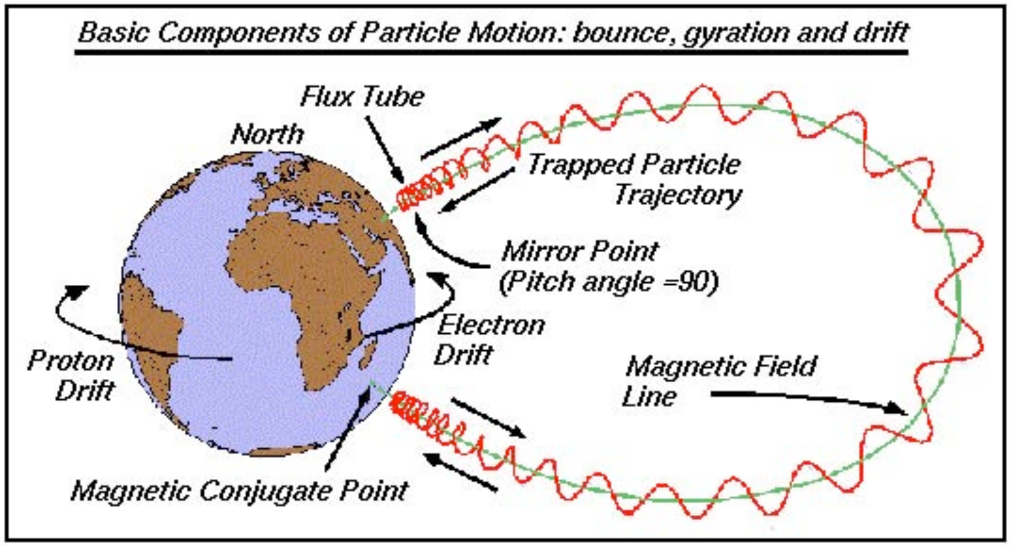
pitch angle α: $\tan\alpha = \frac{V_\perp}{V_\parallel}$



Spjeldvik and Rothwell, 1989



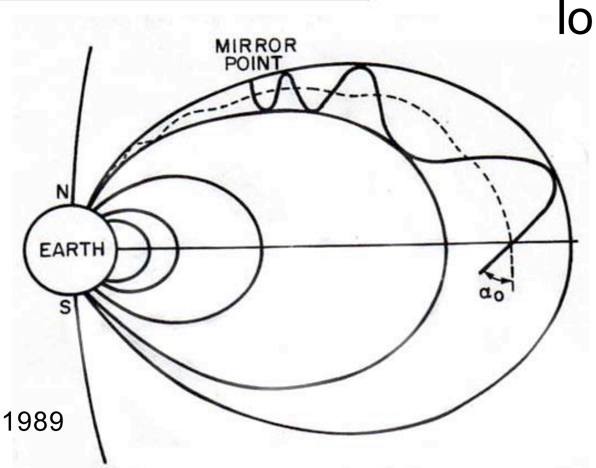
Periodic motions of trapped particles (2)



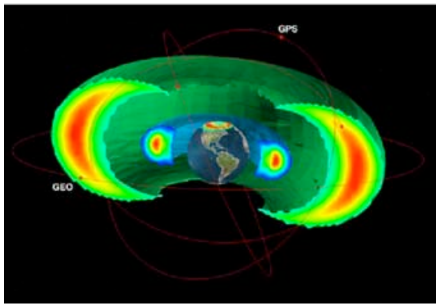
ESA

- Bounce motion:
  - As a particle gyrates down a field line, the pitch angle increases as B increases
  - Motion along field line reverses when pitch angle reaches 90° (mirror point)
  - period ~sec
  - associated 2nd invariant J, longitudinal invariant:

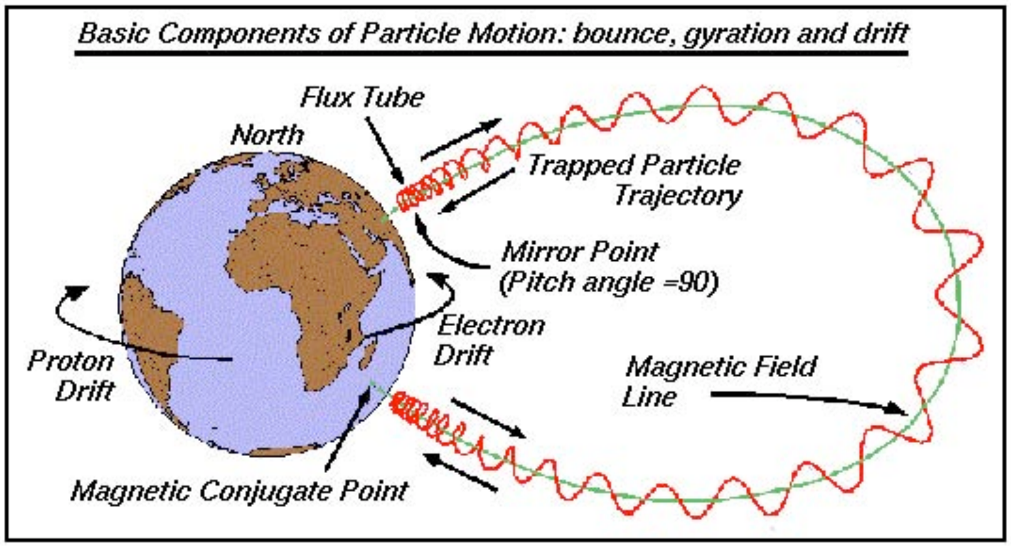
$$J = \int_{-l_m}^{+l_m} p_{\|} dl$$



Spjeldvik and Rothwell, 1989



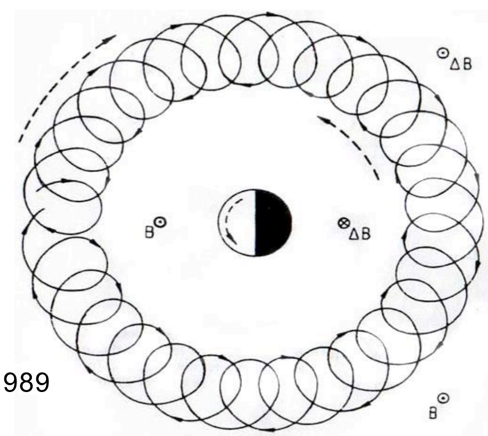
Periodic motions of trapped particles (3)



