The planetary space environment - IV (Plasmasphere and radiation belts)

Lecture 10

W.K. Tobiska

Space Environment Technologies

Announcements

Contributions

– A swarm of polar orbit nanosatellites with cross-link communication and multipoint scientific measurements launches Nov 3, 2015 – can still function even if 1 satellite goes out
– **James Van Allen website** http://www.nasa.gov/externalflash/van_allen_gallery/index_noaccess.html
– **IRI-2007 model website** to predict the concentration of electrons for the Earth's atmosphere: http://omniweb.gsfc.nasa.gov/vitmo/iri_vitmo.html
– **UCAR Windows to the Universe**: http://www.windows.ucar.edu/cgi-bin/tour_def/glossary/IMF.html
– **GSFC movie of the magnetosphere**: http://image.gsfc.nasa.gov/poetry/educator/magnetosphere.mov
– **Lunar gravitational anomalies** affect satellite: http://science.nasa.gov/headlines/y2006/06nov_loworbit.htm

Announcements

Contributions

- Video clip of **solar wind's impact** on the Earth's magnetosphere http://www.youtube.com/watch?v=a27xQy1b1Cs
- **CME from the Sun** impacting on the Earth's magnetosphere http://www.youtube.com/watch?v=HTPrwgP8oFY
- **Movie of space environment** around the Earth http://www.geophys.washington.edu/Space/SpaceModel/Bpicktiffs.avi
- Animation of NASA's **THEMIS Spacecraft**, which will monitor aurorae http://revver.com/watch/451567/flv/affiliate/89563

Announcements

Contributions

- **Balloon solar telescope**
  http://www.space.com/scienceastronomy/071030-st-floating-telescope.html
- **Geomagnetic substorms**
  http://science.howstuffworks.com/geomagnetic.htm
- **other SOHO movies**
  http://sohowww.nascom.nasa.gov/bestofsoho/Movies/movies2.html

Announcements

Contributions

- animation of positions of satellites during the event of a **large geomagnetic storm** on 25 November 2001
http://www.youtube.com/watch?v=_tzq0GMKww0
- reported asteroid, 2007 VN84, with a close approach to the Earth is **ESA's Rosetta spacecraft** performing a gravitational assist flyby of Earth en route to a comet encounter in 2014
http://www.planetary.org/blog/article/00001227/

Announcements

Contributions

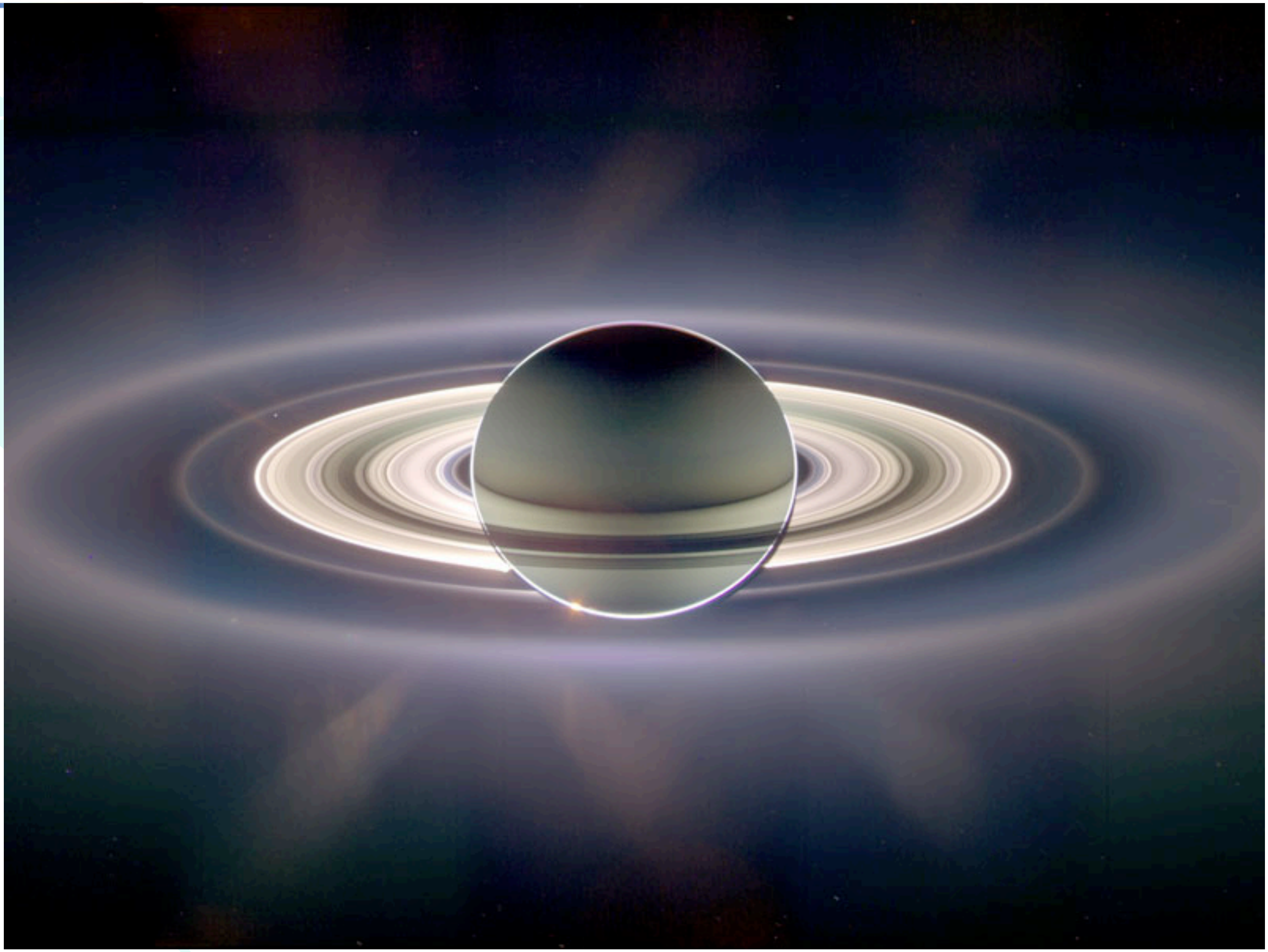
- **US Patent office** has info on spacecraft charging patents http://www.uspto.gov/patft/index.html

