Modeling solar radiation belts

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Abstract: High-energy particles (>10 MeV protons) can be trapped in large-scale coronal magnetic fields for periods of days to weeks. We model this trapping by following the adiabatic motions of particles in test fields, including the Schrijver-DeRosa PFSS models. These are available in a SolarSoft interface for the entire duration of the SOHO mission thus far. In spite of the complexity of the field, we find drift shells in which particles can circulate completely around the Sun, and thus conserve the third adiabatic invariant of motion well. In this work we study the morphology of the these drift shells, including their appearance as a function of phase in the solar cycle.

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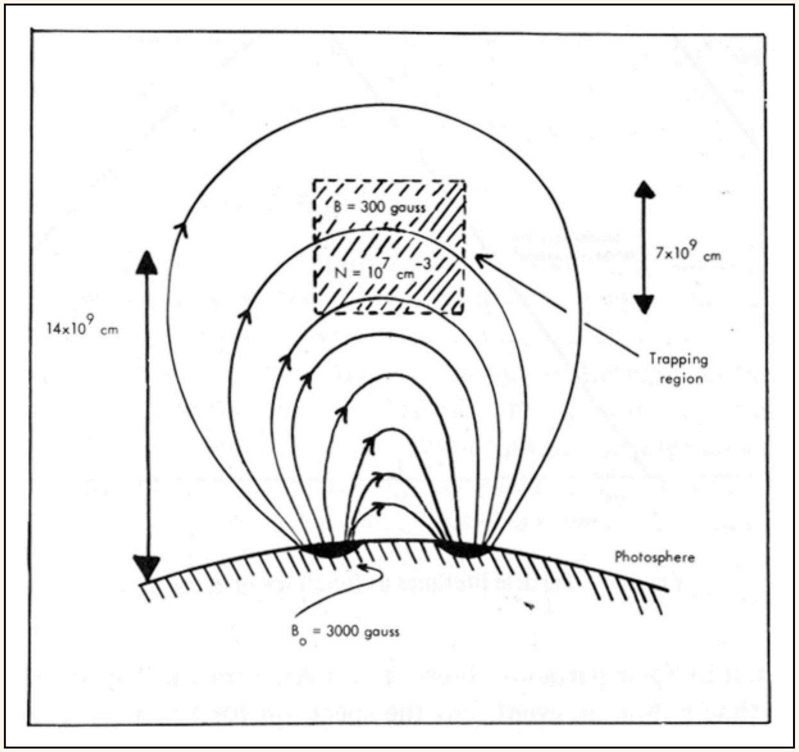
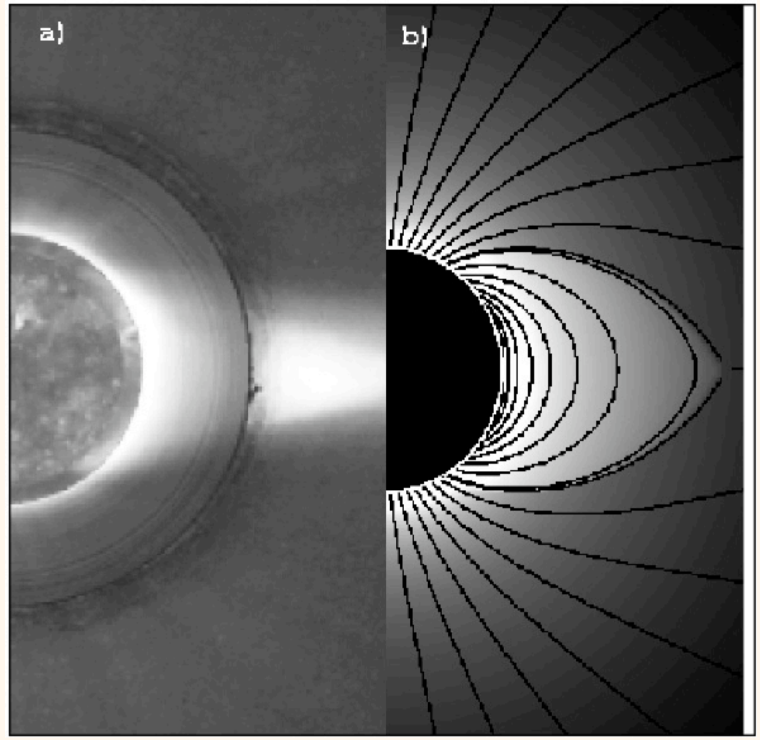
Particle trapping in the corona