ESA

- Drift motion:
  - Gradient in magnetic field leads to drift motion around Earth: east for electrons, west for protons/ions
  - period ~minutes
  - associated 3rd invariant ϕ, magnetic flux:

$$\Phi = -\frac{2\pi B_E R_E^2}{L}$$



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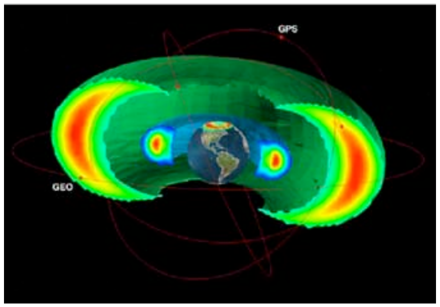
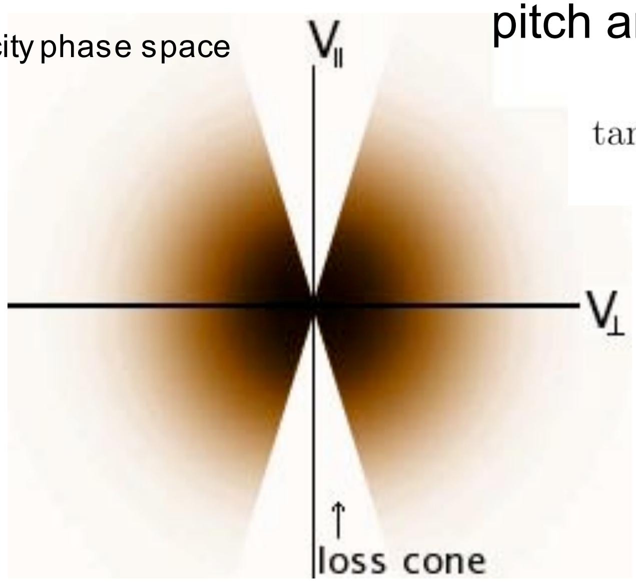


Pitch angle dependence

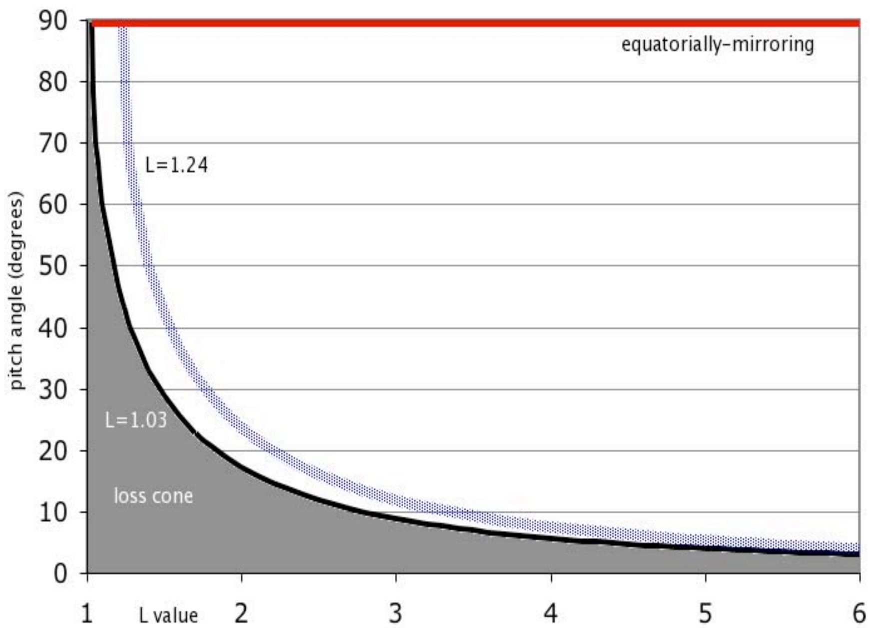
- Radiation belt populations are necessarily nonisotropic.
- Illustrated by nonisotropic distribution in velocity phase space:

velocity phase space

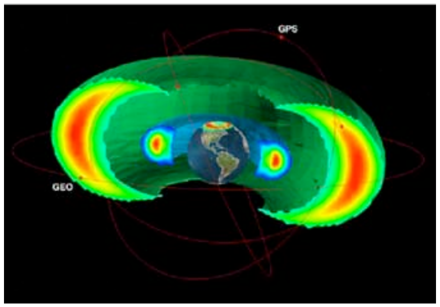


pitch angle α:

$$\tan\alpha = \frac{V_{\perp}}{V_{\parallel}}$$

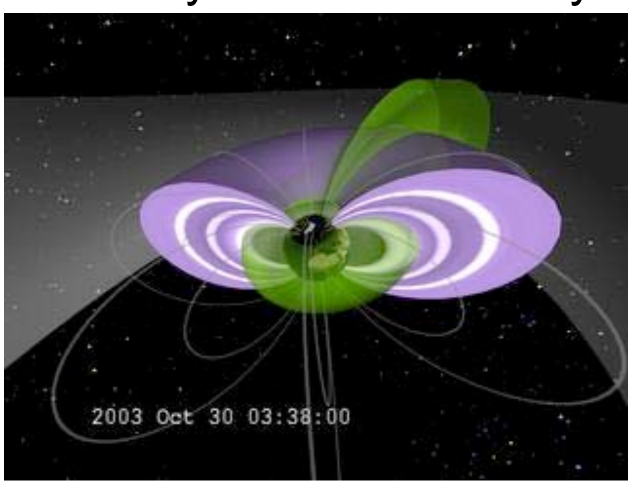


- Figure shows range of equatorial pitch angle values sustainable for mirroring particles.



