Introduction to the Radiation Belts

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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:

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
Periodic motions of trapped particles (1)

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

Gyro motion:
- $V \times B$ acceleration leads to gyro motion about field lines
- frequencies $\sim$kHz
- associated 1st invariant $\mu$, relativistic magnetic moment:

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

pitch angle $\alpha$: \[ \tan \alpha = \frac{V_\perp}{V_\parallel} \]
Periodic motions of trapped particles (2)

- 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:

\[
J = \int_{-l_m}^{+l_m} p_\parallel dl
\]

Spjeldvik and Rothwell, 1989
Periodic motions of trapped particles (3)

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

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

Spjeldvik and Rothwell, 1989
Pitch angle dependence

- Radiation belt populations are necessarily nonisotropic.
- Illustrated by nonisotropic distribution in velocity phase space:
  - Figure shows range of equatorial pitch angle values sustainable for mirroring particles.

\[ \tan \alpha = \frac{V_\perp}{V_\parallel} \]
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
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

Natural and Enhanced Electron Population
One Day After Burst Over Korea
Flux [e/cm²/s]

Energy > 1 MeV electrons
>10⁸

Starfish, 1962, 1.4 mt, 400 km alt.
Nuclear Weapon Archive, 2005

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

Papadopoulos/DTRA, 2000
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

Summers et al., 1998
Diffusion mechanisms

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

Summers et al., 1998
Diffusion equations and phase spaces

- Evolution of particle population described by diffusion equation:

  \[ \text{rate of change in flux} = \text{sources} - \text{losses} + \text{diffusion terms} \]

- What phase space to use to model evolution?

  basic position-momentum space: \( x, y, z, v_x, v_y, v_z \)
  adiabatic invariants:
  \( \mu, J, \phi \)
  observables:
  \( \varepsilon, \alpha_0, L \)

  (hard to use) (easy to use) (for interpretation)
Why there are two electron belts

- plot shows timescales for fixed $\mu=30$ 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
Radiation fluxes from CRRES

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

see my poster Thursday

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