H. Elliott, 1973

Introduces the idea of trapping SEPs in closed fields
(cf Alfvén 1947 for the Earth)

The corona at solar minimum can be quite dipolar - hence the possibility of actual radiation belts

Strategy for studying solar radiation belts

Method:

• Develop tracking procedures for adiabatic particle motions
• Incorporate dE/dx for particle energy losses
• Test particle motions in "Mead models" (G. Mead, 1964), analytic deformed dipoles
• Study particle motions in real-time PFSS models

***Concerns**:*

• Coronal trapping may involve loss-cone instabilities, especially for electrons (Wenzel 1976)
• There may be no particles to trap
• Even if trapped, they might not be useful for anything!

Source particles for solar radiation belts

Possible sources:

- CRAND ("Cosmic Ray Albedo Neutron Decay" - Ney, Kellogg, Vernov; MacKinnon 2007)
- Wave capture of SEPs (SSC; Mullen et al. 1991)
- Direct shock injection (Moreton wave)
- Scattering of galactic cosmic rays (Alfven, 1947)
- Inward diffusion of seed particles
- Stripping of flare-associated ENAs (Mewaldt et al. 2009)

• The CRAND mechanism is more efficient on the Earth than on the Sun - (p,p) reactions
- There are fewer cosmic rays at the Sun
- Little theoretical work has been done

Detectability of solar radiation belts

Ions:

- Radiation signatures would be minimal
- Particles could be stored, built up, and then released (Elliot's original thought)
- Particle inertia may stress the field (store energy at densities below $B^2/8\pi$)
- *In situ* observation is conceivable (Solar Probe)?

Electrons:

- ***Synchrotron radiation? Low frequencies, no calculation available***
- ***Coherent radio emission?***

Particle trajectories

- The *guiding center* approximation is appropriate:

$$\frac{d\mathbf{r}}{dt} = \frac{v_{\parallel}}{B}\mathbf{B} + \mathbf{v}_{\perp}$$

$$\mathbf{v}_{\perp} = c\,\frac{p_{\perp}^2 + 2p_{\parallel}^2}{2m\gamma qB^3}\,\mathbf{B}\times\nabla B$$

