THE ENVIRONMENT OF SPACE

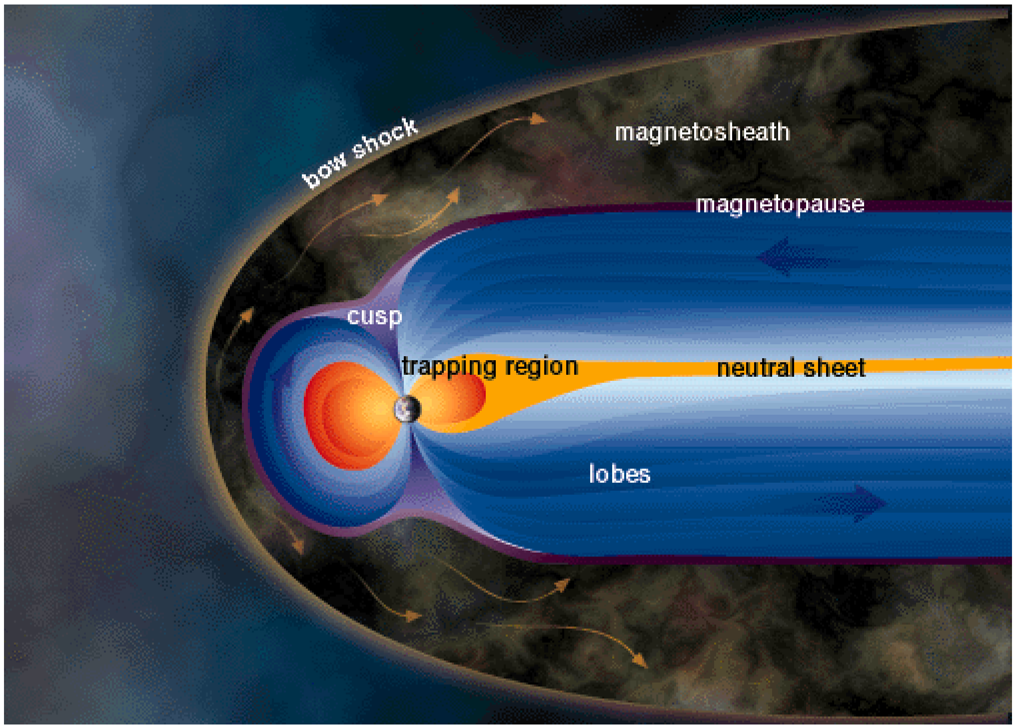


Image courtesy of NASA.

Col. John Keesee

OUTLINE

- Overview of effects
- Solar Cycle
- Gravity
- Neutral Atmosphere
- Ionosphere
- GeoMagnetic Field
- Plasma
- Radiation

OVERVIEW OF THE EFFECTS OF THE SPACE ENVIRONMENT

- Outgassing in near vacuum
- Atmospheric drag
- Chemical reactions
- Plasma-induced charging
- Radiation damage of microcircuits, solar arrays, and sensors
- Single event upsets in digital devices
- Hyper-velocity impacts

Solar Cycle

- Solar Cycle affects all space environments.
- Solar intensity is highly variable
- Variability caused by distortions in magnetic field caused by differential rotation
- Indicators are sunspots and flares

LONG TERM SOLAR CYCLE INDICES

- Sunspot number R

  10 (solar min) $\leq R \leq$ 150 (solar max)
- Solar flux $F_{10.7}$

  Radio emission line of Fe (2800 MHz)

  Related to variation in EUV

  Measures effect of sun on our atmosphere

  Measured in solar flux units (10^{-22} w/m^2)

  50 (solar min) $\leq F_{10.7} \leq$ 240 (solar max)

SHORT TERM SOLAR CYCLE INDEX

- Geomagnetic Index A_p
  - Daily average of maximum variation in the earth's surface magnetic field at mid lattitude (units of 2×10^{-9} T)

$A_p = 0$ quiet

$A_p = 15$ to 30 active

$A_p > 50$ major solar storm

GRAVITY

$$\text{force} = -G\frac{m_1 m_2}{r^2}\hat{r}$$

$$G = 6.672\times 10^{-11}\,m^3 kg^{-1}$$

At surface of earth

$$f_g = -m\frac{Gm_e}{R_E^2} \qquad g = \frac{Gm_e}{R_E^2} \approx 9.8\frac{m}{sec^2}$$

MICROGRAVITY

- Satellites in orbit are in free fall - accelerating radially toward earth at the rate of free fall.
- Deviations from zero-g
  - Atmospheric drag $\ddot{x} = 0.5\left(\frac{C_D A}{m}\right)\rho\, a^2\omega^2$
  - Gravity gradient

    $$\ddot{x} = -xw^2 \qquad \ddot{x} = -yw^2 \qquad \ddot{z} = 2zw^2$$

  - Spacecraft rotation

    $\ddot{x} = x\omega^2 \qquad \ddot{z} = z\omega^2$ (rotation about Y axis)

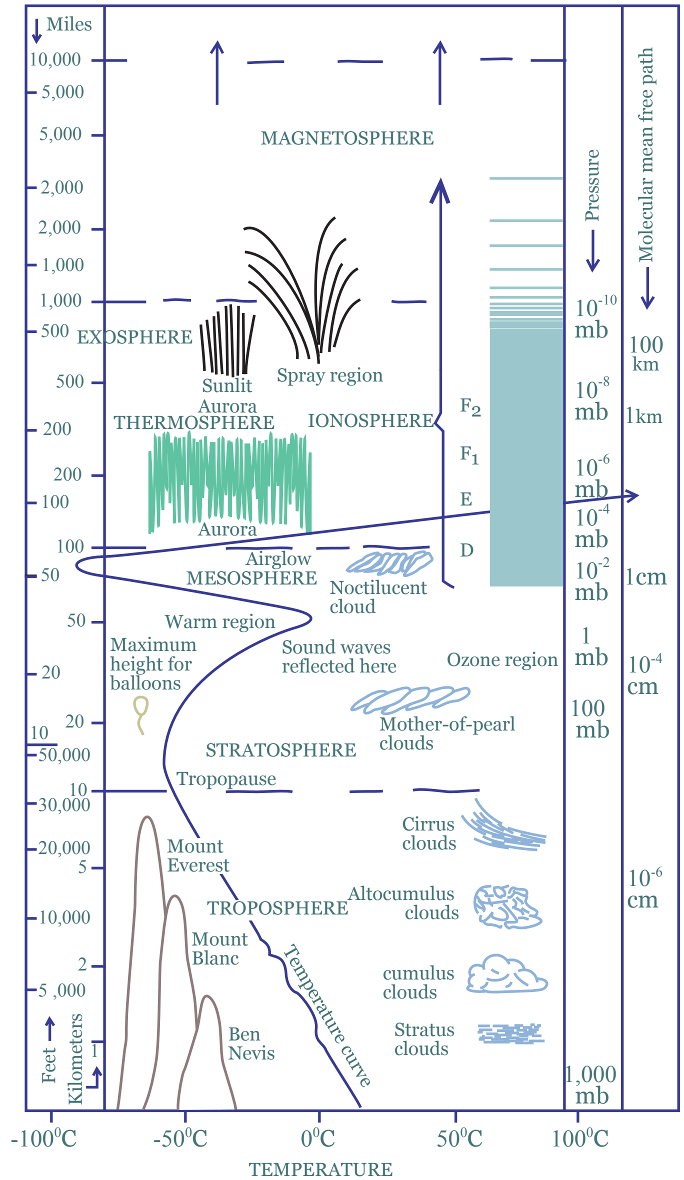
  - Coriolis forces

    $$\ddot{x} = 2z\omega \quad \ddot{y} = o \quad \ddot{z} = -z\dot{x}\omega$$

ATMOSPHERIC MODEL
NEUTRAL ATMOSPHERE

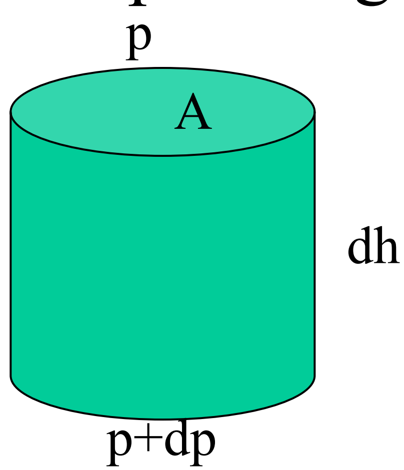
- Turbo sphere (0 ~ 120Km) is well mixed (78% N_2, 21% O_2)
  - Troposphere (0 ~ 10Km) warmed by earth as heated by sun
  - Stratosphere (10 ~ 50 Km) heated from above by absorption of UV by 0_3
  - Mesosphere (50 ~ 90Km) heated by radiation from stratosphere, cooled by radiation into space
  - Thermosphere (90 ~ 600Km) very sensitive to solar cycle, heated by absorption of EUV.
- Neutral atmosphere varies with season and time of day

Layers of the Earth's Atmosphere



DENSITY ALTITUDE MODEL

Assume perfect gas and constant temperature



$$p = n\,k\,T \qquad \frac{dp}{dh} = \frac{d(nkT)}{dh}$$

n is number density (number/m^3) dpA - n m g A d h = o

k is Boltzmann's constant

$$\frac{dp}{dh} = nMg = \frac{d(nkT)}{dh}$$

M is average molecular mass

$$\frac{dn}{n} = \frac{Mg}{KT}dh$$

H ~ 8.4km h ~ 120km

$$n = n_o exp\ (-h/H)$$

H ≡ kT/mg (scale height)

Atmospheric Gases

- At higher altitudes O_2 breaks down into O by UV
- Primarily O from 80 - 90 km to 500 km
- Hydrogen and Helium beyond 500 km
- Kinetic energy of O atom at 7.8 km/s ~ 5eV (enough to break molecular bonds ~1 - 2eV)
- O is highly reactive and destructive to spacecraft
- Temperature at LEO increases with altitude
- Atmosphere expands when heated by high UV (solar max)
- LEO densities ~ 10^8 particles/cm^3

ATMOSPHERIC MODEL

Most common Mass Spectrometer and Incoherent Scatter model - 1986 (MSIS - 1986)

- Based on measured data
- Requires A_p, $F_{10.7}$, month as input
- Gives average values of n, n_o, T, atomic mass as function of altitude
- Instantaneous values can vary by factor of 10

http://nssdc.gsfc.nasa.gov/space/model/atmos/msis.html

AERODYNAMIC DRAG

Drag

$$\bar{D} = -\frac{1}{2}\rho \bar{v} \bullet \bar{v} \left(\frac{\bar{v}}{|\bar{v}|}\right) C_D A$$

$$\bar{D} = m \frac{d\bar{v}}{dt}$$

$$\Delta v = \frac{1}{2}\rho v^2 \left[\frac{C_D A}{m}\right] \Delta t$$

Ballistic coefficient $\beta = \left|\frac{m}{C_D A}\right|$

ρ=density of the atmosphere=$m_o n_o$

=16x1.67x10^{-27}x10^{13}=2.67x10^{-13}kg/m^3

V=7.8km/s

C_D - Drag coefficient

A - Cross sectional area

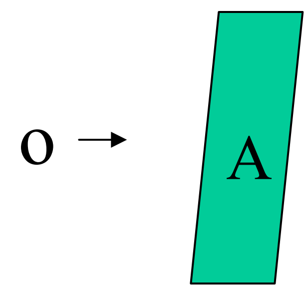
DRAG COEFFICIENTS

Derived from Newtonian Aerodynamics. Depends on what air molecule does at impact

- Reflected $C_D = 4$
- Absorbed $C_D = 2$

Since F = d(mv)/dt

D = - F = - d(mv)/dt



$$C_D = \frac{D}{\frac{1}{2}\rho V^2 A} = -\frac{m\left(V_f - V_i\right)}{\frac{1}{2}\rho V_i^2 A dt}$$