Plasmasphere

- Plasmasphere--a torus of cold (~1 eV), dense (10-10^3 cm^{-3}) plasma trapped on field lines in corotation region of the inner magnetosphere
  - outer boundary (plasmapause) tends to correlate with inner boundary of outer radiation belt
  - typically extends to L=3-5, but can be very structured and dynamic



NASA/GSFC

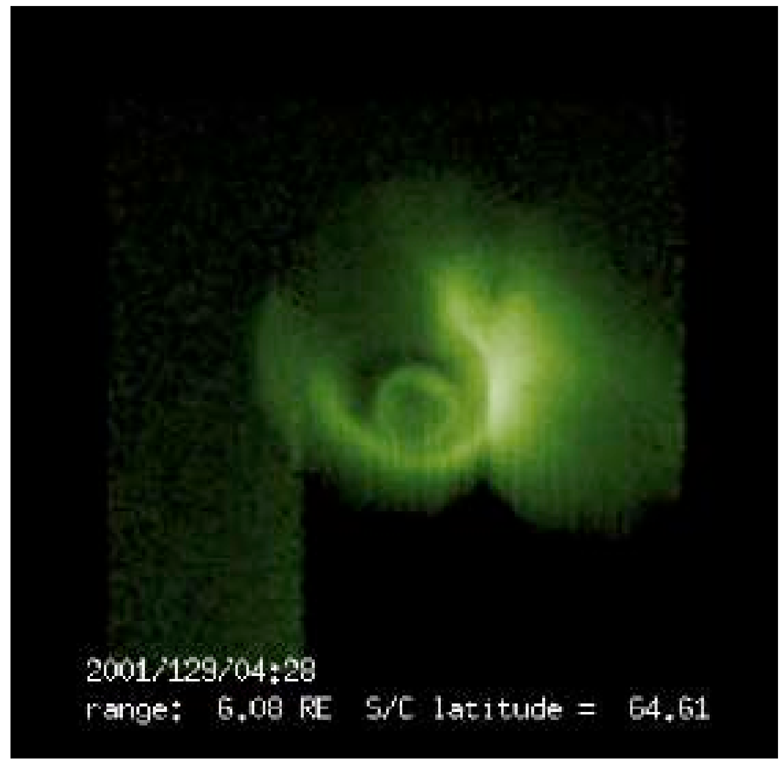
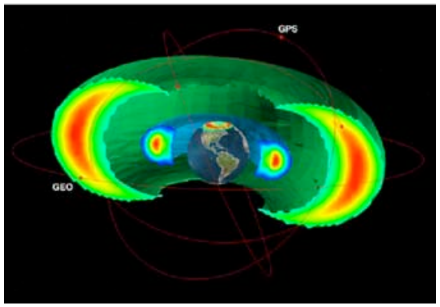
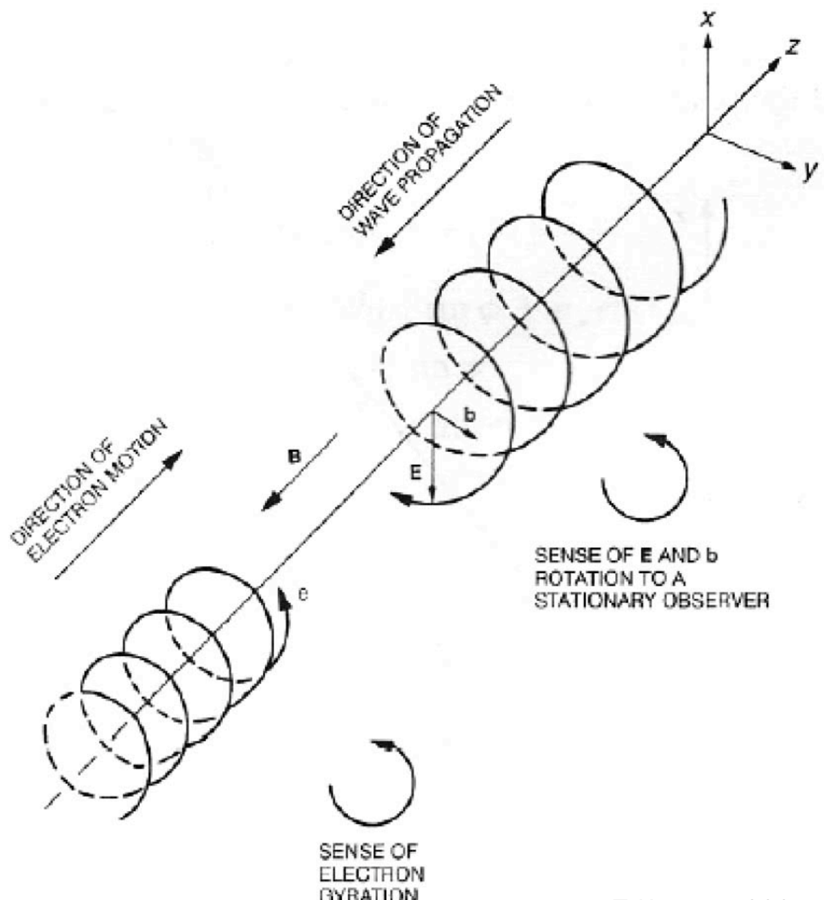


IMAGE EUV web site

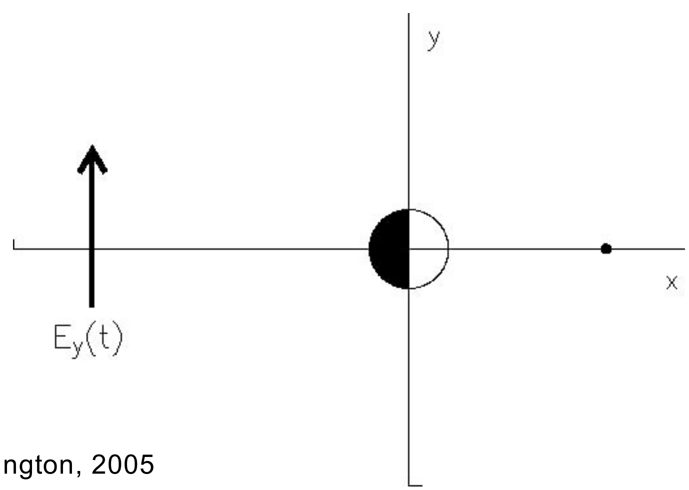


Wave-particle interactions

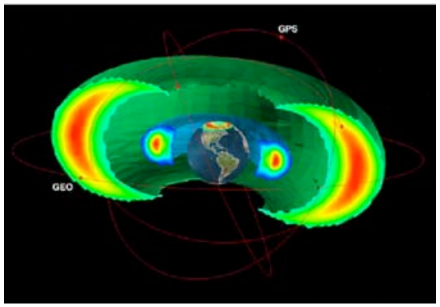


Elkington, 2005

- Wave-particle interactions: resonances between periodic particle motion and EM waves can energize or scatter particles
  - Whistler waves
  - ULF waves