$$\frac{dv_{\parallel}}{dt} = -\frac{\mu}{m}\frac{\partial B}{\partial s}$$

$$\mu = \frac{p_{\perp}^2}{2mB}$$

$$\frac{dE}{dt} = -\frac{K\Lambda(E)n_e(\mathbf{r})}{\beta}$$

$$\beta = \frac{v}{c}$$

$$\gamma = \left(1-\beta^2\right)^{-1/2}$$

$$E = (\gamma - 1)mc^2$$

- We integrate numerically using 4th order Runge-Kutta

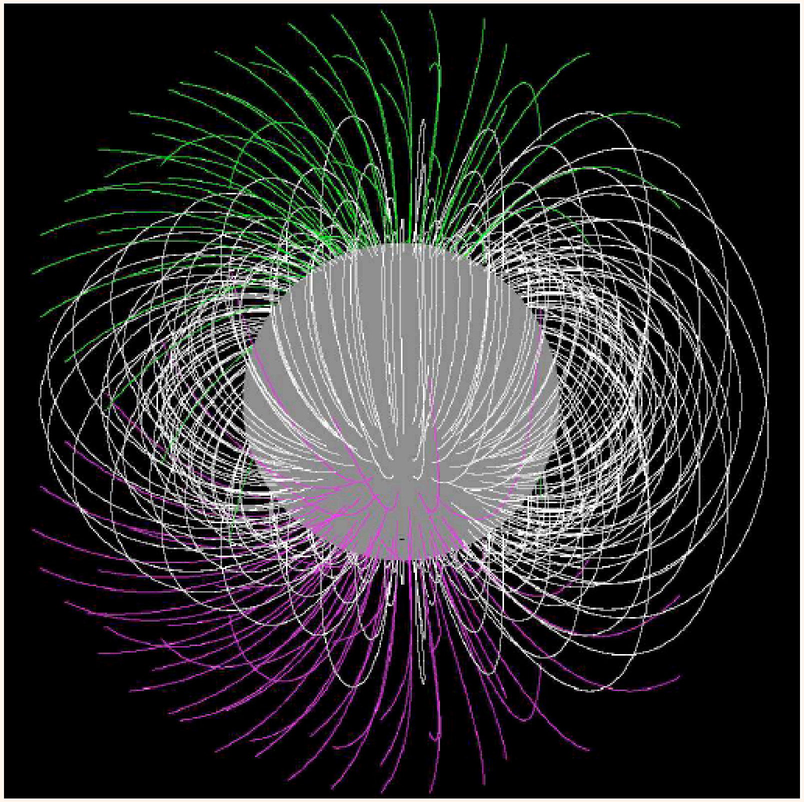
Drift 'shells'

- A particle travels along field lines conserving its magnetic moment, with bounce motion between mirror points
- Curvature and grad-B drifts perpendicular to **B** and ∇B
  - Do *not* transport to greater B than at mirror points
  - Mirror points trace out trajectories in surfaces defined by B = constant
- In *potential* fields with symmetry perpendicular to **B** (e.g. terrestrial dipole), mirror points follow intersections of
  - B = constant
  - ϕ = constant
- In a more realistic field the trajectories are more complex

The Mead Field

Mead (JGR 69, 1181, 1964) modeled the Earth's magnetic field by assuming a current sheet at the magnetopause along with the Earth's natural dipole, and describing it analytically with spherical harmonics. Using just the first three spherical harmonics, the potential is:

$$V_m(r,\theta,\varphi) = -B_0(a^3/r^2)\cos\theta - \left[B_1 r\sin\varphi - B_2 r(r/b)\sin\theta\sin\varphi\cos\varphi\right](a/b)^3$$



The magnetic field is then given by the negative gradient of the potential:

$$B_r = -2B_0(1/r)^3\cos\theta + B_1(a/b)^3\cos\theta$$
$$-2B_2(a/b)^4(r/a)(2\sin^2\theta - 1)\cos\varphi$$

$$B_\theta = -B_0(a/r)^3\sin\theta - B_1(a/b)^3\sin\theta$$
$$+B_2(a/b)^4(r/a)(2\sin^2\theta - 1)\cos\varphi$$