7,082,019 Method and apparatus to protect solar cells from electrostatic discharge damage

6,844,714 Satellite charge monitor

6,679,456 Spacecraft protected by a coating including pyroelectric/ferroelectric particles, and the coating material

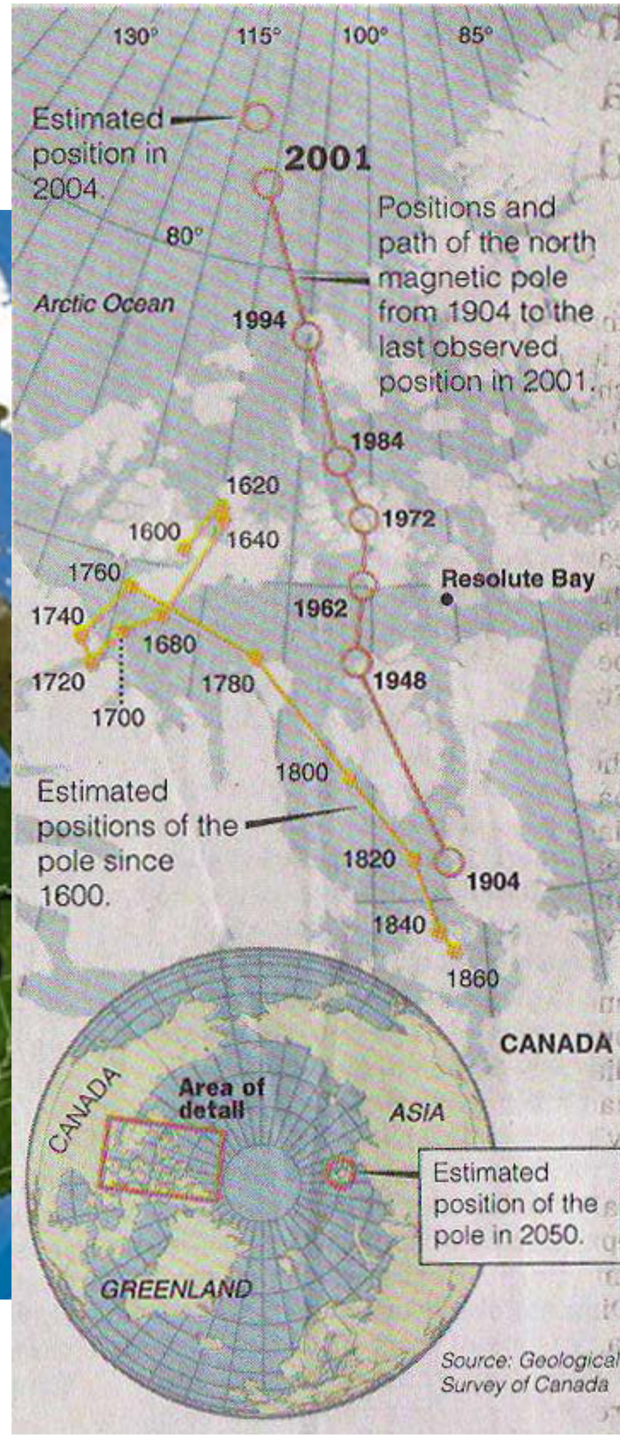
6,816,786 Space weather prediction system and method

