Radiation Belt Remediation

Plasma Physics Summer School

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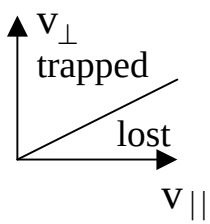
July 8, 2004

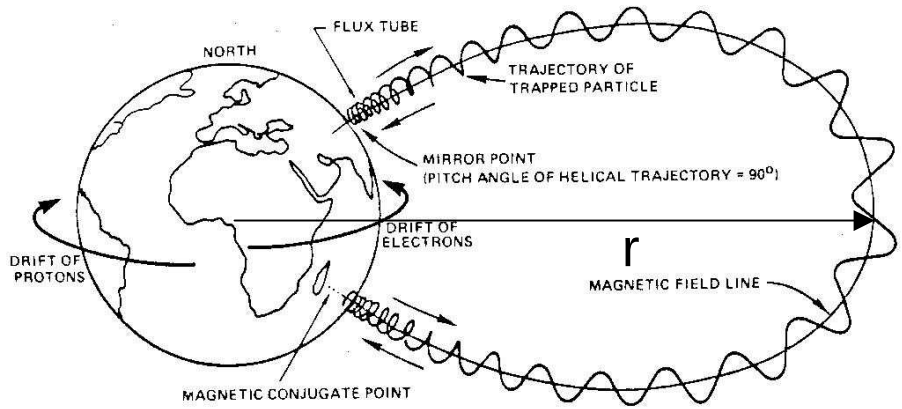
Low-altitude Nuclear Blast Threat

- A (10 kT) nuclear detonation at (100-300 km) altitude could create a long-lived intense artificial radiation belt of energetic electrons
- Many satellites would be destroyed in a few weeks (Starfish US blast, 1962)
- Recent publicity: “Armageddon”, Launchspace, 6/00, “Nuclear Explosions in Orbit”, Scientific American, 6/04

The Earth's Radiation Belts

- The earth' dipole magnetic field efficiently confines charged particles from eV's to GeV's





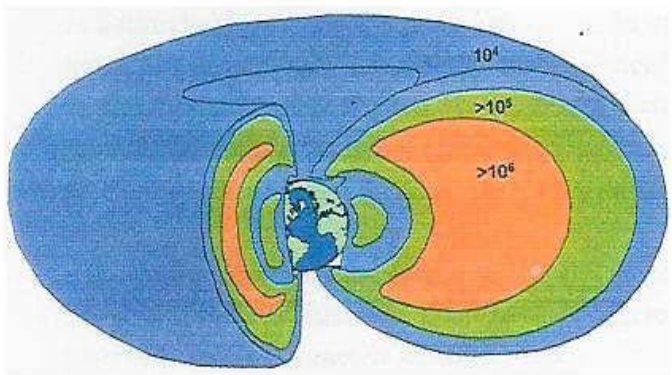
$L = r/a$, $B = B_0/L^3$
$a = 6{,}378$ km
$B_0 = 0.31$ G

1.5 MeV electrons at L = 1.5: gyrate (10 μs), bounce (0.1 s), and drift (30 min)

Natural Electron Belts

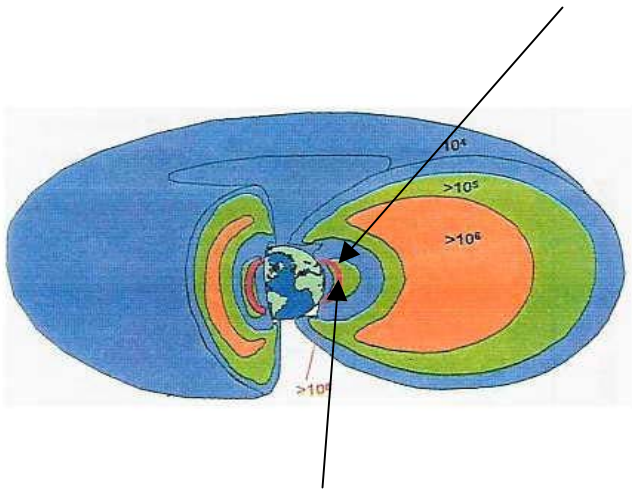
- Average electron population results from solar wind influx and from radial diffusion and pitch-angle scattering into the loss cone

Electron Flux contours ($cm^{-2}s^{-1}$) of (> 1 MeV) electrons



Artificial Electron Belt

Nuclear blast at 20 to 45° latitude ⇒ electron belt at L ~ 1.2 - 2



Artificial belt > 10^8 $cm^{-2}s^{-1}$

Example

- 10 kT nuclear detonation, 10^{24} electrons (1 – 8 MeV) per kT yield, 10% trapping efficiency $\Rightarrow$ 10^{24} electrons (peak at ~ 1.5 MeV)

- Artificial belt (L = 1.5, ΔL ~ 0.1, Vb ~ 3×10^{20} m^3)
  $\Rightarrow$ n ~ 3×10^3 m^{-3}, Γ ~ nc ~ 10^{12} $m^{-2}s^{-1}$