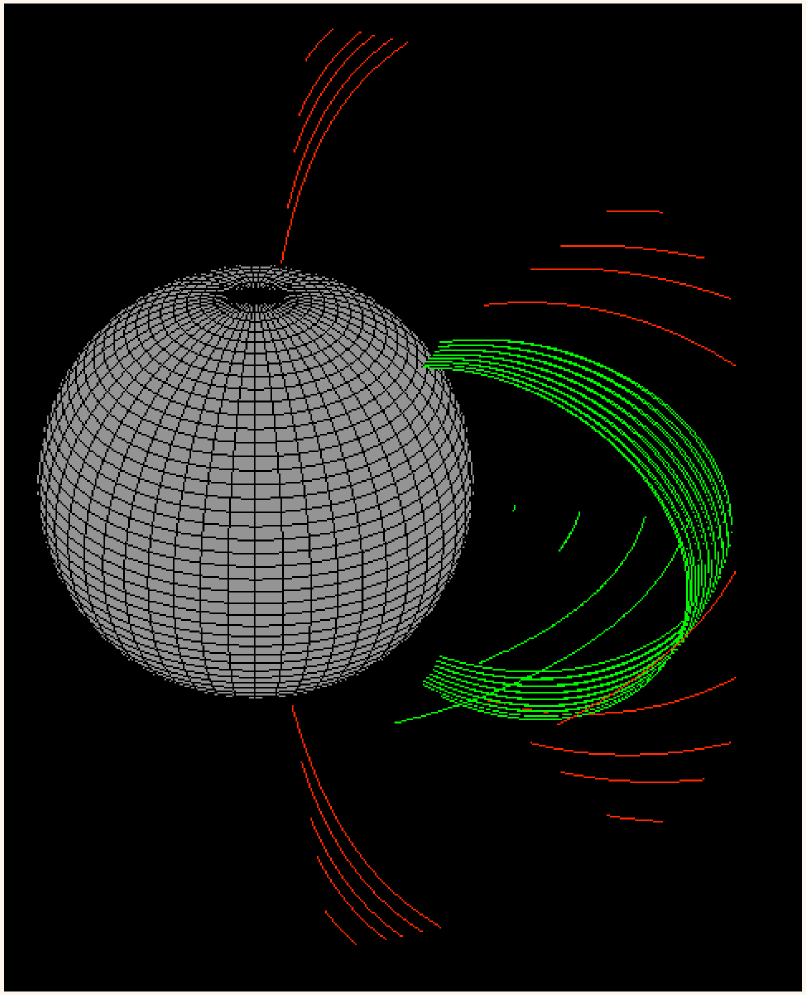
$$B_\varphi = +B_2(a/b)^4(r/a)\cos\theta\sin\varphi$$

Constants *a* and *b* depend on the environment of the field. Though *b* ~10*a* for the geomagnetic field, we use *b*=2.5*a* to increase the distortion since we only go out to 2.5 radii.

The Mead field is more complex than a dipole but still simple enough that test-particle trajectories can be described (almost) analytically. This makes it a good test case for our code.

The Mead Field - Results

Particles (E = 500 MeV, pitch angle 90º) behaved as expected in the Mead field, stable near the equator and short-lived elsewhere.

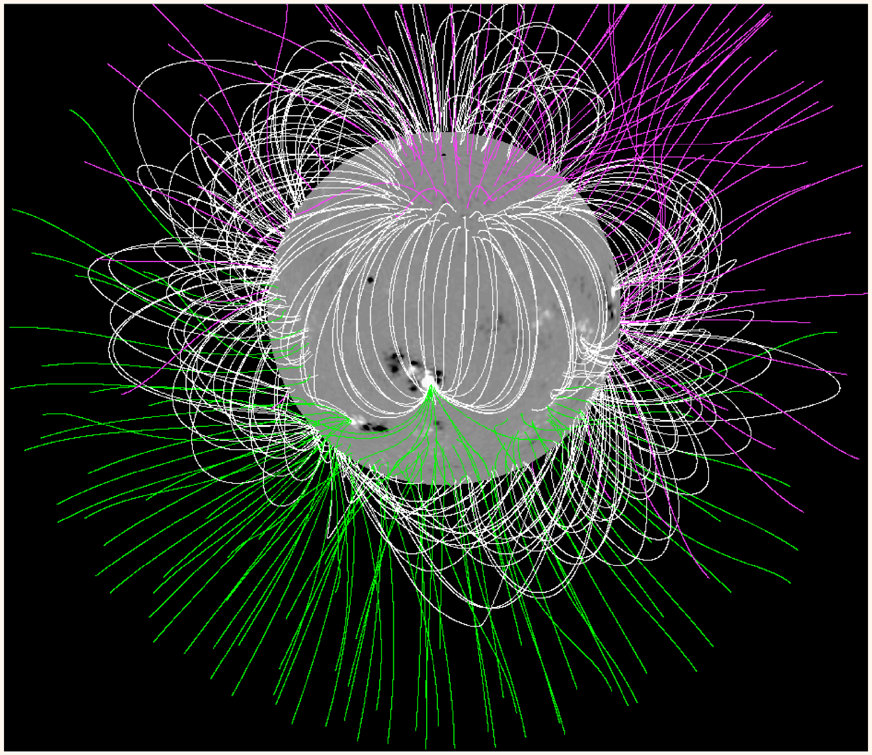


- Particles near the poles quickly escaped, following “open” field lines
- Particles near the equator oscillated between mirror points while drifting
- Particles at the equator starting at 90º pitch angle drifted without bouncing.