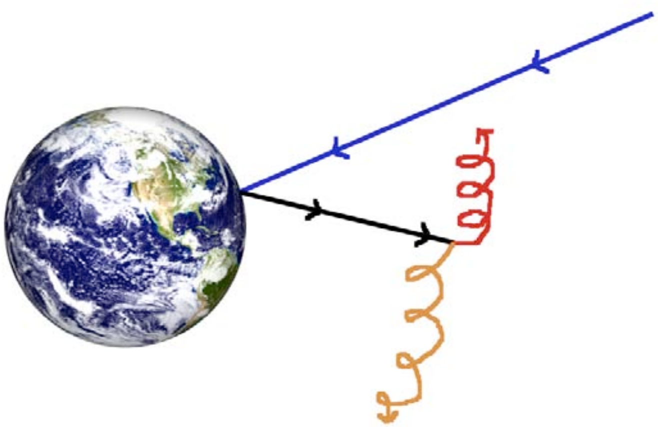


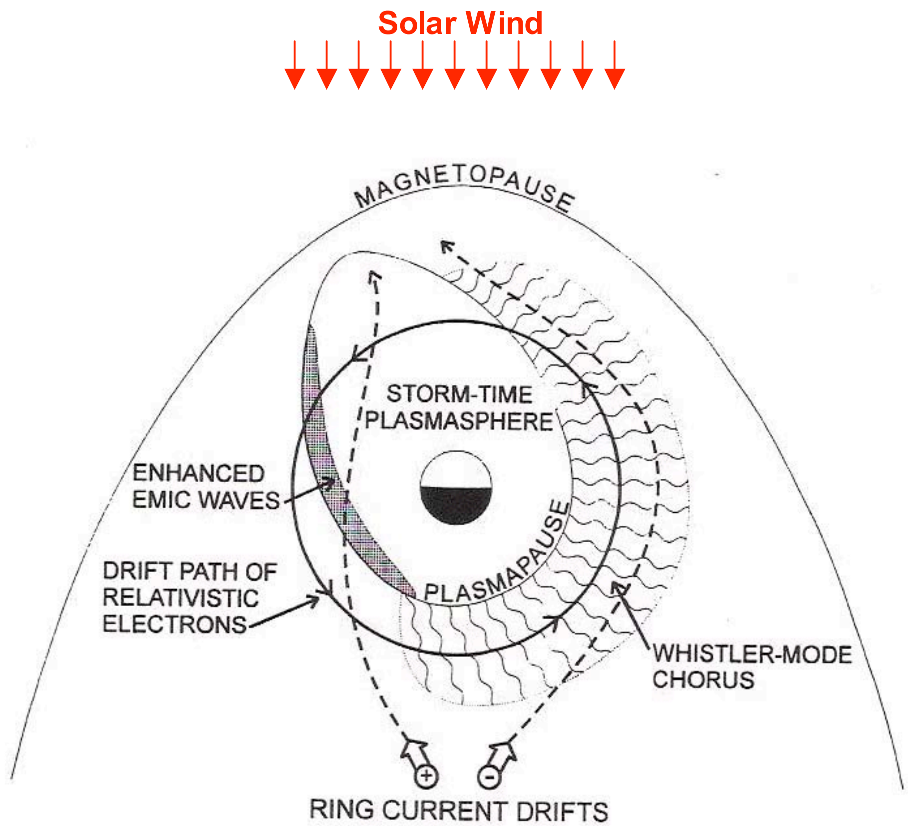
Elkington, 2005



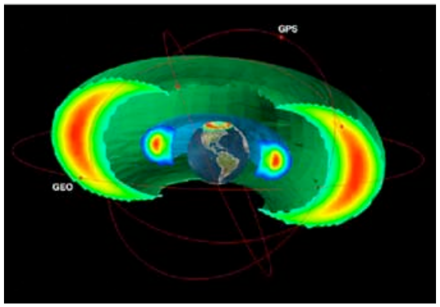
Sources and energization mechanisms

- Sources include solar wind via outer magnetosphere or from plasmasheet plasma
- These particles energized by wave-particle interactions (e.g. whistler waves), crosstail E field fluctuations
- Cosmic ray albedo neutrons
  - cosmic rays --> n --> H^+ and e^-



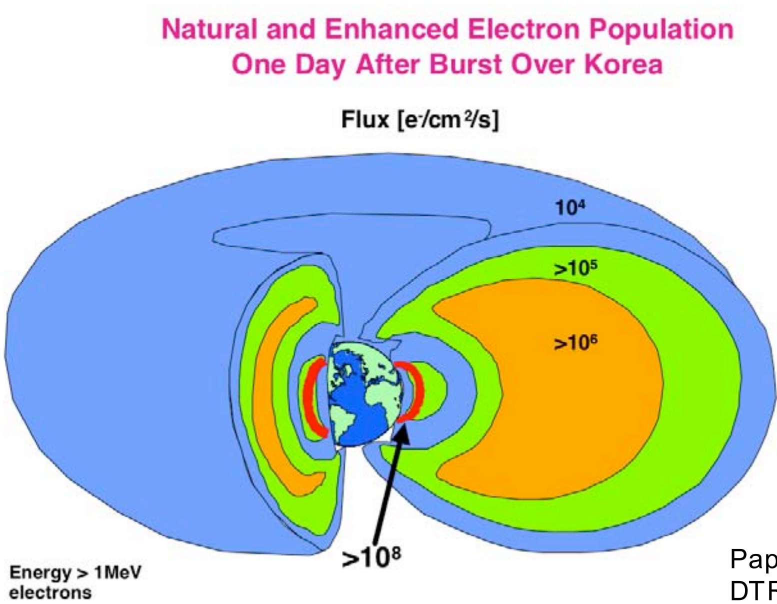


Summers et al., 1998



Man-made sources

- High altitude nuclear explosions can produce artificial radiation belts
  - several US, Soviet tests in 1958-1962 produced short-lived belts inside the inner belt

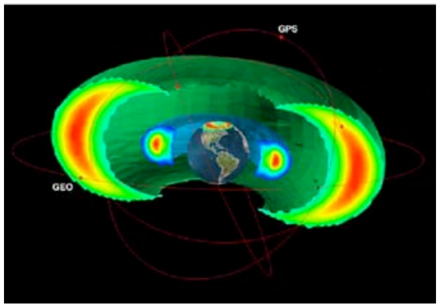


Papadopoulos/
DTRA, 2000

Starfish,
1962,
1.4 mt,
400 km alt.