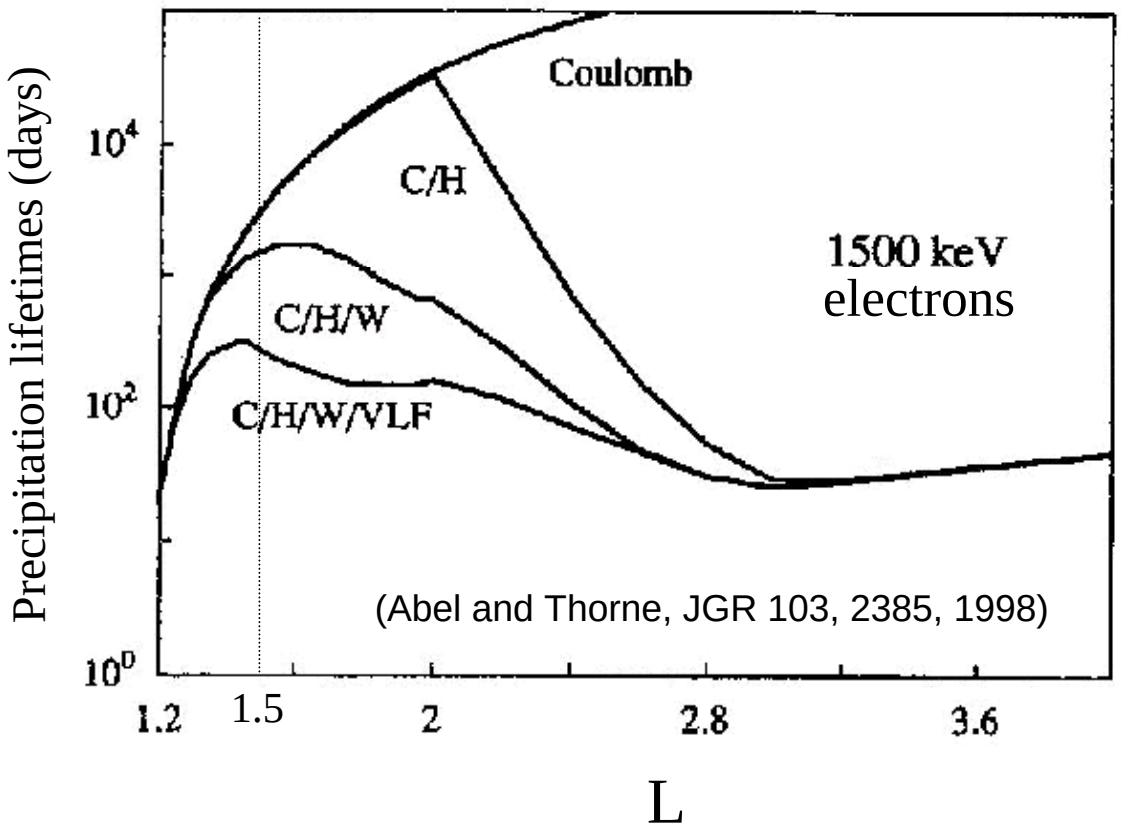
- Γ increased by ~ 10^3 $\Rightarrow$ many LEO satellites quickly destroyed

- Remediation needed within ~ 2 weeks

Possible Remediation Techniques

- Natural precipitation (do nothing!)
- Gas release (absorb energetic electrons)
- Electrical scattering (electrostatic tethers)
- Magnetic scattering (electrodynamic tethers)
- Wave scattering (in-situ VLF-wave injection)

Natural Precipitation (do nothing!)



C: Coulomb collisions
H: Hiss (< 1 kHz)
W: Whistlers (2-6 kHz)
VLF: transmitters (17-23 kHz)

Gas Release

- Vent gas from satellite(s)
- Spherical gas volume Vg (radius R, density ρ)
- Energy loss faster than scattering for 1.5 MeV electron
- $\rho R \sim 6$ kg/m^2 required for electron absorption
- $dN/dt \sim (4\pi R^2)nc$, $\tau \sim nVb/(dN/dt) \sim (1/3)(Vb/Vg)(R/c)$
- $Vb \sim 3\times10^{20}$ m^3, $\tau \sim 2$ weeks $\Rightarrow$ $R \sim 260$ m
- Gas mass $\sim \rho Vg \sim 1.7\times10^6$ kg (too much!)
- Plasma or electron emission also impractical

Electrical Scattering
(DARPA, Tethers Unlimited, U. Michigan..)