The addition of binary collisional energy loss makes little difference to the trajectories far from thermalization. Our test particles were fully ionized Bi nuclei, an extreme worst case. Protons see a dramatically slower collisional energy loss and trace out many full drift shells. This is also the case with PFSS model fields.

The PFSS Field

"Real" coronal fields can be approximated in real time by extrapolating solar magnetograms in the "potential-field source surface" approximation (Schatten et al 1967; Altschuler & Newkirk 1967)

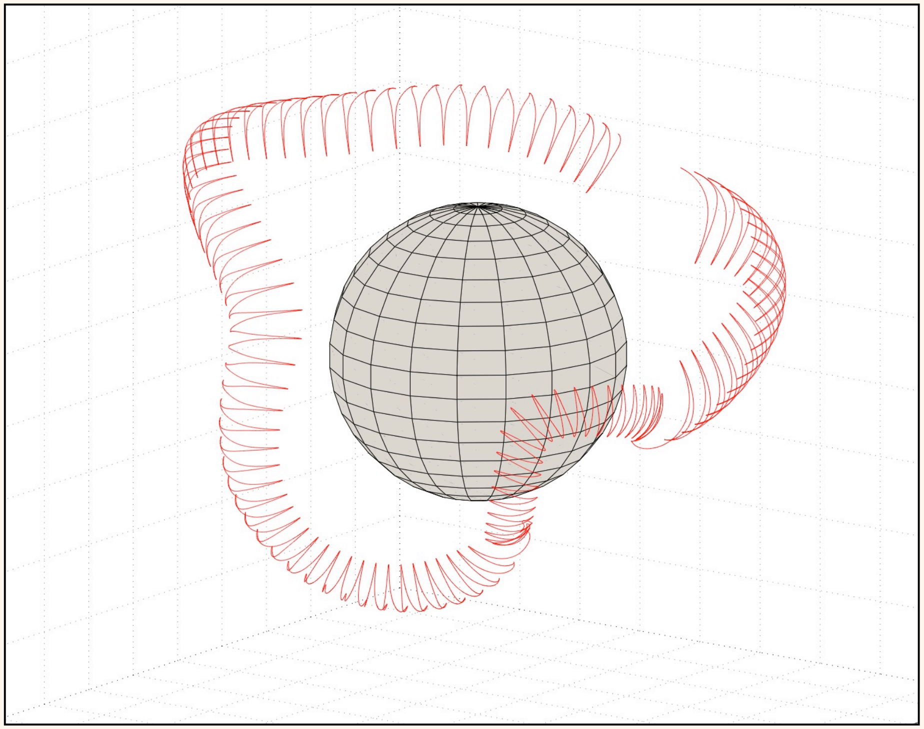


We use the global PFSS models of Schrijver & DeRosa (2003). These are available through SolarSoft with 6-hour updates since SOHO first light.

The quiet-Sun models show a strong dipole component, but can also have other potential trapping domains

PFSS Field - Results

Particles in a fixed PFSS field can almost conserve all three invariants and thus remain trapped for long periods of time.