$m = \rho A v_i dt$

$C_D = -2 (v_f - v_i)/v_i$

$= 2$ if $v_f = o$ in rarefied atmosphere

$= 4$ if $v_f = - v_i$

TYPICAL DRAG PARAMETERS

	β (kg/m_2)	C_D	
LANDSAT	25 - 123	3.4 - 4	
ERS - 1	12 - 135	4	
Hubble	29 - 192	3.3 - 4	90,000Kg
Echo 1	0.515	2	

Typically $C_D \sim 2.2 - 4$ for spacecraft. (see SMAD Table 8.3)

ΔV over one year ($\beta = 100$ kg/m^2)

h (km)	ΔV /year (m/s)	
100	10^7	
200	$2 - 5 \times 10^3$	solar (min - max)
300	40 - 600	
400	3 - 200	

SATELLITE LIFETIMES

Large variation depending on initial altitude and solar min/max condition (see SMAD Fig. 8 - 4)

At LEO, design must compensate for effects of drag.

MAGNETIC FIELD EFFECTS

- Deflects charged particles/solar wind.
  - South Atlantic Anomaly
- Creates the structure of the ionosphere/plasmasphere
  - Magnetosphere
  - Van Allen radiation belts
- Direct effects on Spacecraft systems
  - Avionics - induced potential effects
  - Power - induced potential effects
  - GN&C - magnetic torquer performance, sizing
  - Structures - induced currents
  - TT&C - location of SAA

GEOMAGNETIC FIELD

- Earth's Magnetic field comes from three sources
  - internal field (99%)
    - currents inside the Earth
    - residual magnetism of elements contained in crust
  - External field 1%
    - Currents in the magnetosphere
- B_i internal field varies slowly

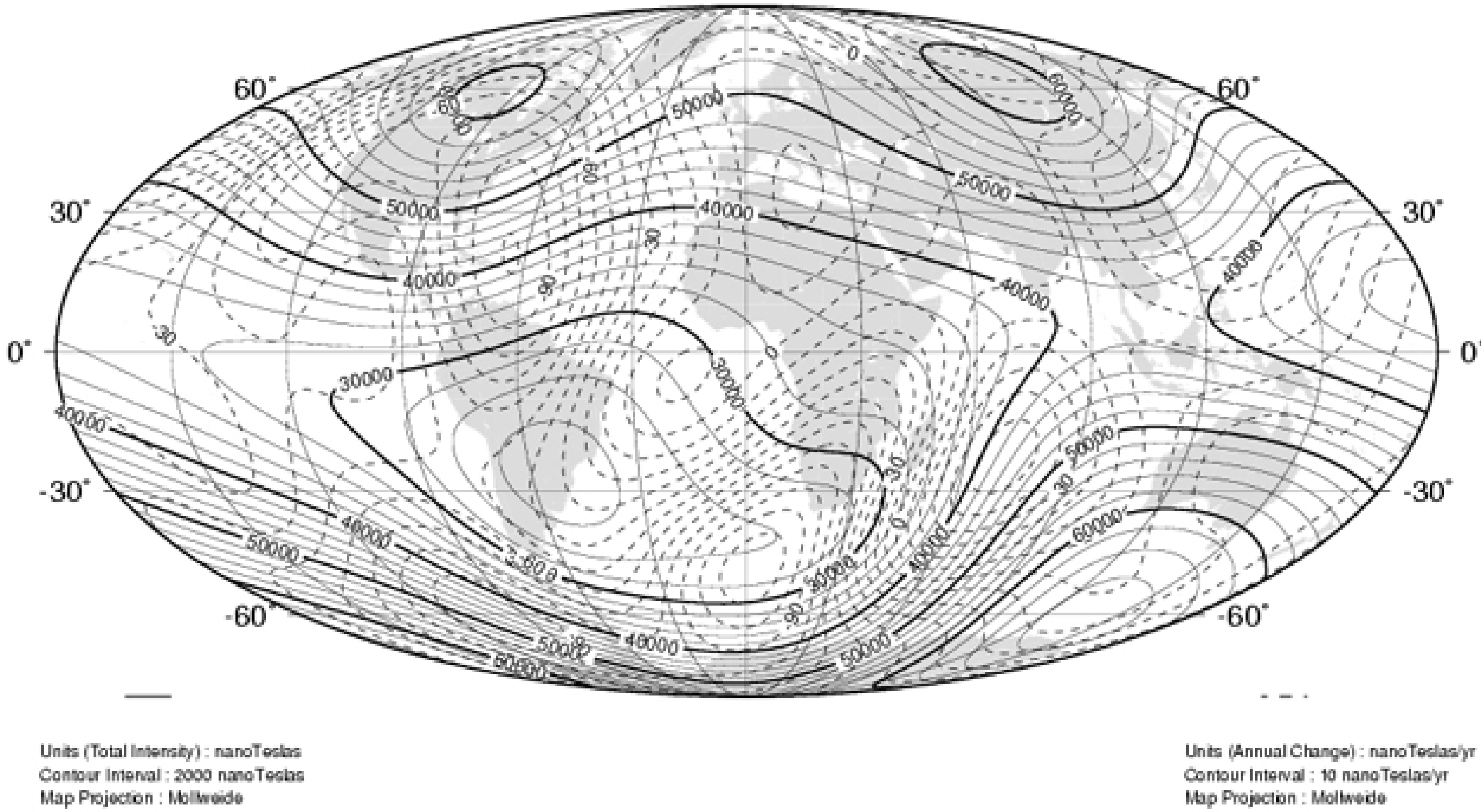
on the order of 100 years

(0.05%/year.)

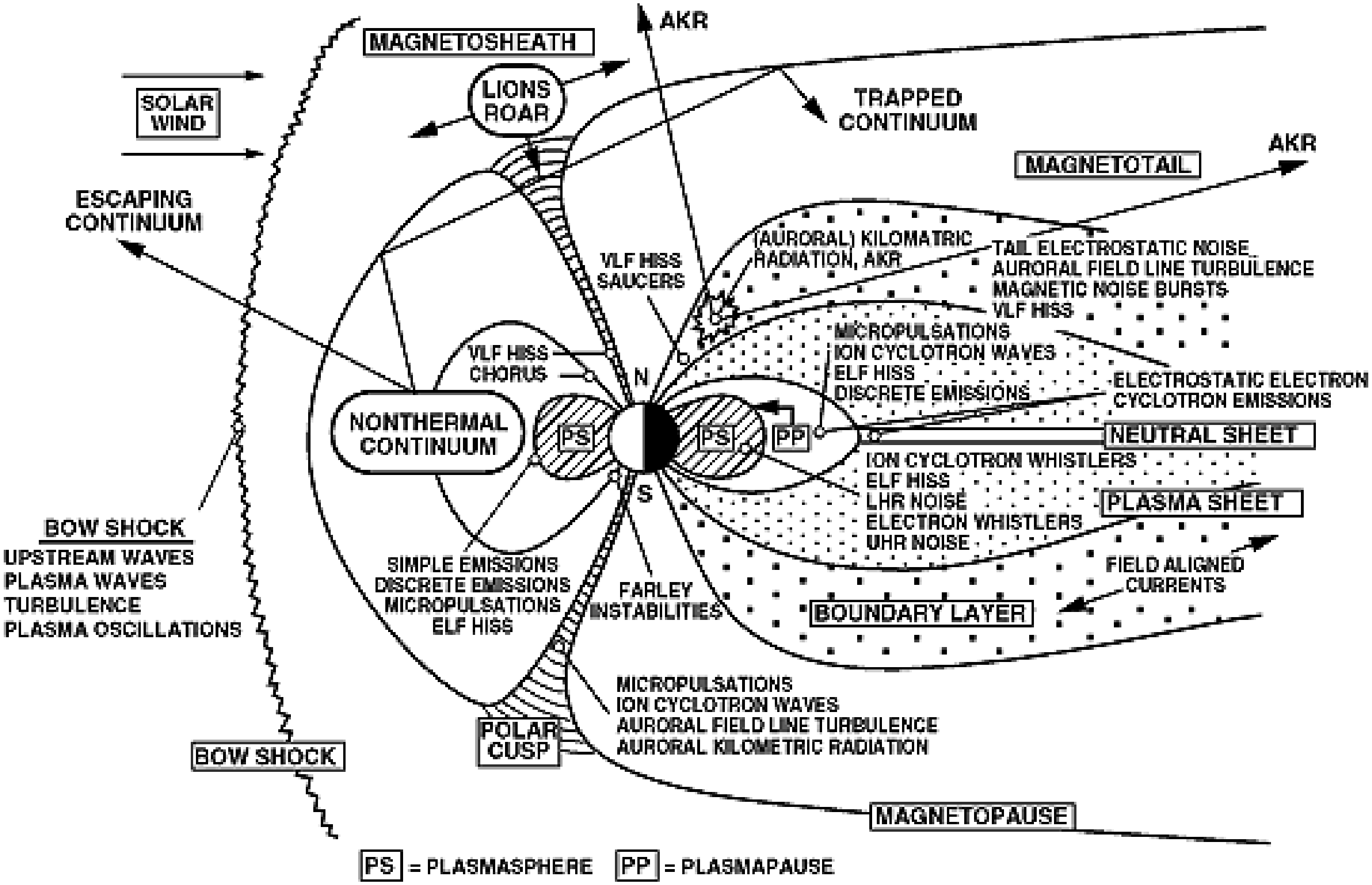
- Poles of magnetic field lie in

Siberia and South Australia.