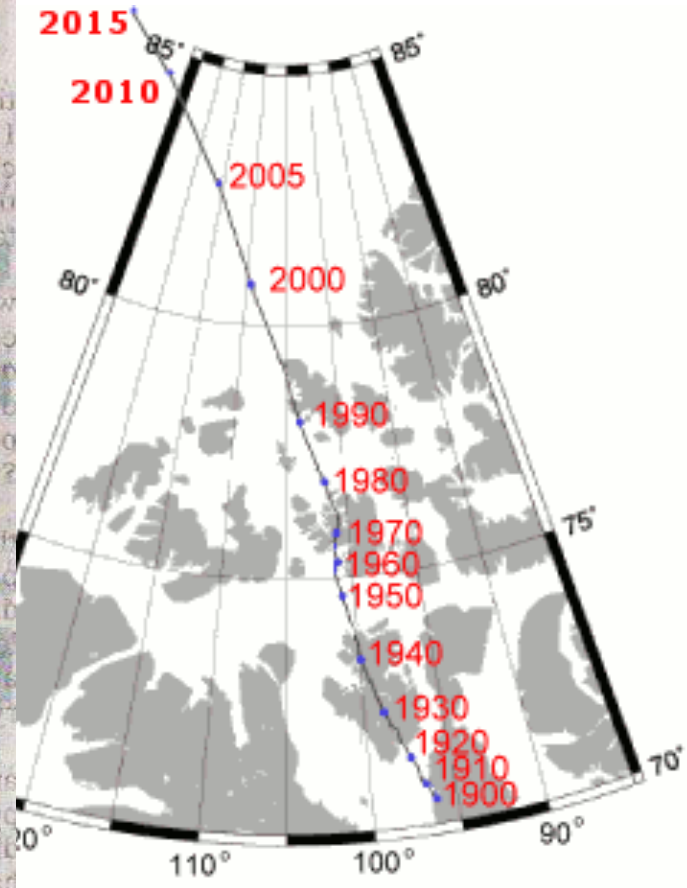


Credit: Cassini

Lecture 10


2011
2000
1600
1700
1900
1800
MAGNETIC NORTH POLE
1600-2011


130°
115°
100°
85°
Estimated position in 2004.
2001
80°
Positions and path of the north magnetic pole from 1904 to the last observed position in 2001.
Arctic Ocean
1994
1984
1972
1620
1600
1640
1760
Resolute Bay
1962
1740
1680
1720
1780
1948
1700
1800
Estimated positions of the pole since 1600.
1820
1904
1840
1860
CANADA
CANADA
Area of detail
ASIA
Estimated position of the pole in 2050.
GREENLAND
Source: Geological Survey of Canada


2015
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110°
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90°

Lecture Overview

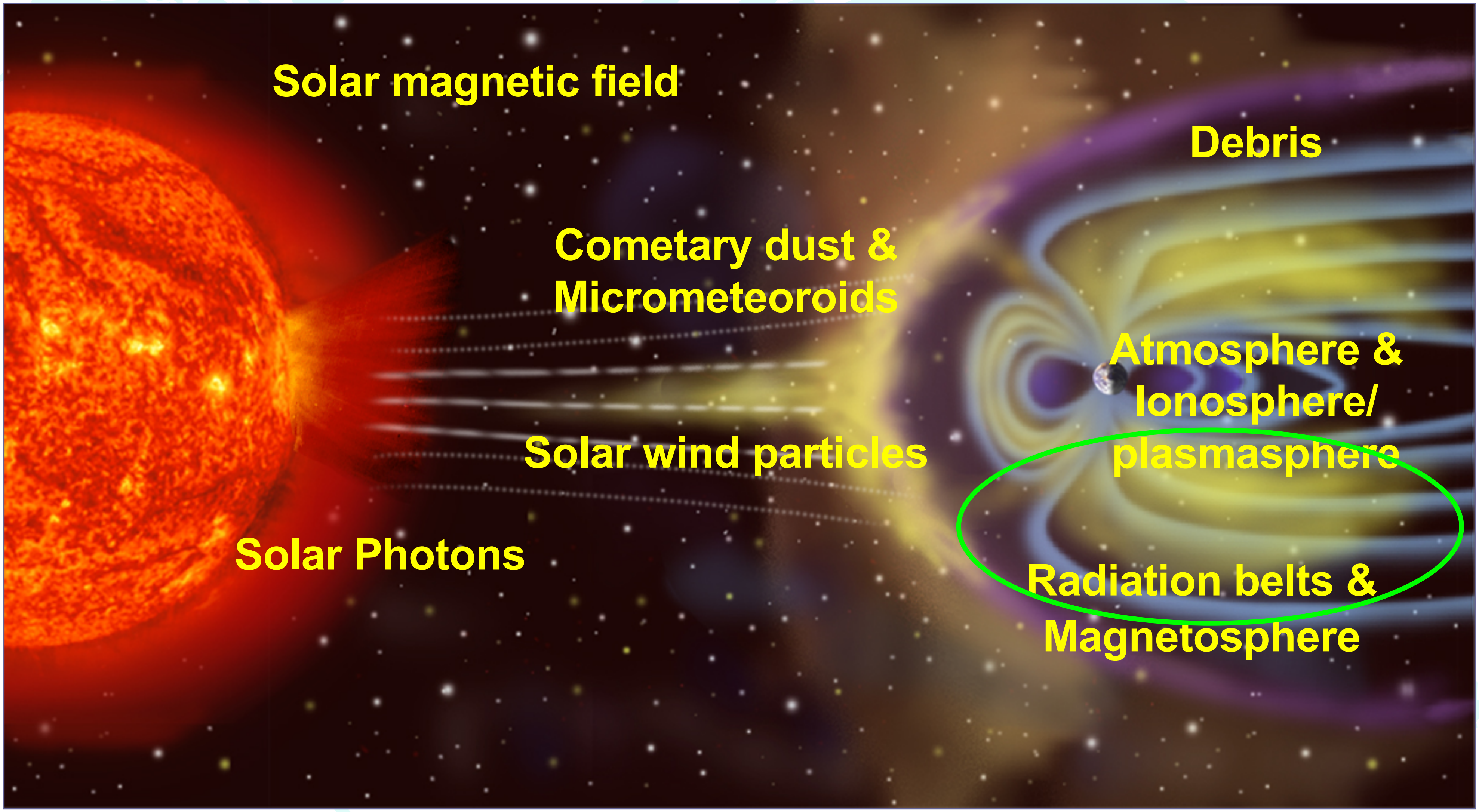
Planetary space environment (Plasmasphere and radiation belts)