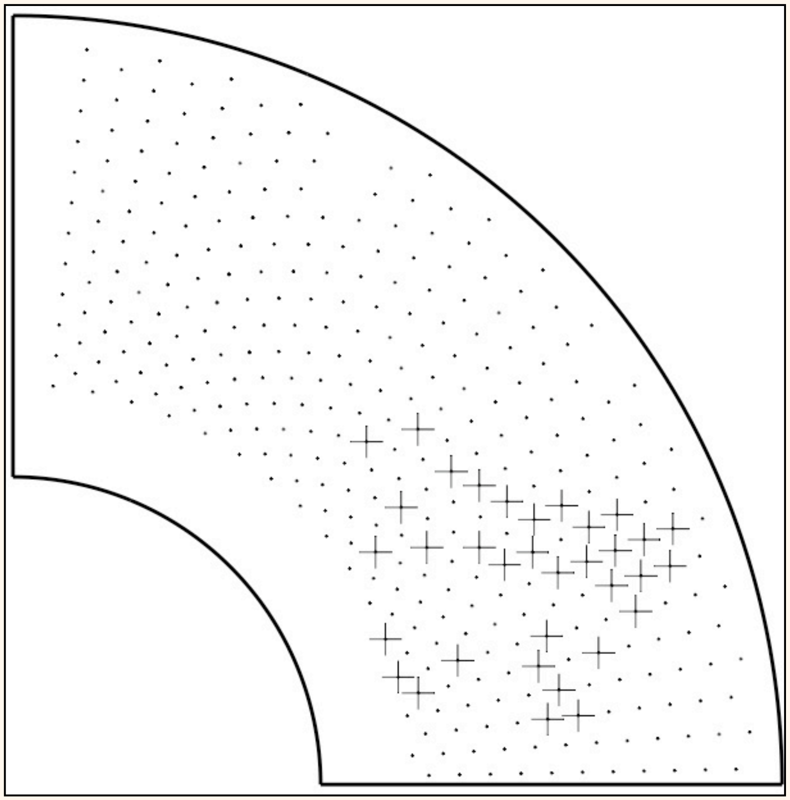


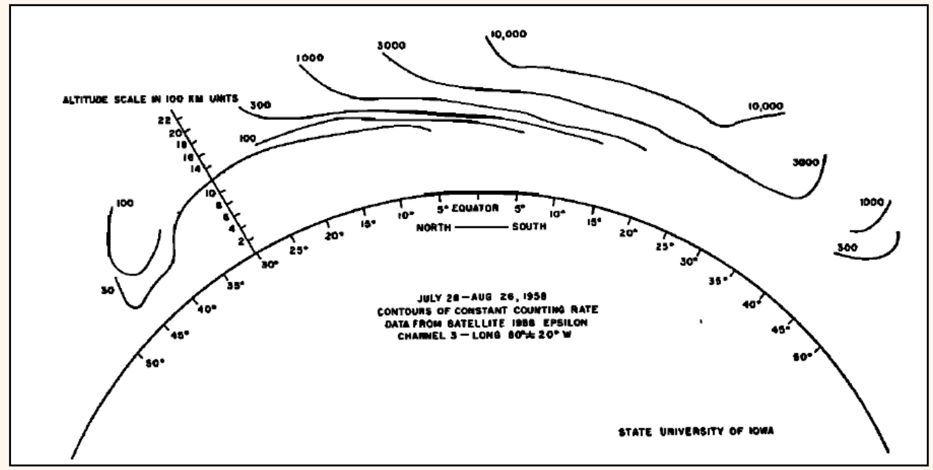
- Bi LXXXIII test ion
- PFSS 2006/09/30 12:04:00
- Start (E, α) = (150 MeV, 90º)
- Start (θ, φ, R) = (6.02, 1.04, 2.0)

A weird ion such as Bi LXXXIII has a large Larmor radius (km scale) and thus exaggerates the drift motions.

PFSS Field - Results

Locus of trapping orbits
for 2006/09/30 12:04:00





Contours of terrestrial radiation intensity found by Van Allen, McIlwain, and Ludwig (1959) with Geiger-counter observations from a very early spacecraft

Conclusions

- High-energy particles can be stably trapped in large-scale coronal magnetic fields
- There are plausible sources of high-energy particles
- Such particles may play a role in coronal dynamics, with several processes analogous to terrestrial ones
- We have begun to explore the parameter space
- The trapping zones are probably too near the Sun for *In situ* observations with Solar Probe Plus (10 R_{sun} perihelion)