GEOMAGNETIC FIELD



MAGNETOSPHERE



Magnetosphere (continued)

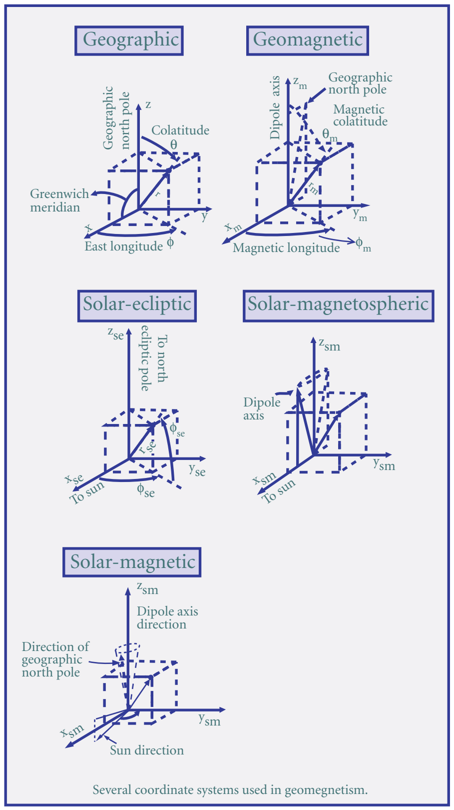
- Earth's field extends 10 Earth Radii (R_{ε}) toward the sun - terminates at magneto pause
- Earth's field slows and deflects solar wind
  - Compressed, heated, turbulent
  - Bow shock at about 14 R_{ε}
- Polar field lines are swept back in night-side tail
  - Does not close
  - Neutral sheet
- Surface of discontinuity in magnetic field implies current flow in the surface
  - Sunward magnetopause - eastward current flow across sub-solar point.
  - Neutral sheet current flow is westward across the tail

EXTERNAL MAGNETIC FIELD

- B_e generated by ring currents and solar wind. Large variation with time
  - Milliseconds to 11-year cycle scales.
- Variations caused by
  - Magnetosphere fluctuations (geomagnetic storms)
  - Solar activity
- Geomagnetic storms dump large numbers of charged particles from magnetosphere into atmosphere
  - Ionizes and heats the atmosphere
  - Altitudes from 300 km to over 1000 km
  - Persist 8-12 hours after storm subsides

GEOMAGNETIC COORDINATE SYSTEMS

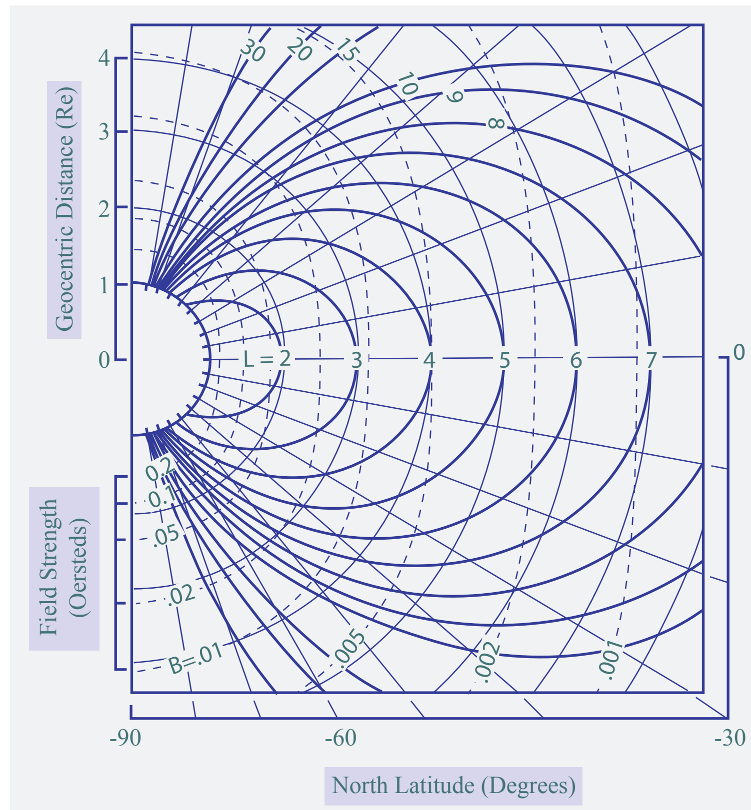
Geomagnetic



Several coordinate systems used in geomegnetism.

B - L

B



L=8

GEOMAGNETIC FIELD

Magnitude Formula/Models

Tilted dipole (11° from geographic north)

$$B_i(r,\theta_m,\phi_m) = -\frac{M}{r^3}\left(3\cos^2(\theta_m)+1\right)^{1/2} \quad \text{at LEO}$$

where

$M = 0.311 \times 10^{-4}$ $\quad T - R_e^3$

$= 7.9 \times 10^{15}$ $\quad T - m^3$

$$B_r = -\frac{M}{r^3} 2\cos\theta_m$$

$$B_{\theta m} = -\frac{M}{r^3} \sin\theta_m$$

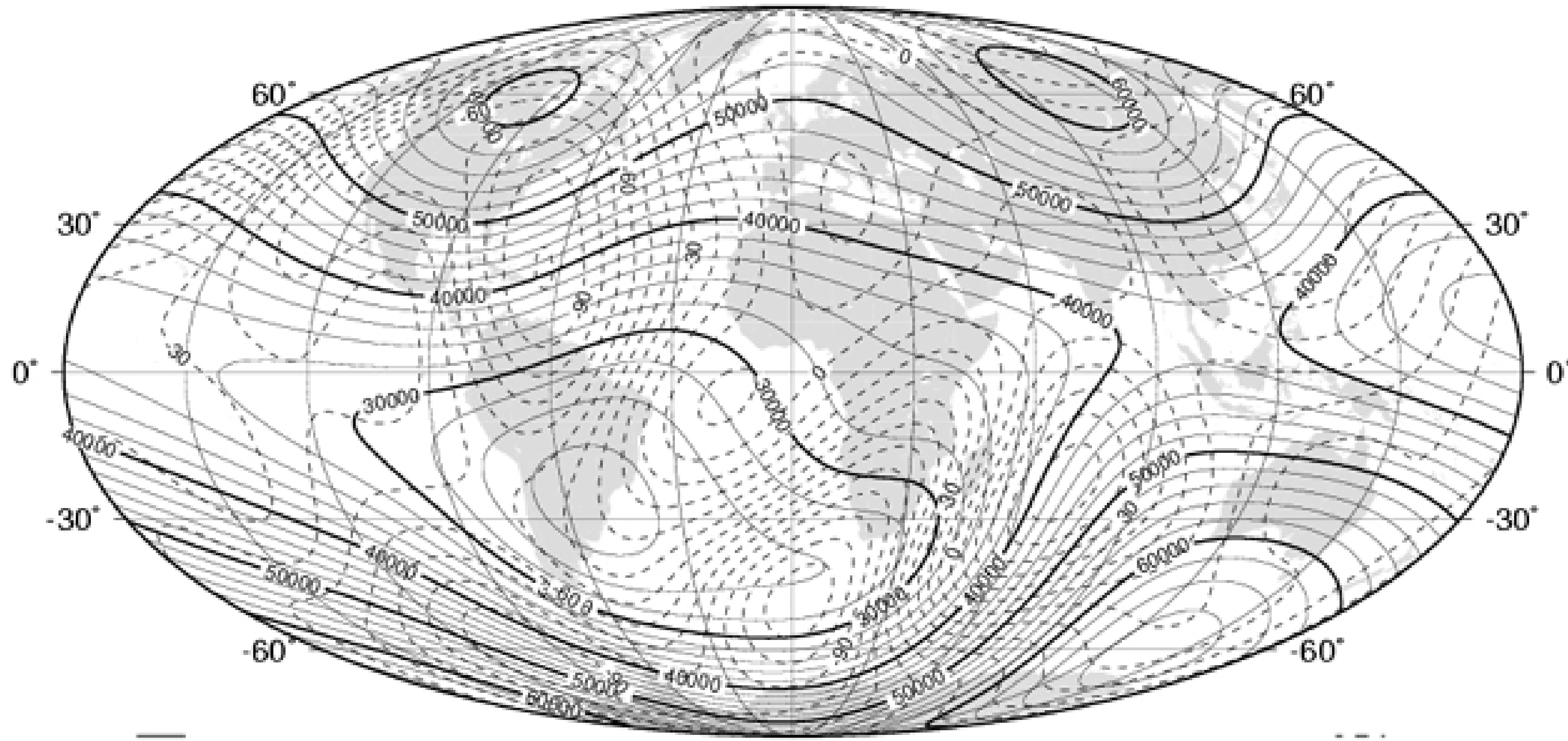
$$B_{\phi m} = 0$$

International Geomagnetic Reference Field 1987 (IGRF1987)

FIELD VALUES

- Minimum (near equator) = 0.25×10^{-4} T
- Maximum (near polar caps) = 0.50×10^{-4} T
- Two peaks near north pole
- Two minimum near equator
- Largest minima is known as South Atlantic Anomaly
  - Much higher radiation exposure at LEO
- Geomagnetic storms impose variations of 0.01×10^{-4} T

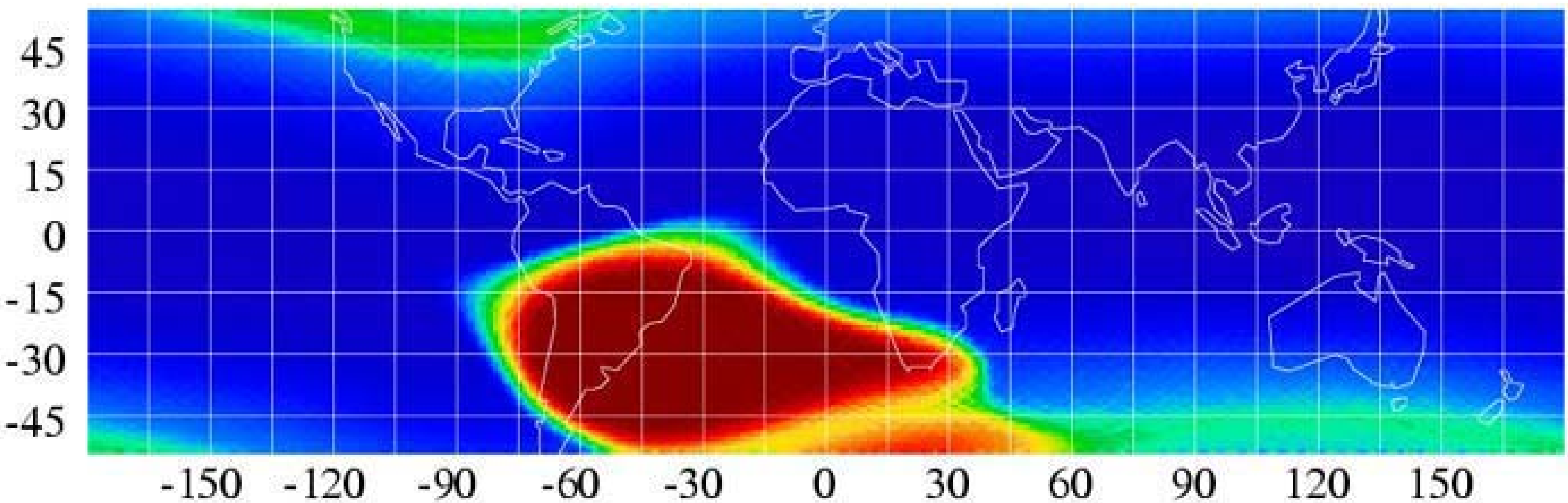
TOTAL FIELD INTENSITY



Units (Total Intensity) : nanoTeslas
Contour Interval : 2000 nanoTeslas
Map Projection : Mollweide

Units (Annual Change) : nanoTeslas/yr
Contour Interval : 10 nanoTeslas/yr
Map Projection : Mollweide

SOUTH ATLANTIC ANOMALY



Reduced protection in SAA allows greater effect of high energy particles - electronic upsets, instrument interference.