- Magnetosphere
  - BL coordinate system, L-shells, magnetic rigidity
- Plasmasphere
  - Ionosphere topside, composition, formation, variability
- Radiation physics
  - Radiation-surface interactions (photons: photoelectric effect, Compton scattering, pair production)
  - Linear attenuation
  - Radiation damage effects
- Radiation environment - the Van Allen Belts
  - Inner, outer, new belts and their sources
- Standards and guidelines

Homework

The planetary space environment

The space environment



Credit: Steele Hill/NASA

Geomagnetic coordinate system

Geomagnetic coordinates

- The BL coordinate system describes trapped plasma in Earth’s magnetic field
- B is the magnetic field strength and L is the magnetic shell parameter; the invariant latitude Ψ is where a magnetic field line touches the Earth
- An L-shell is the surface traced out by the center of a trapped particle as it drifts in longitude while oscillating between mirror points
- Magnetic rigidity is the total energy required to penetrate the magnetosphere at a given L-shell and is given in units of GeV or MeV

Geomagnetic coordinates

Asymmetries in the geomagnetic field cause the particle's physical distance from the Earth to change as it follows an L-shell

At very high altitudes, L-shells are no longer applicable because particles on high latitude open field lines are not trapped

For a pure dipole field, the L-shell is equivalent to the equatorial radius:

$$L = R/Re \qquad (10\text{-}1)$$

This is where the field lines intersect the geomagnetic equatorial plane at a distance R from the center of the Earth

Geomagnetic coordinates

In terms of L-shells, the invariant latitude, Ψ, is

$\Psi = \cos^{-1}\sqrt{1/L}$ and if $\Psi=\Phi$, $L = (1/\cos(\Phi))^2$ **(10-2)**