- Use long (ℓ ~ 10 km) electrostatic tethers biased at V = – 100 kV
- Single tether of radius $r_t \sim 10^{-3}$ m yields a sheath radius s ~ 10 m, $s \sim (V/n)^{5/12} r_t^{1/6}$, $n \sim 5\times10^9$ m^{-3} at L = 1.5
- Electrons entering the sheath experience small random variations in their pitch angle α ($v_\perp/v = \sin\alpha$)
- Relativistic Monte-Carlo calculations (Bryan Minor, ScienceOps)

  yield $\langle\Delta\alpha\rangle \sim 3°$ for 1.5 MeV electrons ($\langle\Delta\alpha\rangle \sim 0.14°$ for 10 MeV)
- $\tau \sim (1/10)(Vb/Vt)(s/c)(1/\langle\Delta\alpha\rangle^2) \Rightarrow s \sim Vb/(10\pi N\ell c\tau\langle\Delta\alpha\rangle^2)$
- τ ~ 2 weeks, N = 13 satellite systems $\Rightarrow$ s ~ 55 m

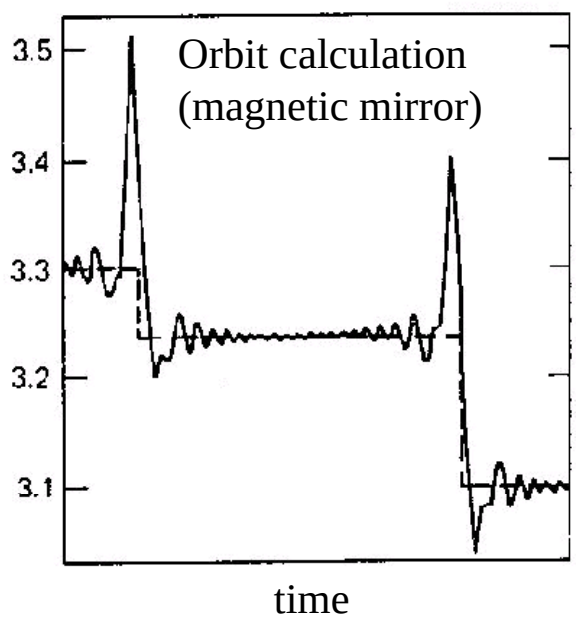
Electrical Scattering (continued)

- A ring (R = 20 m) of (m = 25) tethers $\Rightarrow$ s ~ 50 m
- Periodic (100 m length) egg-beater configuration
- Power P ~ VI, V ~ 100 kV, I ~ $mN(1+\gamma_e)I_{OML}$, γ_e ~ 1.5
- $I_{OML} \sim enr_t\ell(eV/m_i)^{1/2}$ ~ 25 mA per wire
- I ~ 20 A for N = 13 $\Rightarrow$ P ~ 2 MW
- High power and high voltage technology!

Magnetic Scattering

- Charged particles can experience small $\Delta\alpha$ jumps if their Larmor radius ρ_L is comparable to $B/\nabla B$ (non-adiabatic scattering)

$\mu \sim (\sin\alpha)^2/B$



$(\Delta\mu)/\mu \sim \exp(-\rho_L \nabla B/B)$

Magnetic Scattering (continued)

- 1.5 MeV equatorial electrons at L = 1.5 have ρ_L ~ 0.5 km while dipole B/∇B ~ 3000 km $\Rightarrow (\Delta\mu)/\mu << 1$
- Electrodynamic tether (10 A) can achieve ρ_L ~ B/∇B within r ~ 5 m
- τ ~ (1/10)(Vb/Vt)(r/c)(1/<$\Delta\alpha$>^{2}) ~ 10 weeks (<$\Delta\alpha$> ~ 0.3)
- N ~ 5 satellite systems required for τ ~ 2 weeks
- P ~ VI ~ 5(4 kV)(10 A) ~ 0.2 MW
- Issues: electron emitters, return plasma currents…

Wave Scattering
(DARPA, AFRL, Stanford…)

- 70 kW of (17 - 23 kHz) VLF transmitter power reduces 1.5 MeV electron precipitation lifetime by one order of magnitude at L = 1.5
- Whistler waves can resonate with energetic electrons, changing the electron energy and/or the pitch angle

$$\omega - k.v = - m\omega_{ce} \quad (m = 0, \pm 1, \pm 2, \ldots)$$

- $m = - 1 \Rightarrow f = \omega/2\pi \sim 2 - 5$ kHz ($n\omega \sim \omega_{ce}$, $n \sim 100$) $\Rightarrow$ pitch-angle diffusion higher by factor 30 (compared to 20 kHz)
- multiple wave reflections in dipole B field (gain ~ 10 – 20) may lower the required power to < 0.1 kW !

Wave Scattering Issues

- Electron “hole” replenished by energy and/or spatial diffusion
- Local anisotropies may drive instabilities
- Lower-energy electrons may be accelerated to MeV energy
- Variable VLF frequencies, antenna/sheath/plasma coupling
- Long (~ 100 m) antennas with high (~ 1 kV) voltages
- DSX (Deployed Structure eXperiment) satellite proposed

Summary

- A low-altitude nuclear detonation could create an intense belt of MeV electrons
- Many satellites would be destroyed within a few weeks
- Draining the artificial MeV electron belt is challenging but possible
- VLF wave scattering may be the most promising remediation technique
- LANL possible contributions: modeling (X-1, ISR-1), experiments(?)