PLASMA EFFECTS OVERVIEW

- Plasma is a gas made up of ions and free electrons in roughly equal numbers.
- Causes
  - Elecromagnetic Interference
  - Spacecraft charging & arcing
  - Material effects
- Effects
  - Avionics - Upsets from EMI
  - Power - floating potential, contaminated solar arrays, current losses
  - GN & C - torques from induced potential
  - Materials - sputtering, contamination effects on surface materials

PLASMA EFFECTS (cont.)

- Effects continued

  Optics systems - contamination changes properties of surface materials.

  Propulsion - Thruster firings change/shift the floating potential by contacting the plasma.

PLASMA GENERALIZATION

- Plasma is caused by UV, EUV, X-ray photoelectric effect on atmospheric molecules.
  - Breaks diatomic molecule bonds.
  - Ejects electrons from outer shells.
- As UV, EUV, X-ray penetrate the atmosphere, ion density increases with atmospheric density until most UV, EUV have been absorbed (>60 Km altitude). Varies dramatically with altitude, latitude, magnetic field strength, time of day and solar activity.
- Electrically charged region of atmosphere is called the ionosphere.
- Gas in ionosphere is called ionospheric plasma.

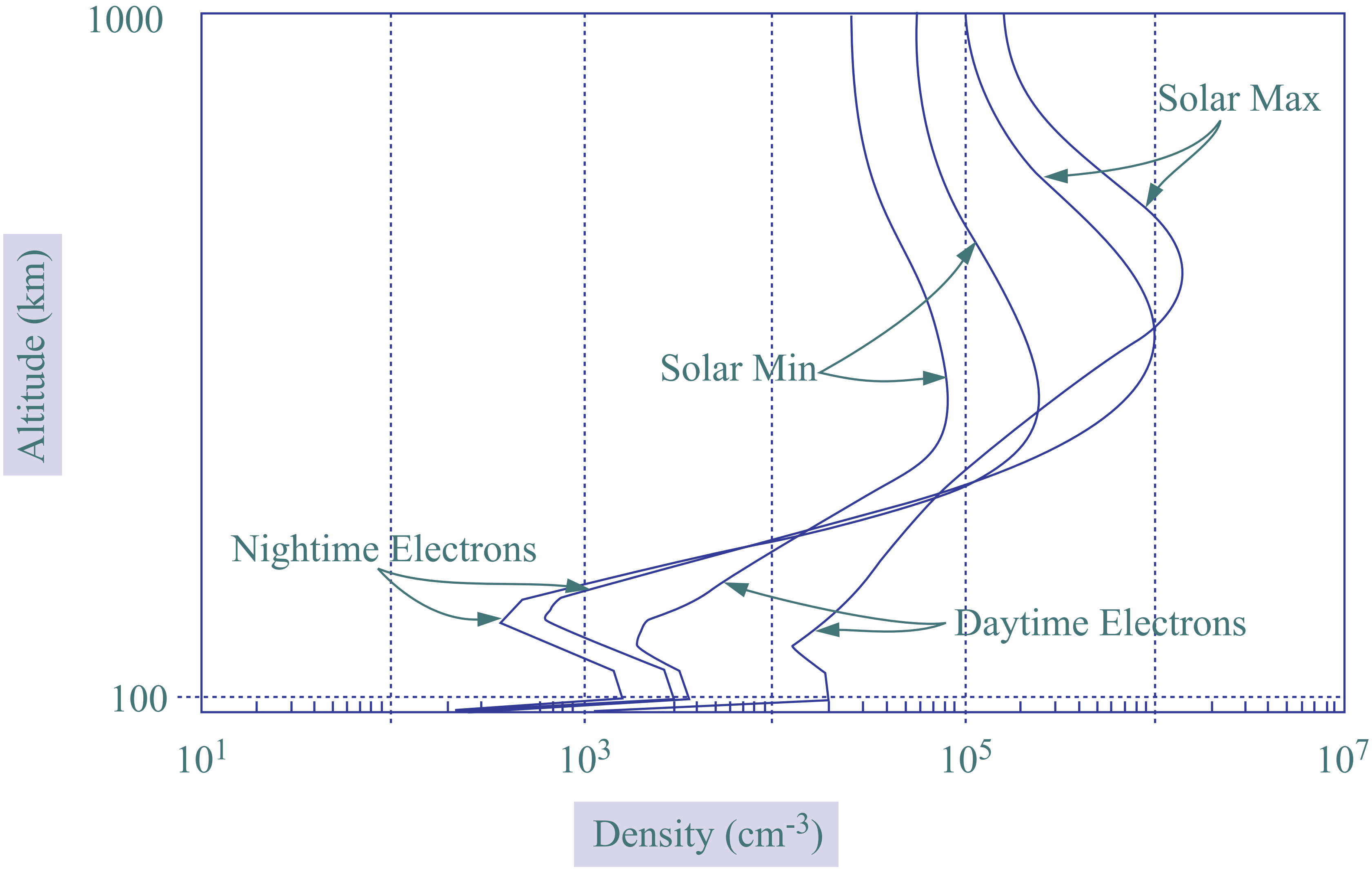
LEO PLASMA ENVIRONMENT

- Balance between increasing density and increasing absorption leads to formation of ionization layers.

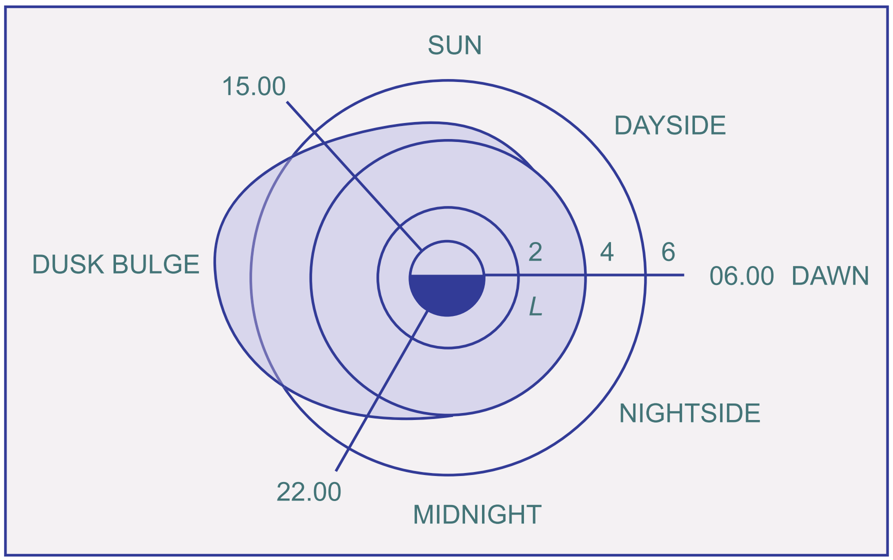
F - layer	150 km - 1000 km
E - layer	100 km - 150 km
D - layer	60 km - 100 km

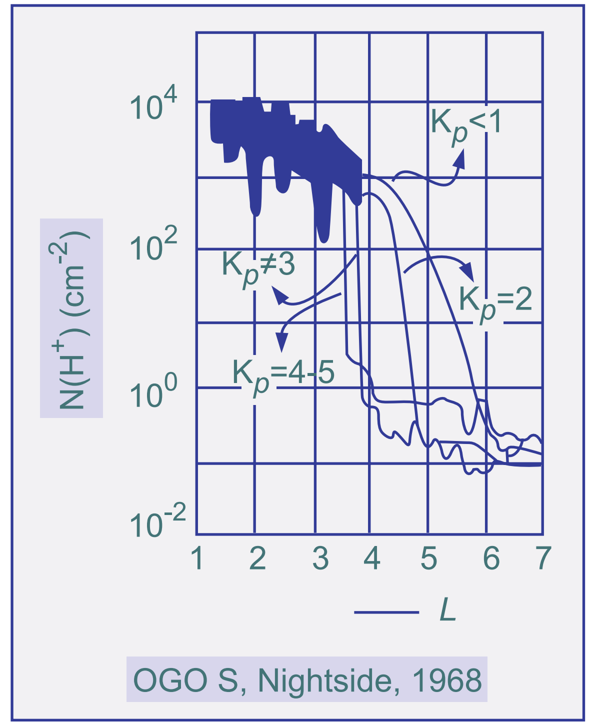
- Transition region from ion-free atmosphere to fully ionized region called the plasmasphere.
- Plasmasphere ion densities peak at $10^{10}/m^3$ to $10^{11}/m^3$ at 1000 km
  - Drops to $10^9/m^3$ at its boundary
- Outer boundary called plasmapause
  - Density drops to $10^5/m^3$ to $10^6/m^3$
  - Height is ~ 4 R_ε between 0000 and 1800 hours
  - Expands to ~ 7 R_ε during the local dusk (dusk bulge)