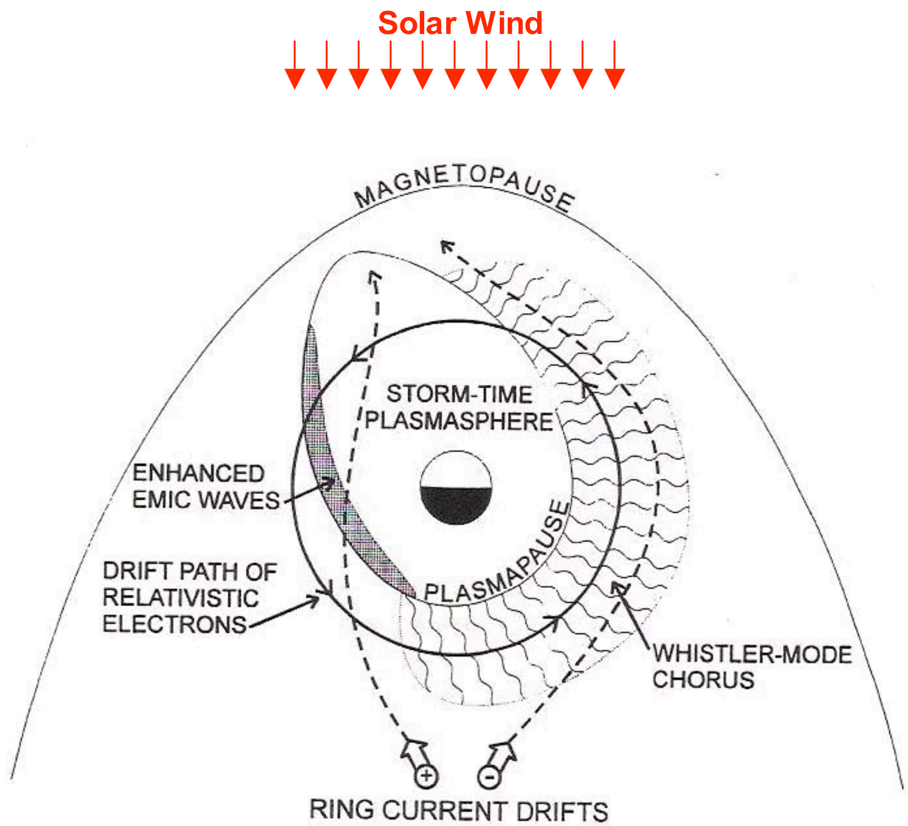
Nuclear Weapon
Archive, 2005

- Currently a national security concern given our dependence on space assets



Loss mechanisms

- Anything that scatters particles into loss cone in phase space
  - such particles will collide with atmosphere
- Coulomb collisions with cold charged particles in plasmasphere, ionosphere
- Enhanced EMIC waves inside plasmapause
- Magnetopause shadowing
  - loss of particles with orbits carrying them outside the magnetopause



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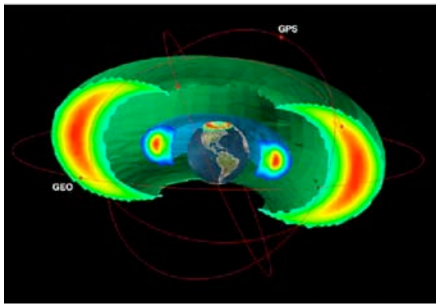
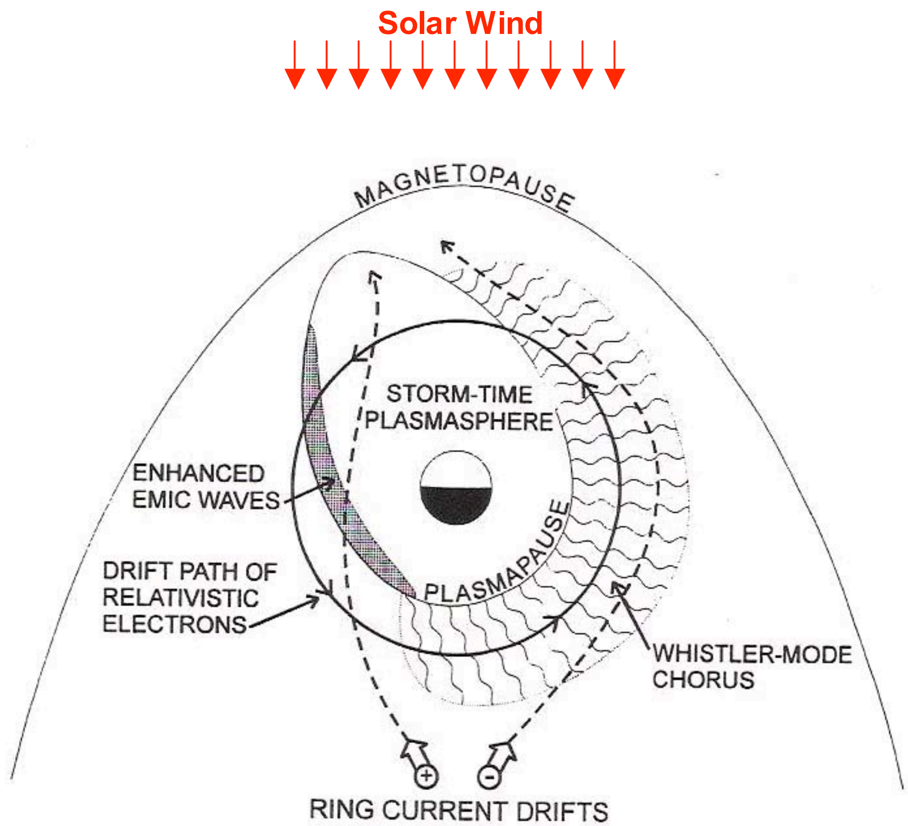


Diffusion mechanisms

- Wave-particle interactions
  - whistler chorus
  - EMIC waves
- Fluctuations in magnetospheric electric field



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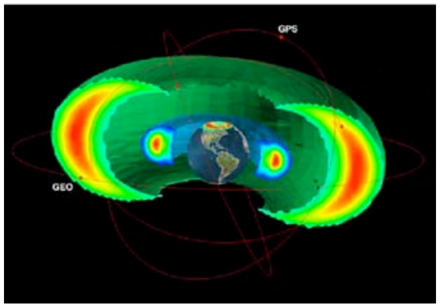


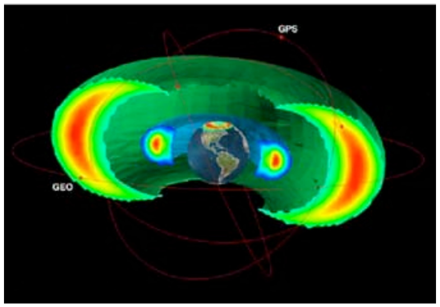
Diffusion equations and phase spaces

- Evolution of particle population described by **diffusion equation**:

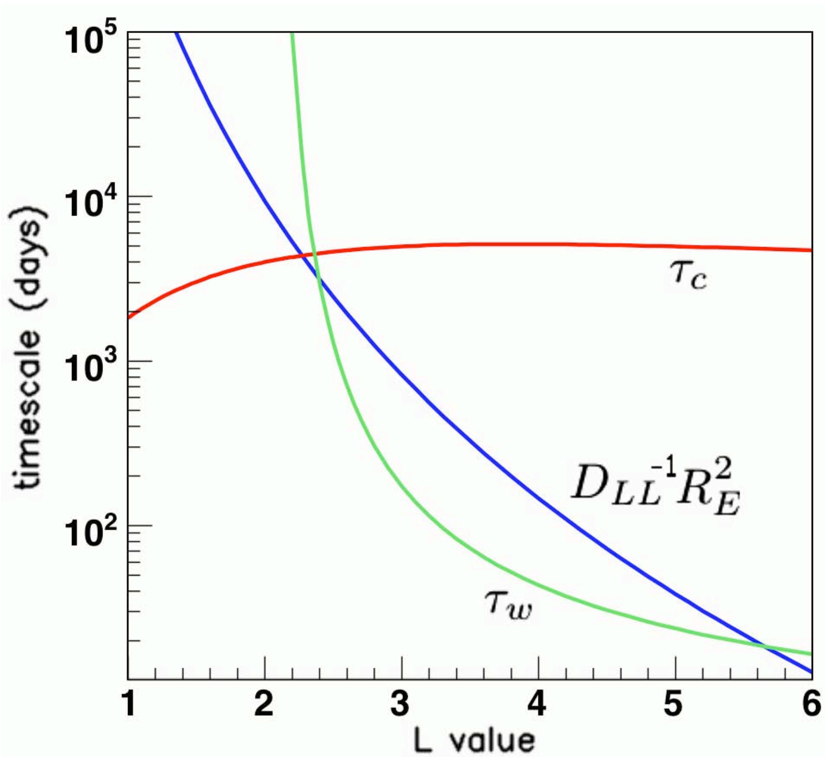
  rate of change in flux = sources - losses + diffusion terms

- What phase space to use to model evolution?

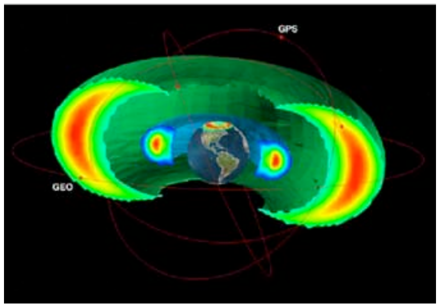
basic position-momentum space:	adiabatic invariants:	observables:
x, y, z, v_x, v_y, v_z	μ, J, ϕ	ε, α_o, L
(hard to use)	(easy to use)	(for interpretation)



Why there are two electron belts

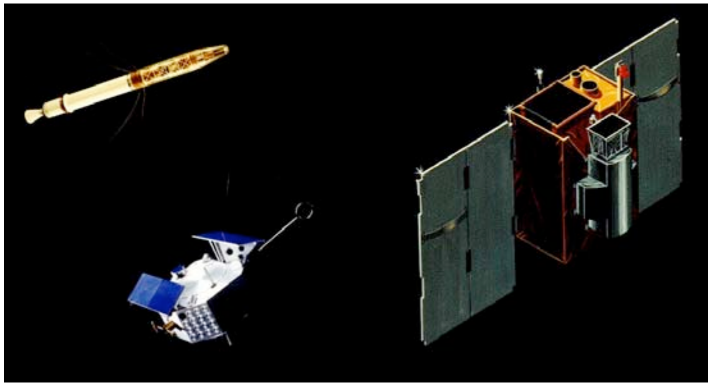


- plot shows timescales for fixed μ=30 MeV/G *(after Lyons and Thorne, 1973)*
- D_{LL} drives inward diffusion, faster at large L
- whistler losses faster than replacement by diffusion in slot region
- those particles that reach low L have lifetimes of years

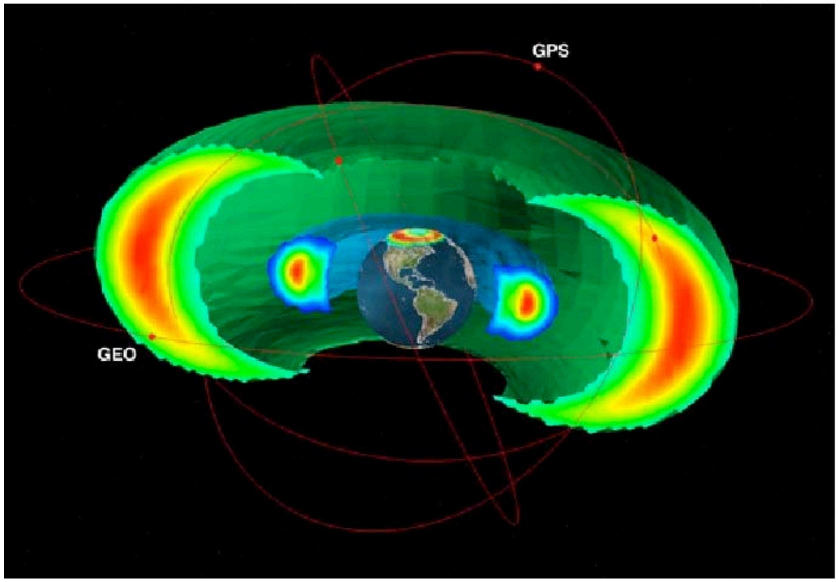


Illustrative satellites

- Explorer 1/3 (1958)
  - low Earth orbit, eccentric
  - geiger counter
- later satellites: multiple particle detectors, pitch angle info if spinning
- GOES (multiple, 1975-now)
  - geosynchronous orbit
- CRRES (1990-91)
  - eccentric orbit
- SAMPEX (1991-now)
  - low Earth orbit