and the distance, R, from the center of Earth at the equatorial plane is

$$R = L\cos^2 d \qquad \textbf{(10-3)}$$

And magnetic field strength, B, is

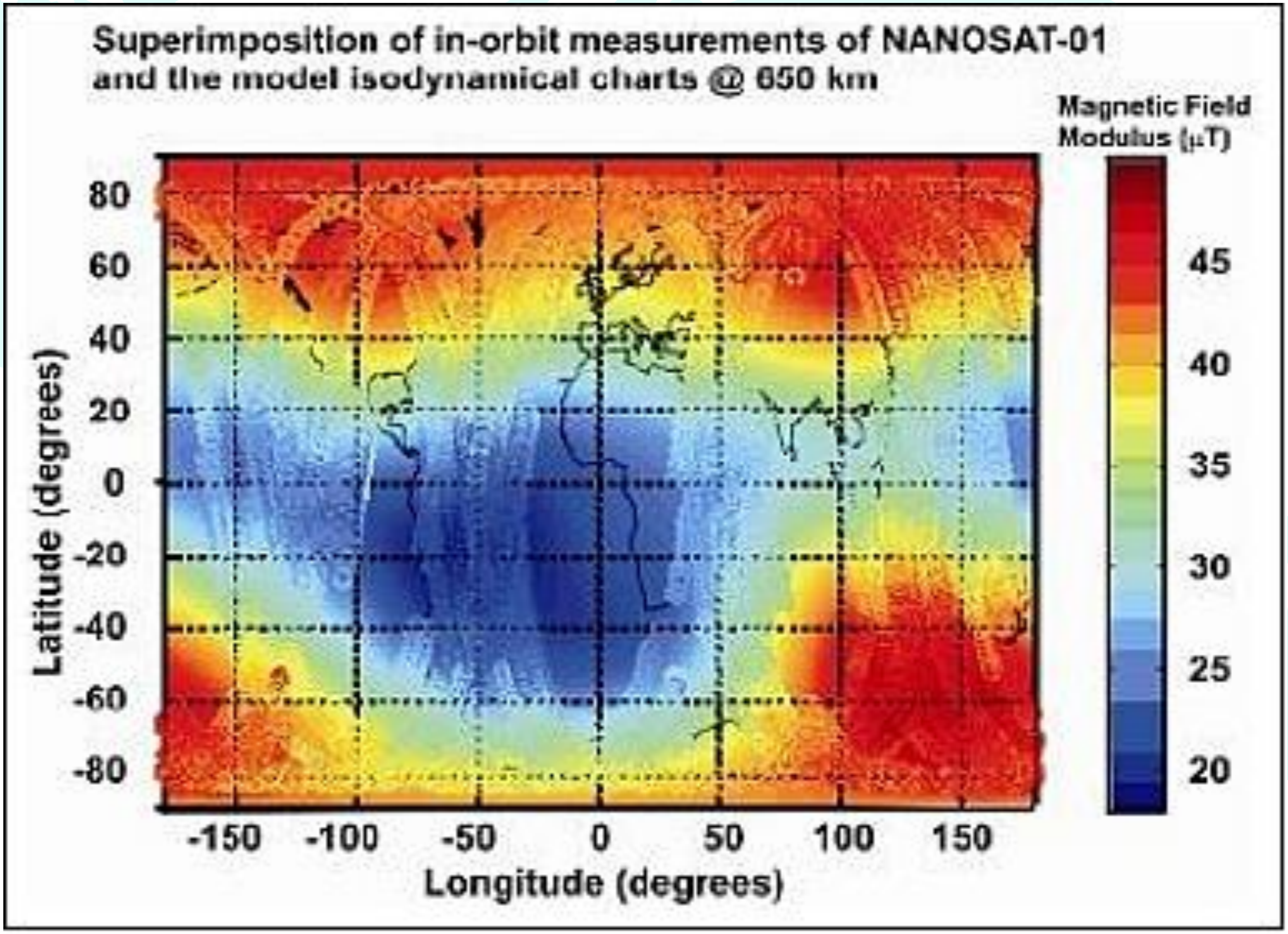
$$B = \frac{M}{R^3}\sqrt{4 - \frac{3R}{L}} \qquad \textbf{(10-4)}$$

where d is the magnetic dip latitude given by

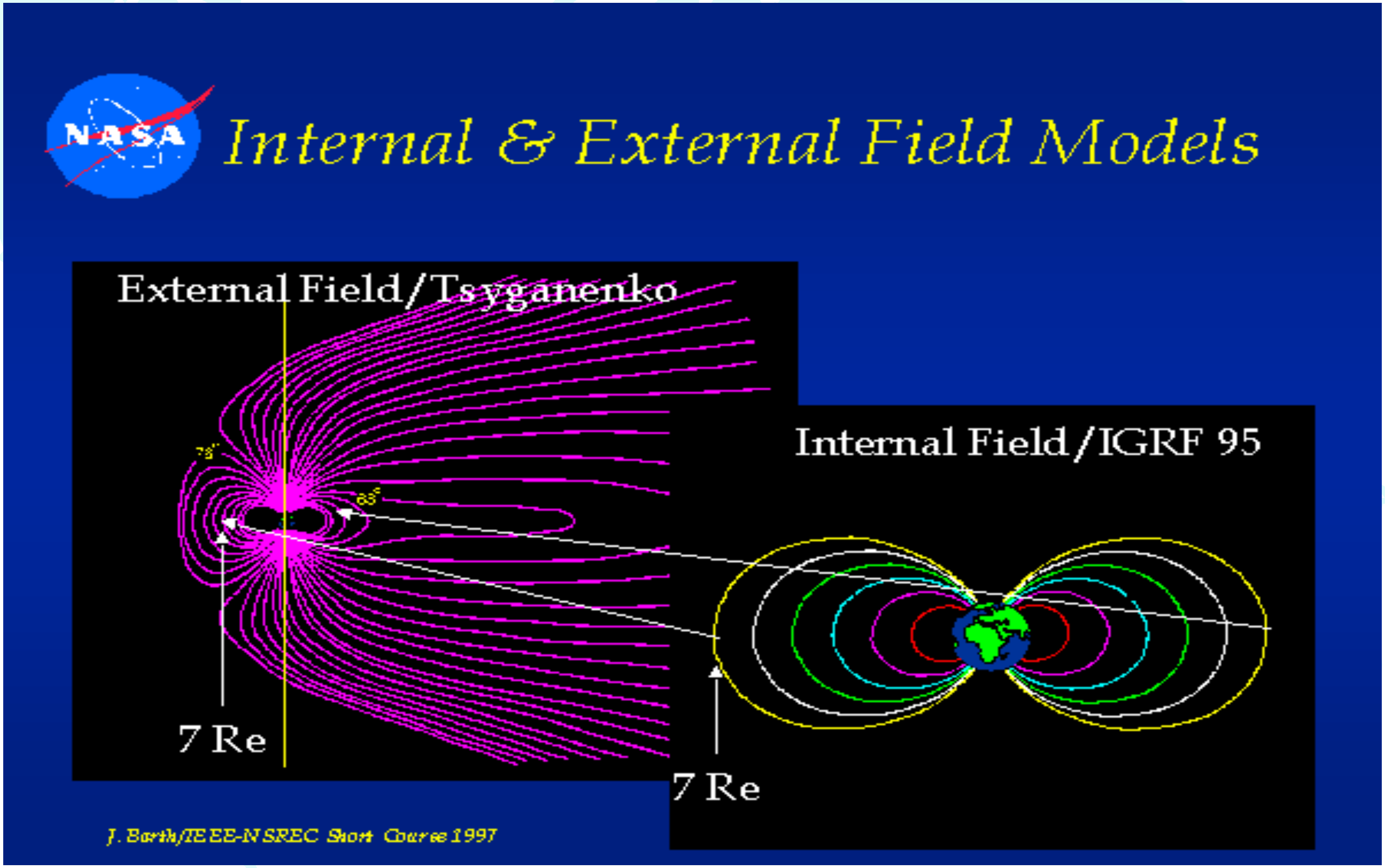
$$d = \arctan(\frac{1}{2}\tan I) \qquad \textbf{(10-5)}$$