ELECTRON DENSITY



PLASMAPAUSE HEIGHT VS LOCAL TIME





K_p is Magnetic Activity Index

ION CONCENTRATIONS

– Similar to neutral atmosphere

D - layer NO^+/O^+

E - layer O^+

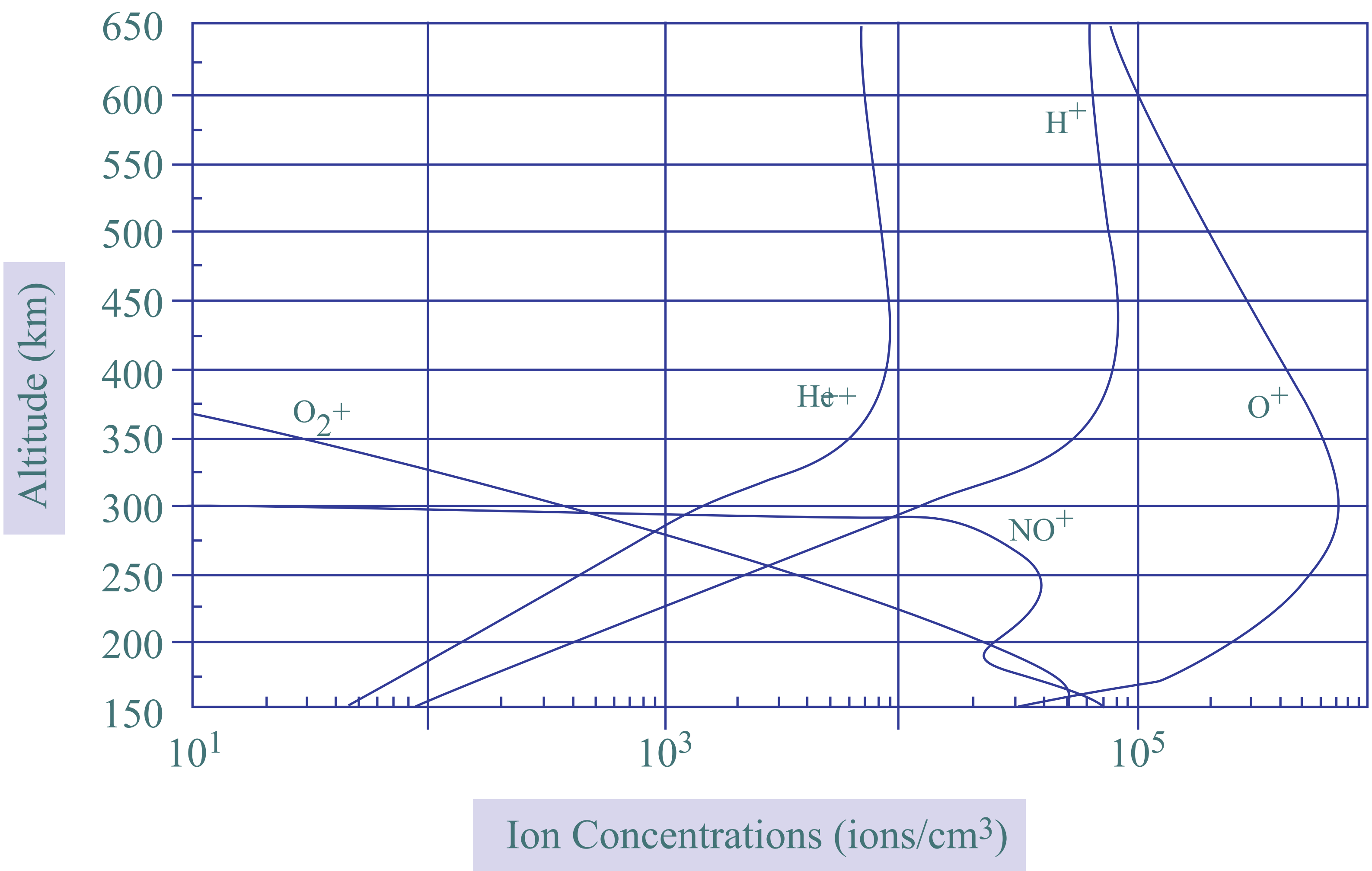
F - layer $O^{+/}H^+$

-Daytime F layer density peaks at $10^{12}/m^3$ (300 km)

-Nighttime F-layer density drops to $10^{11}/m^3$ (500 km)

– Composition transitions from O^+ to H^+

ION CONCENTRATIONS (cont.)



PLASMA TEMPERATURES

Increases from ~100K at 50 - 60 km to
2000 - 3000K above 500 km

Electron temperature T_e = 4000K - 6000K

Ion temperature T_i = 2000K - 3000K

Density much higher at solar maximum due to higher UV/EUV fluxes.

LEO PLASMA ENVIRONMENT MODELS

International Reference Ionosphere (IRI)

-Outputs - electron density n_e

- ion composition n_i
- Temperature T_e, T_i

-Inputs (latitude, longitude, altitude, solar activity (R), time).

Available at :

http://nssdc.gsfc.nasa.gov/space/model/ionos/iri.html

"Ionospheric models" Carlson, Schunk, Heelis, Basu

RADIO FREQUENCY TRANSMISSIVITY

– Plasma transitions from a perfect conductor to perfect dielectric as a function of frequency.

– Plasma frequency $\omega_{pe} = \left(\frac{n_e e^2}{\varepsilon_o m} \right)^{\frac{1}{2}}$

– Dielectric constant $\varepsilon = \varepsilon_o \left(1 - \left(\frac{\omega_{pe}}{\omega} \right)^2 \right)$

– For $\omega \gg \omega_{pe}$ the plasma appears like free space

– For $\omega \sim \omega_{pe}$ electromagnetic waves cannot propagate

- Transmissions from below are reflected
- Transmissions from within are absorbed

– For $\omega \gtrsim \omega_{pe}$ random variations in n_e can cause random delays and phase shifts

SPACECRAFT CHARGING

- At LEO spacecraft become negatively charged
  - Plasma is dense but low energy
  - Orbital velocity is higher than ion thermal velocity
  - Lower than electron thermal velocity
  - Electrons impact all surfaces
  - Ions impact ram surfaces only
- Geo spacecraft charge during magnetospheric substorms between longitudes corresponding to midnight and dawn
- Biased surfaces (solar arrays) influence the floating potential

CHARGING EFFECTS

- Instrument reading bias
- Arcing-induced EMI, electronics upsets
- Increased current collection
- Re-attraction of contaminants
- Ion sputtering, accelerated erosion of materials

Spacecraft must be designed to keep differential charging below the breakdown voltages or must tolerate the effects of discharges.

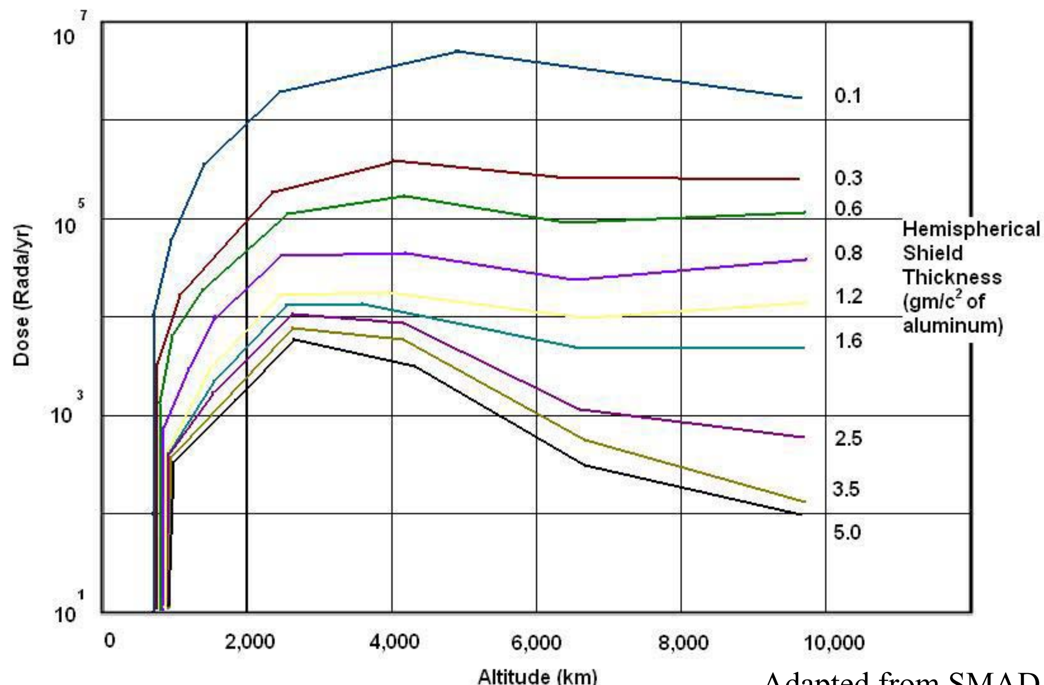
RADIATION

- Most radiation effects occur by energy depostion
  - Function of both energy, type of particle and material into which energy is deposited.
- Definitions

  1 rad (Si) = 100 ergs/gm into Silicon

  1 Cray (Si) = 1 J/kg into Si

  1 rad (Si) = 10^{-4} Cray



Adapted from SMAD.

RADIATION DAMAGE THRESHOLDS

In many materials the total dose of radiation is the most critical issue. In other circumstances the time over which the dose is received is equally important.

Material	Damage Threshold (rad)
Biological Matter	10^1 - 10^2
Electrical Matter	10^2 - 10^4
Lubricants, hydraulic fluid	10^5 - 10^7
Ceramics, glasses	10^6 - 10^8
Polymeric materials	10^7 - 10^9
Structural metals	10^9 - 10^{11}

SPACECRAFT EFFECTS

- High energy particles travel through spacecraft material and deposit kinetic energy
  - Displaces atoms.
  - Leaves a stream of charged atoms in their wake.
- Reduces power output of solar arrays
- Causes sensitive electronics to fail
- Increases sensor background noise
- Radiation exposure to crews

HIGH ENERGY RADIATION

- Definition

For Electrons	E > 100 keV
For protons and heavy ions	E > 1 MeV

- Sources
  - Van Allen Belt → (electrons and protons) (trapped radiation)
  - Galactic cosmic rays → interplanetary protons and ionized heavy nuclei
  - Protons associated with solar proton events

VAN ALLEN BELTS

- Torodial belts around the earth made up of electrons and ions (primarily protons) with energies > 30 keV.
- Two big zones
  - Inner belt ~ 1000 Km $\rightarrow$ 6000 km altitude
    - Protons E > 10's of MeV
    - Electrons E ~ 1 - 10 MeV
  - Outer belt 10,000 - 60,000 km
    - Electrons E ~ 0.04 - 4.5 MeV

VAN ALLEN BELTS (cont.)

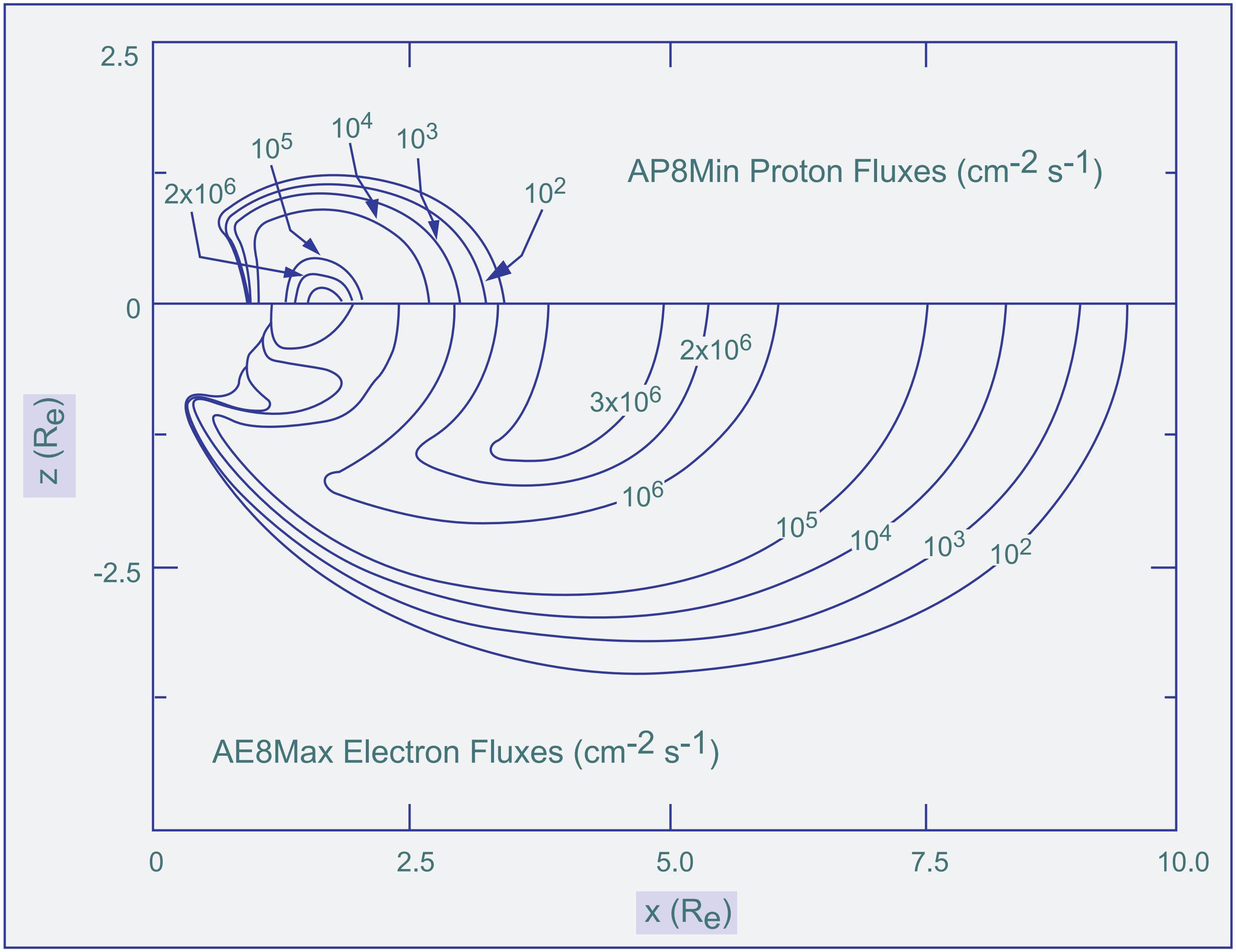
- Sources
  - acceleration of lower-energy particles by magnetic storm activity
  - trapping of decay products produced by cosmic ray collisions with the atmosphere
  - solar flares