NASA



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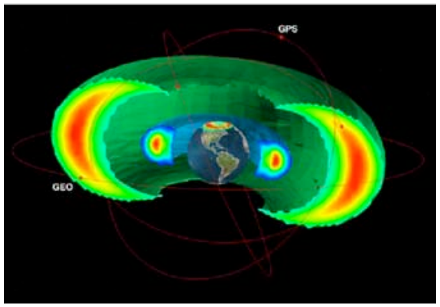
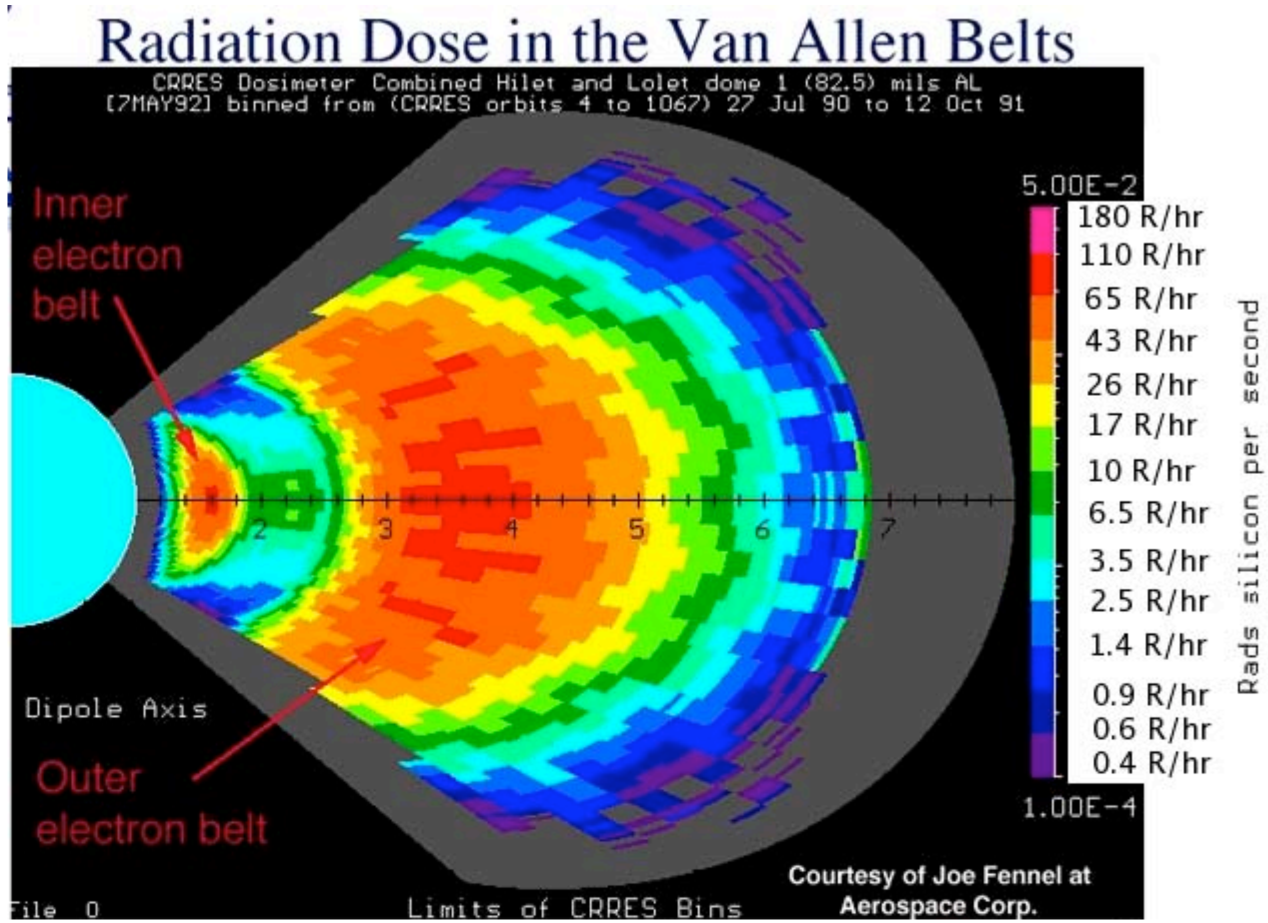
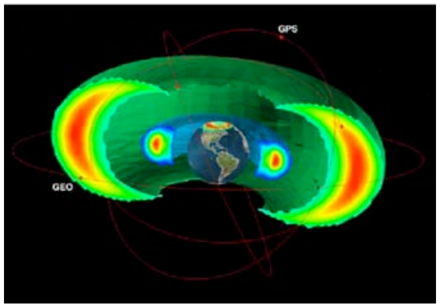


Radiation fluxes from CRRES

- CRRES= Combined Release and Radiation Effects Satellite
- radiation flux observations from CRRES, 1990-91
- scale converted to rads/hour