for dip latitude, I, and magnetic moment, M

Earth Magnetic Field

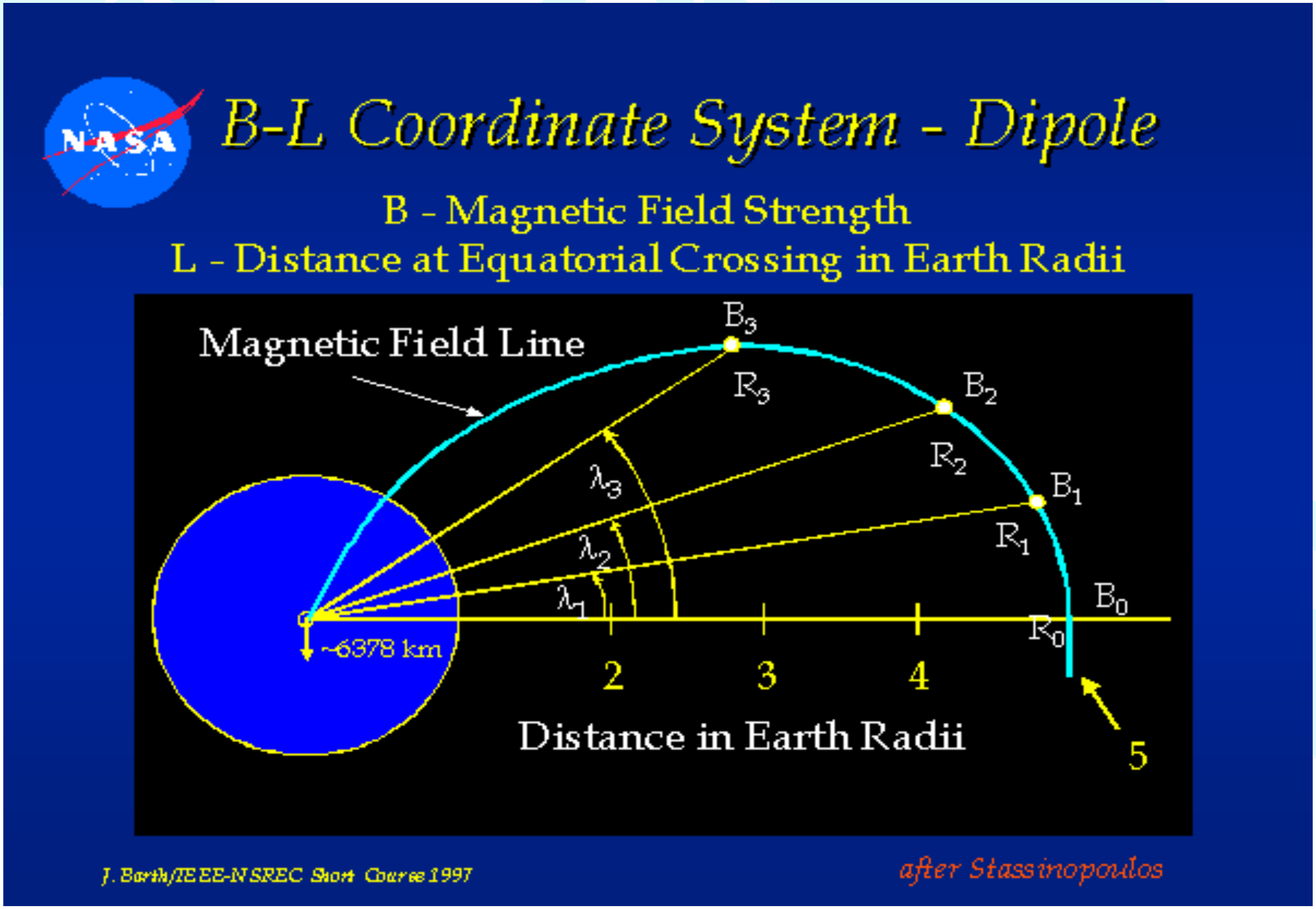


Magnetic field components

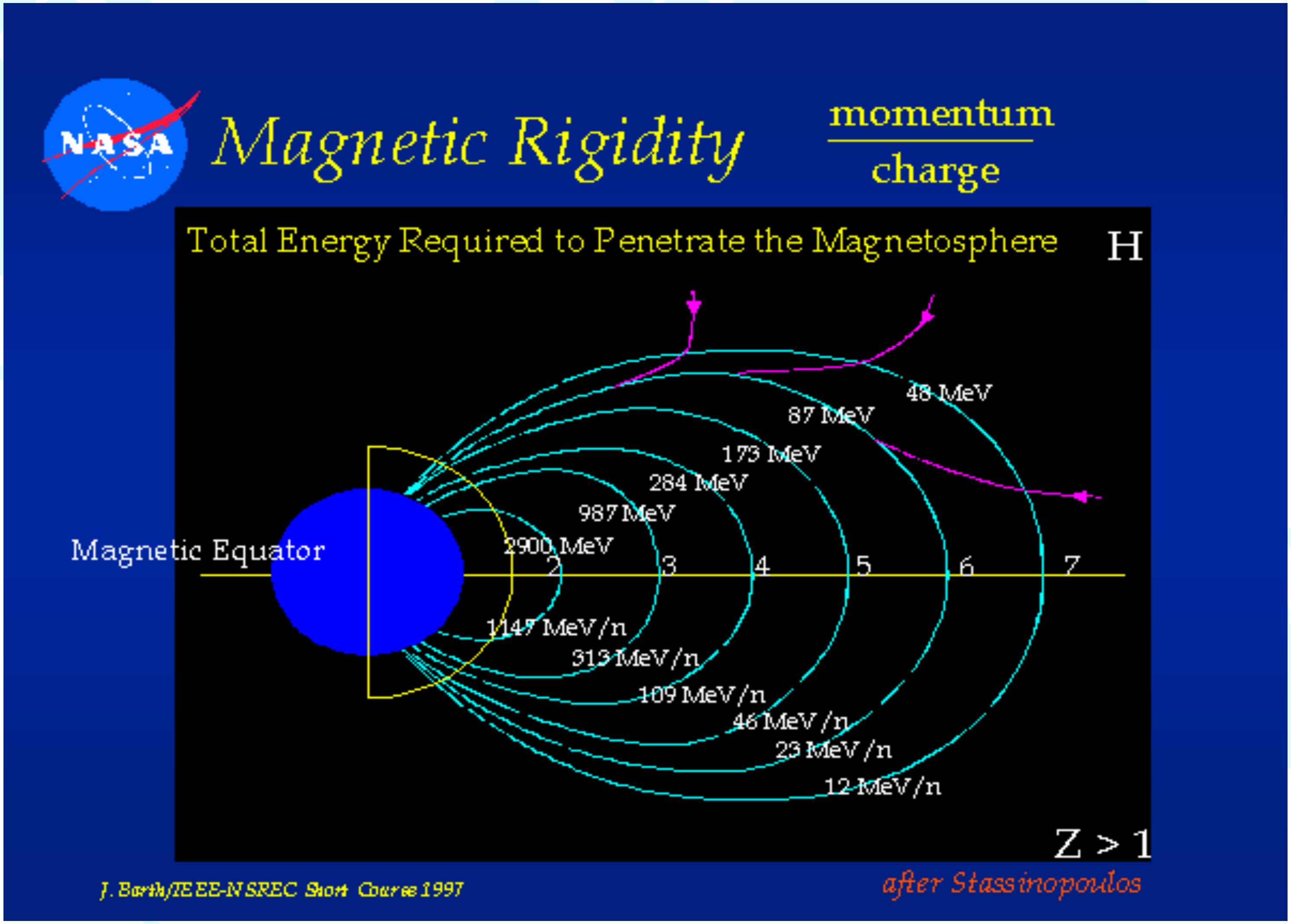


Lecture 10

BL coordinate system



Magnetic Rigidity



Plasmasphere – low energy (~1eV) plasma

Topside ionosphere

We recall the **ionosphere** is created by photoionization of the neutral upper atmosphere by extreme ultraviolet and ultraviolet solar radiation

The ionosphere typically has a peak around 250-300 km altitude (F2). The peak electron density varies on the order of 10^{10} to 10^{12} electrons/m^3

The peak height and the peak electron density depend on solar activity, geographical location, time and season

In the 1950's it was found that the region beyond the ionosphere, now known as the plasmasphere, had unexpectedly high electron densities

Plasma source

The source of this plasma was the charge exchange reaction:

$$O^+ + H \Leftrightarrow O + H^+ \quad (10\text{-}6)$$

which is energetically resonant and proceeds rapidly in both directions

Chemical equilibrium, as controlled by (10-6), is established at altitudes where the oxygen ions (O^+) are the dominant species. Consequently, the lighter hydrogen ions (H^+) experience an outward force due to the ambipolar electric field created between the oxygen dominated ions and the electrons

The H^+ are constrained to move parallel to the Earth's magnetic field lines.