CONCENTRATION MECHANISM

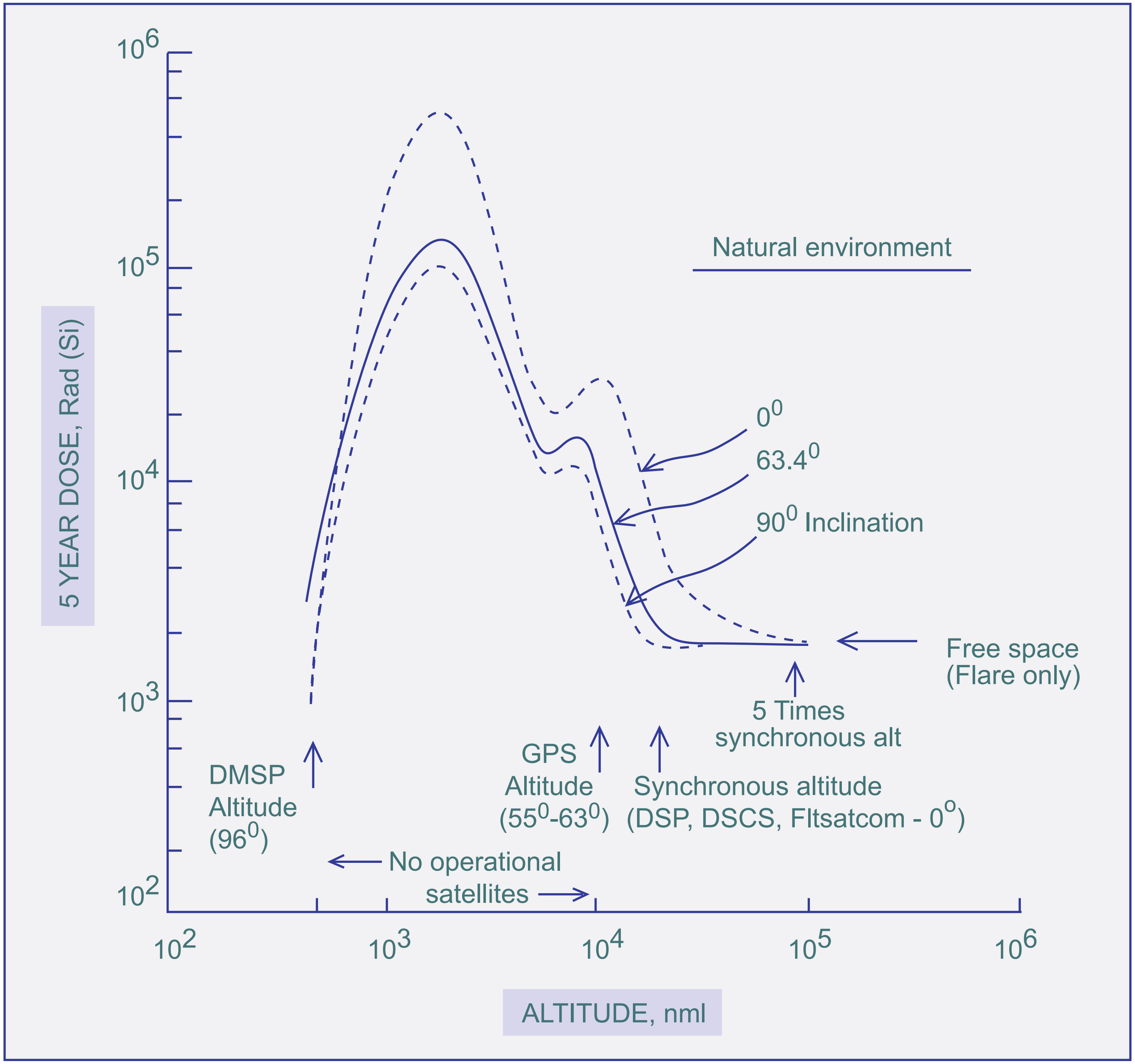
- Earth's magnetic field concentrates on large fluxes of electrons, protons and some heavy ions.
- Radiation belt particles spiral back and forth along magnetic field lines.
  - Ionizing radiation belts reach lowest altitude of the eastern coast of the eastern coast of South America (SAA).

(Image removed due to copyright considerations.)

ELECTRON AND PROTON FLUXES

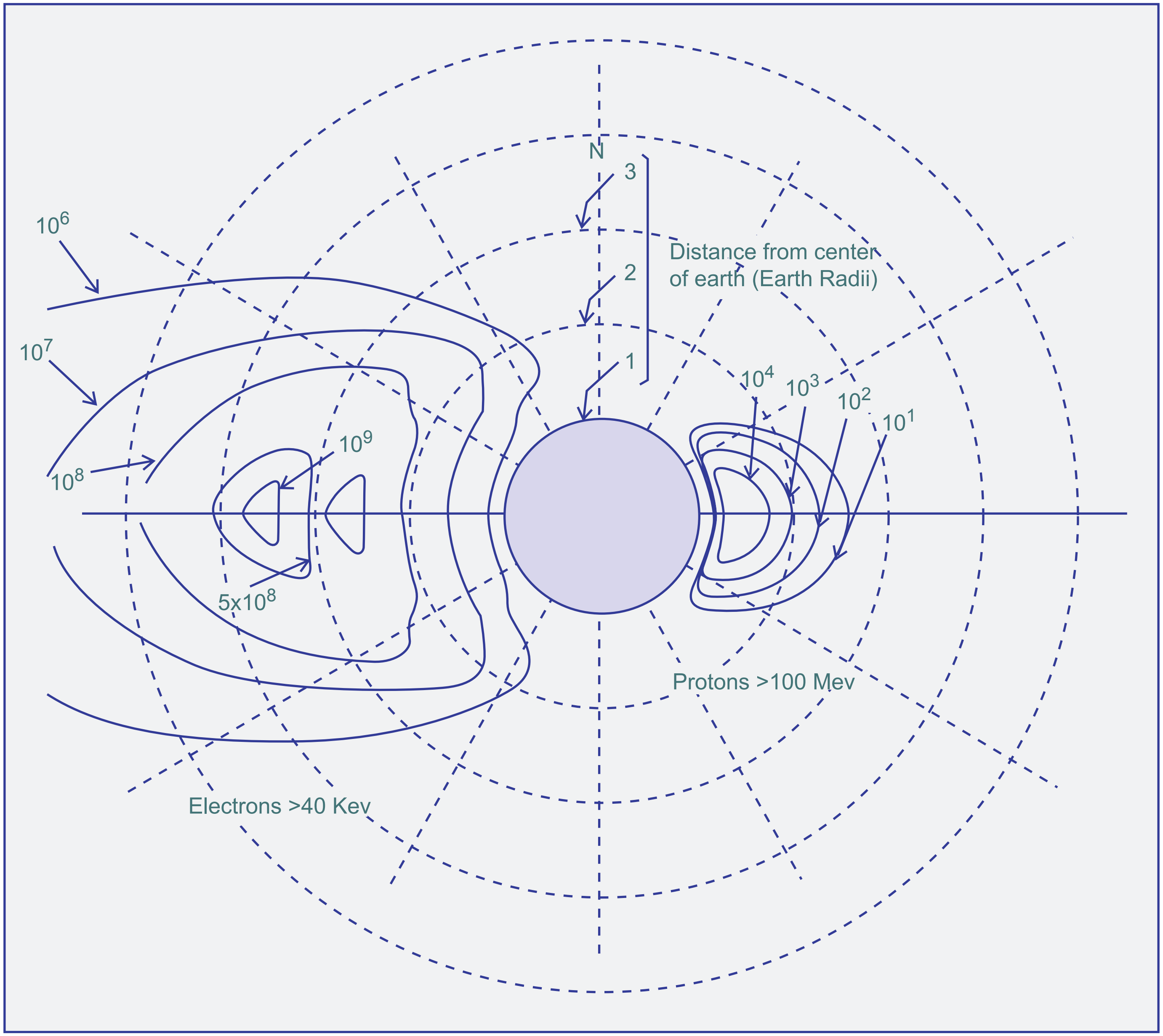


5 YEAR DOSE



5 YEAR DOSE, Rad (Si)
10^6
10^5
10^4
10^3
10^2
Natural environment
0^0
63.4^0
90^0 Inclination
Free space
(Flare only)
5 Times
synchronous alt
GPS
Altitude
(55^0-63^0)
Synchronous altitude
(DSP, DSCS, Fltsatcom - 0^o)
DMSP
Altitude
(96^0)
No operational
satellites
10^2
10^3
10^4
10^5
10^6
ALTITUDE, nml