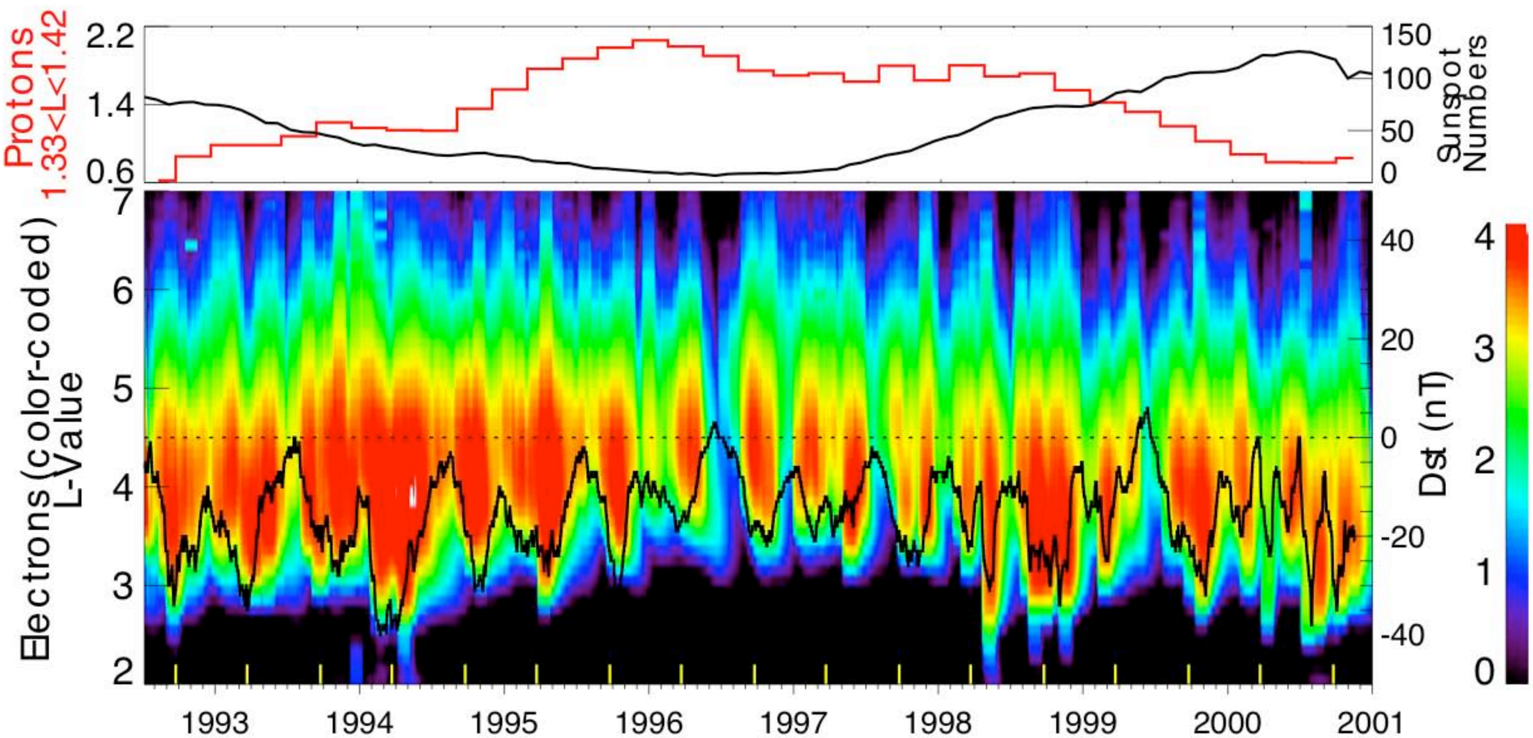
Fennel/Aerospace Corp., 2003

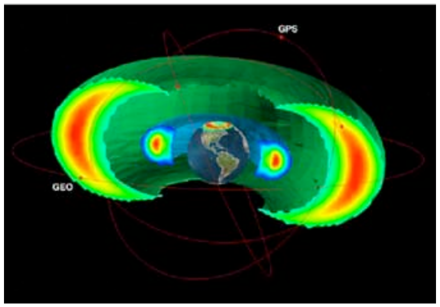


Long term dynamics from SAMPEX

- SAMPEX=Solar Anomalous and Magnetospheric Particle Explorer
- SAMPEX observations over most of a solar cycle
- shows long-term dynamics in outer radiation belt

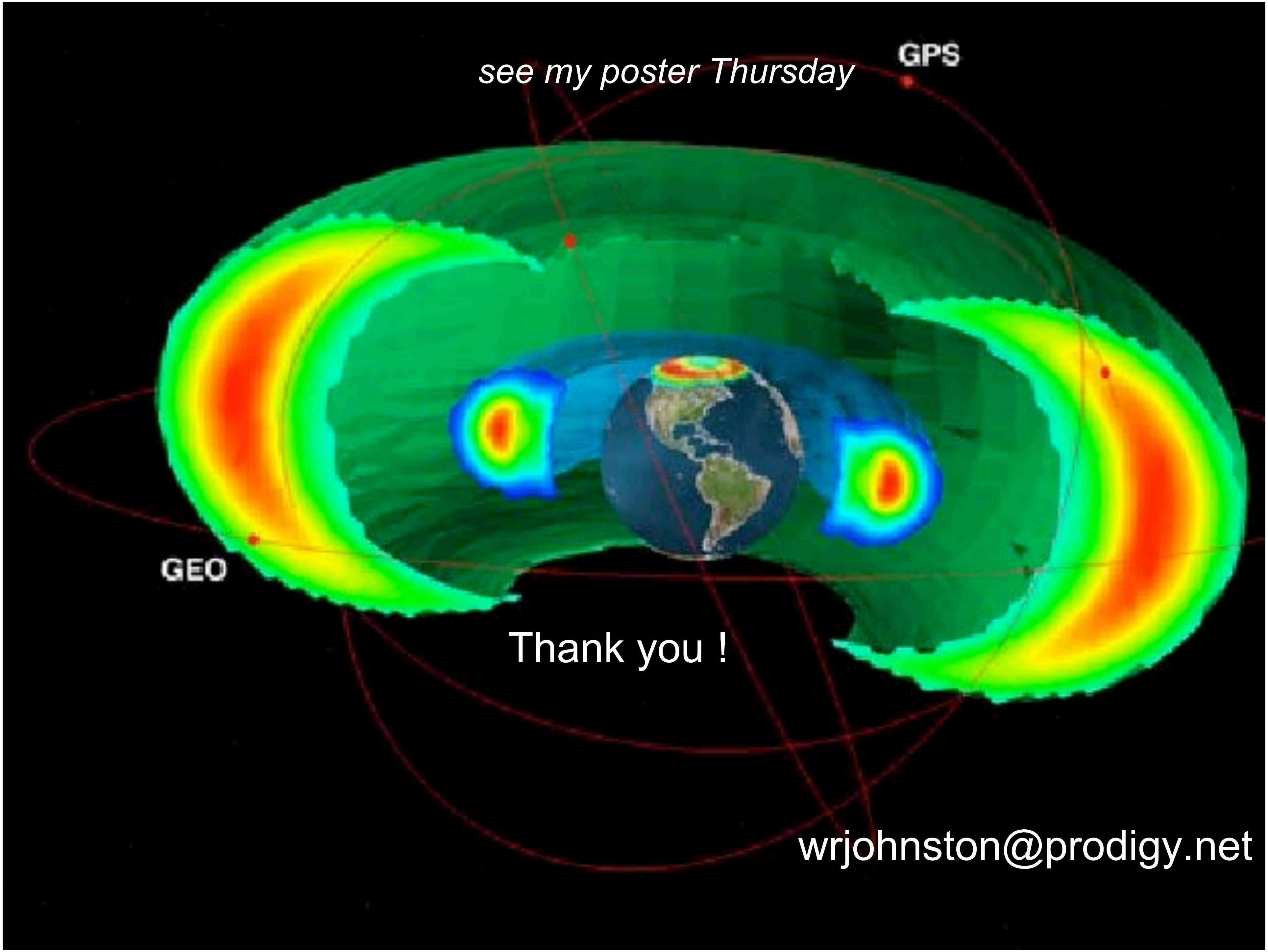
Li et al., 2001





Conclusion

- Study of radiation belts is a rich topic with connections to many space physics subfields.
- Understanding of radiation belts is important to space operations, both manned and unmanned.
- Currently a "hot" topic from many different perspectives!


see my poster Thursday
GPS
GEO
Thank you !
wrjohnston@prodigy.net