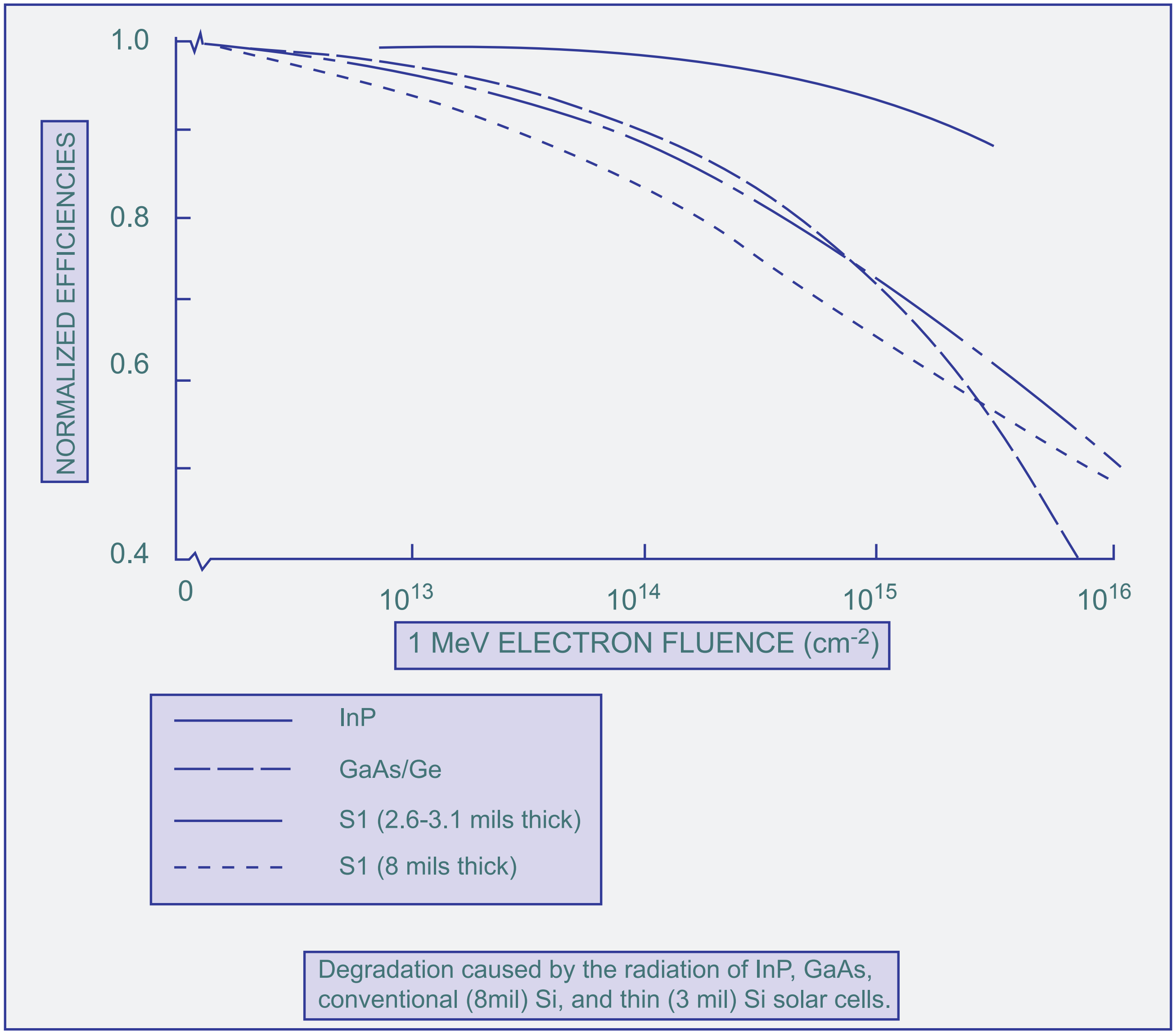
TRAPPED RADIATION BELTS



VAN ALLEN BELT RADIATION STABILITY

- Inner belt
  - Fairly stable with changes in solar cycle
  - May change by a factor of three as a result of geomagnetic storms loading in high energy electrons.
- Outer belt
  - Electron concentrations may change by a factor of 1000 during geomagnetic storms.
- Standard Models (AP8 protons) and (AE8 electrons)
  - Require B, L and whether solar min/solar max
  - Provide omni-directional fluxes of protons 50 keV < E < 500 MeV and electrons 50 keV < 7 Mev

SOLAR CELL DEGRADATION



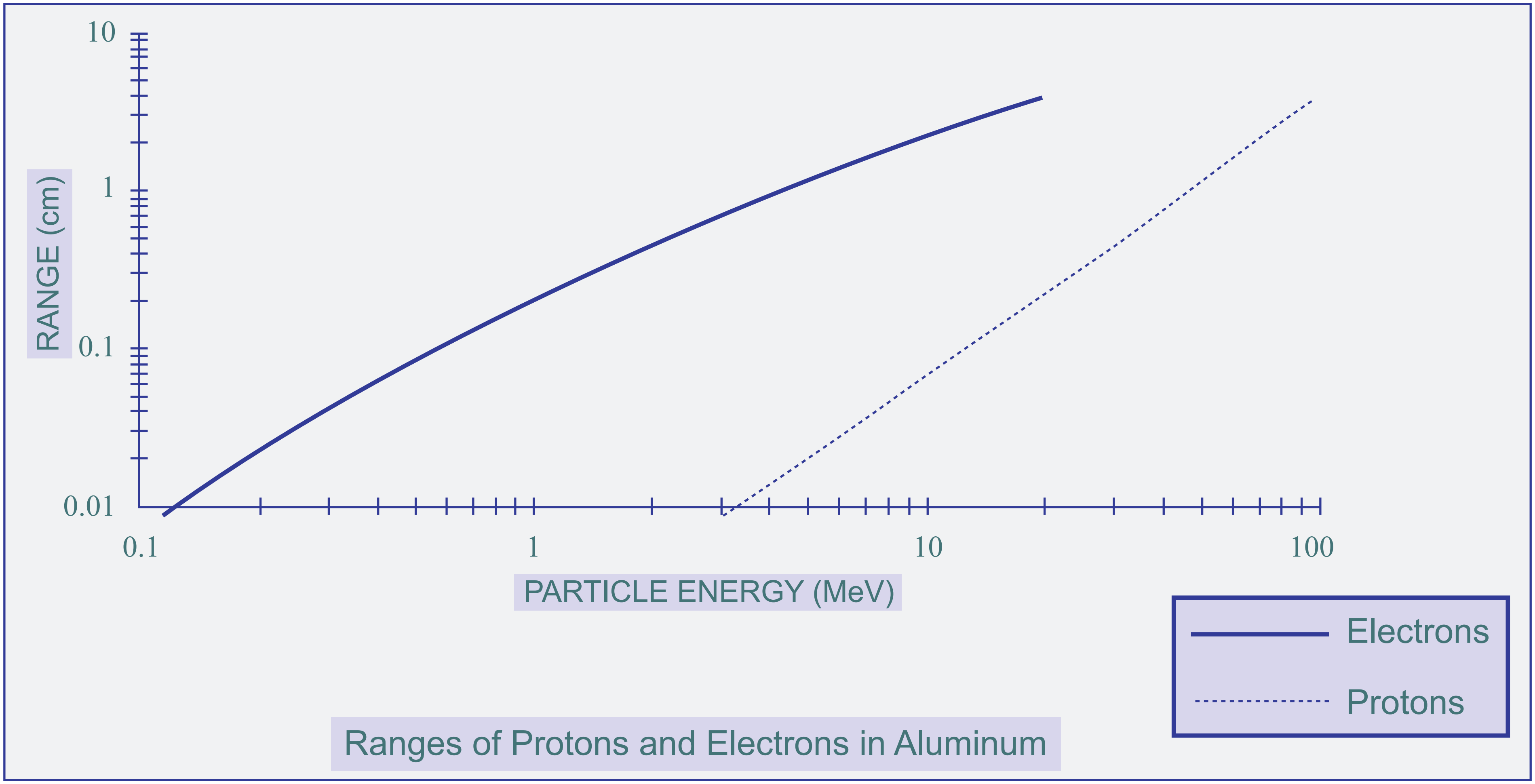
GALACTIC COSMIC RAYS

- Primarily interplanetary protons and ionized heavy nuclei
  - $1 \text{ MeV} < E < 1 \text{ GeV}$ per nucleon

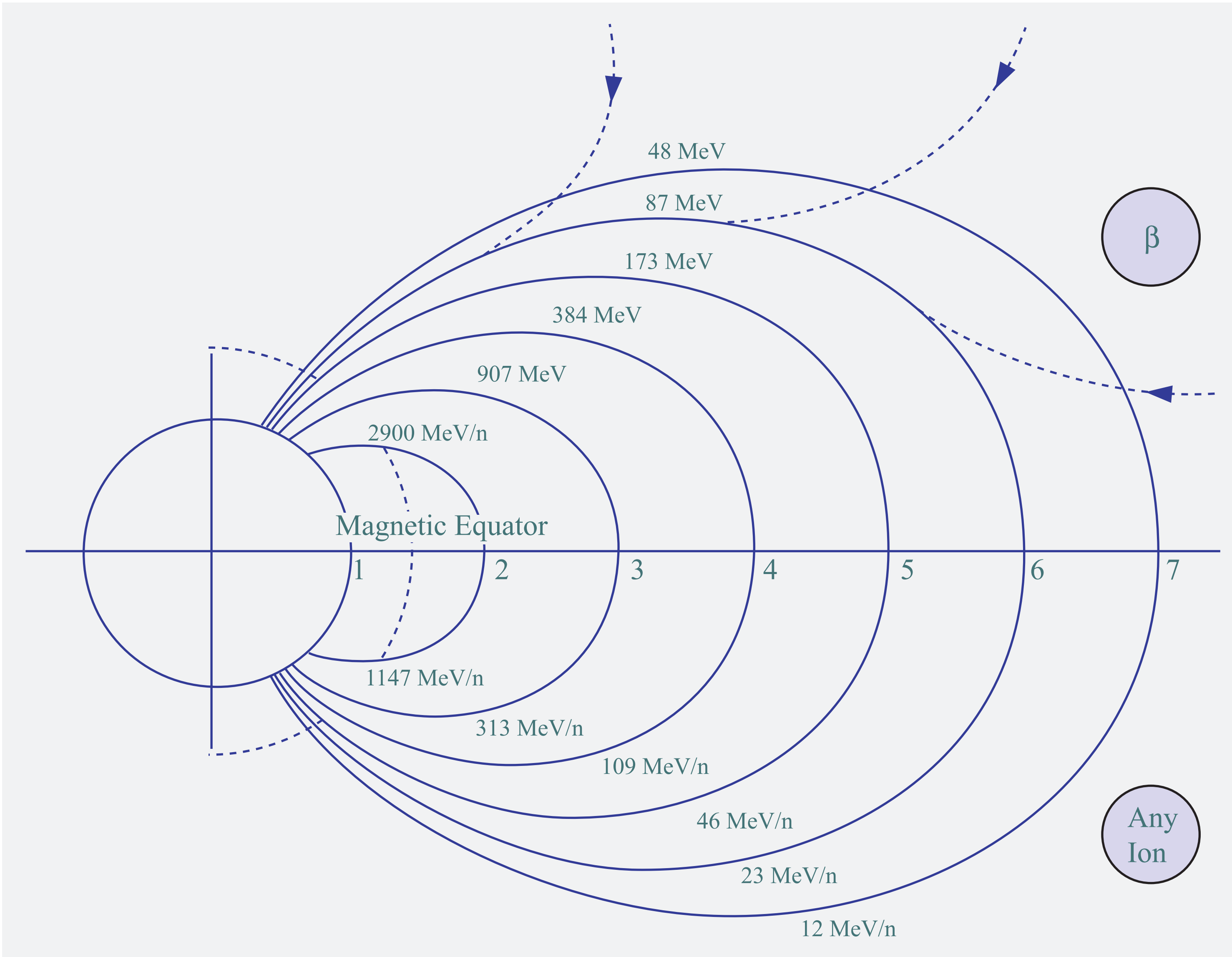
    Cause Single Event Upsets (SEU)

- Sources are outside the solar system
  - other solar flares
  - nova and supernova explosions
  - quasars

PARTICLE RANGE



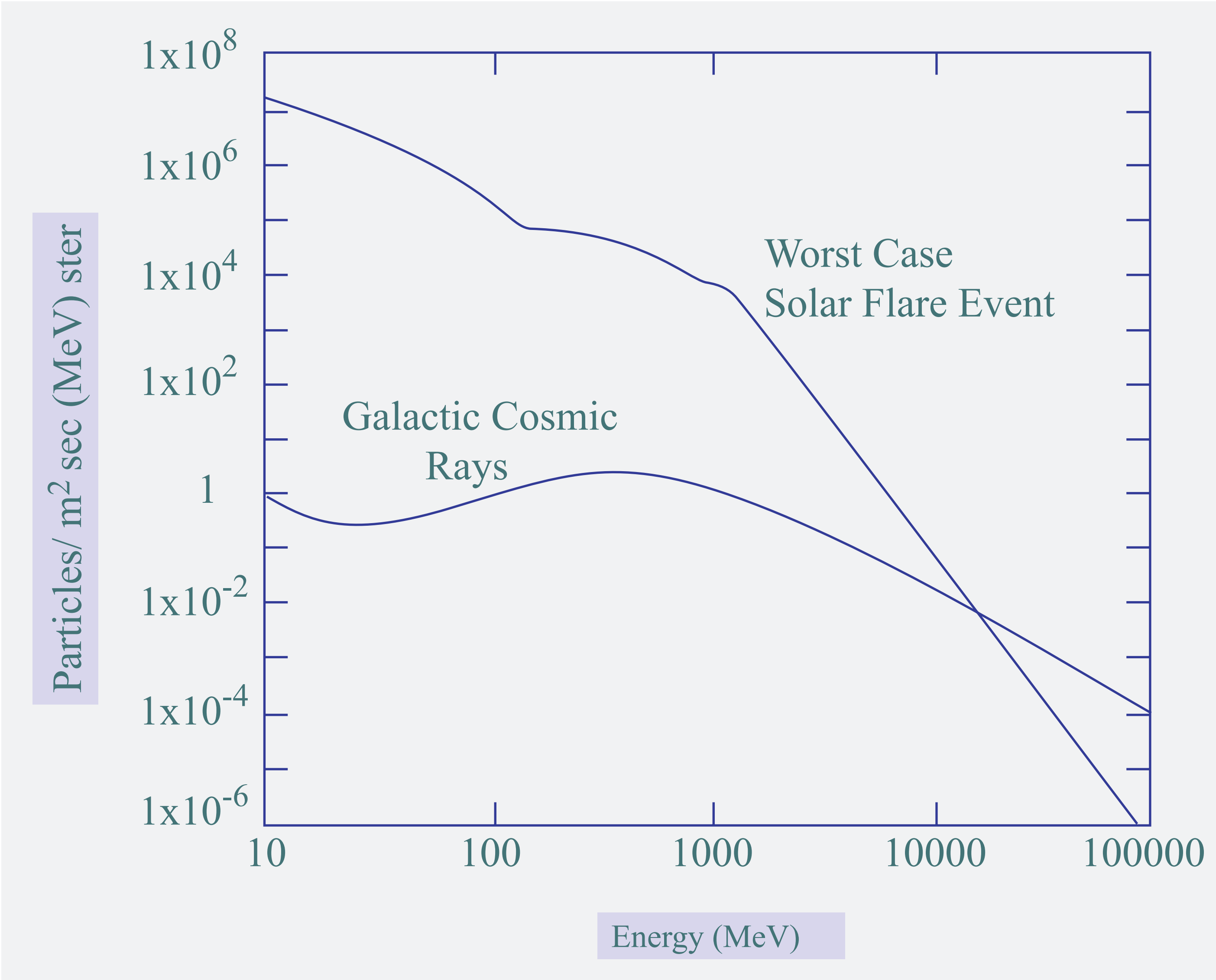
MAGNETIC SHIELDING



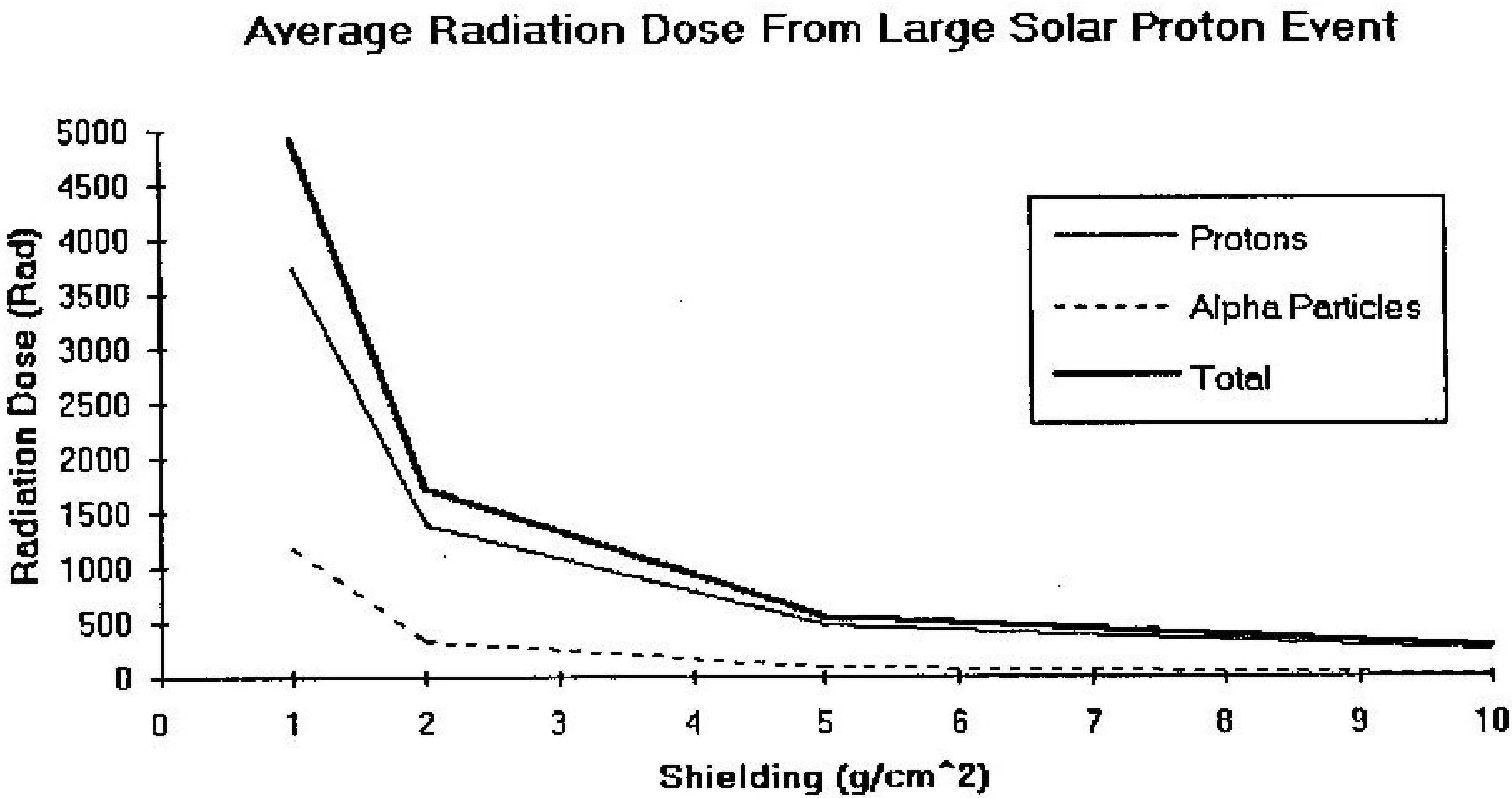
SOLAR PROTON EFFECTS

- Solar flares often eject high energy hydrogen and other nuclei
  - 1 MeV < E < 10 GeV/nucleon
  - At low energies the number can be much greater than galactic comic radiation level
- Solar events are sporadic but correlate somewhat with the solar cycle
- These events make a Mass Mission hazardous

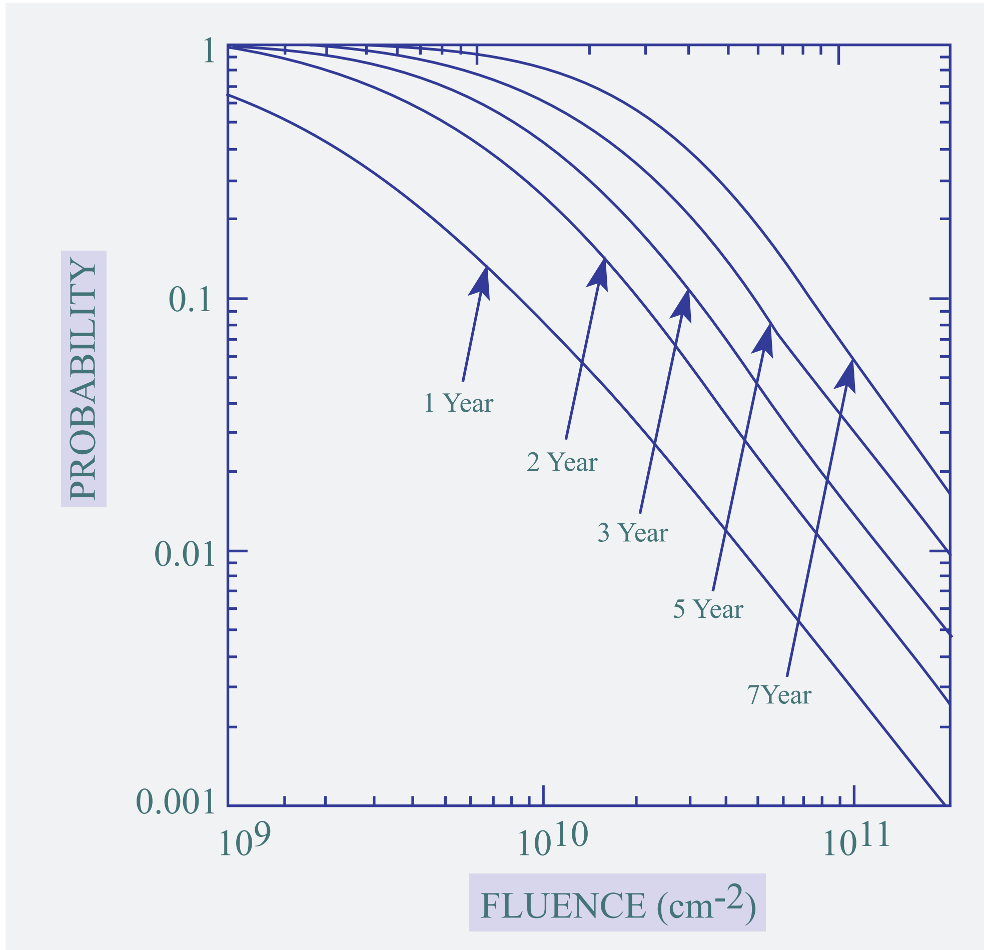
PARTICLE ENERGY



SOLAR PROTON DOSE



FEYNMAN MODEL



Based on data from 1963 to 1991

ELECTROMAGNETIC RADIATION

- Radio
  - 1 - 10 MHz galactic electromagnetic radiation
  - terminal noise
  - not significant for single event environment
- Visible/IR
  - solar flux
  - heating
- UV/EUV/X-ray
  - EUV @ 100 to 1000 Å is significant for surface chemistry

References

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