Topside ionosphere

At lower latitudes where the Earth's field lines are closed, the upward flowing H^+ are trapped in the region centered on the magnetic equator

In the polar regions where the field lines are open, the H^+ do not become trapped and flow out into space, producing what is called the 'polar wind'

The trapped plasma forms the plasmasphere, which generally extends out to 20,000 - 40,000 km with plasma densities of the order of 10^9 electrons/m^3

The shape and density of the plasmasphere is constantly changing due to changes in the underlying ionosphere (the source and sink of the plasmasphere) and the effects of magnetic storms

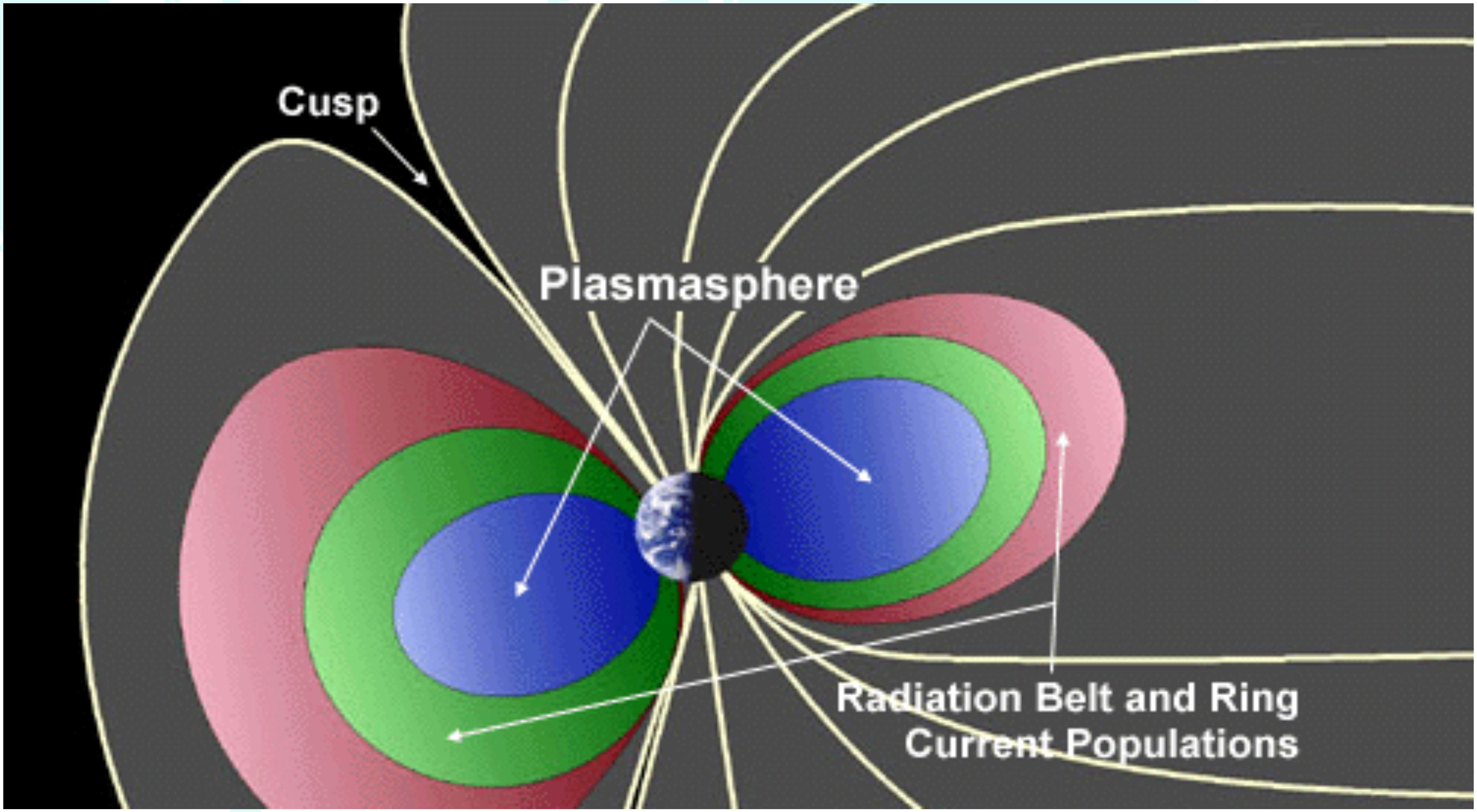
Plasmasphere

Earth's plasmasphere

- is a torus shape containing cold (~1 eV), dense plasma (tens to thousands of particles per cubic centimeter)
- occupies roughly the same region of the inner magnetosphere as the ring current and outer radiation belts (between L = 2 and L = 7)
- populated by the outflow of ionospheric plasma along mid- and low-latitude magnetic field lines (i. e., those that map to magnetic latitudes of ~60 degrees and less)

H+ is the principal plasmaspheric ion, with singly ionized helium accounting for ~20% of the plasma

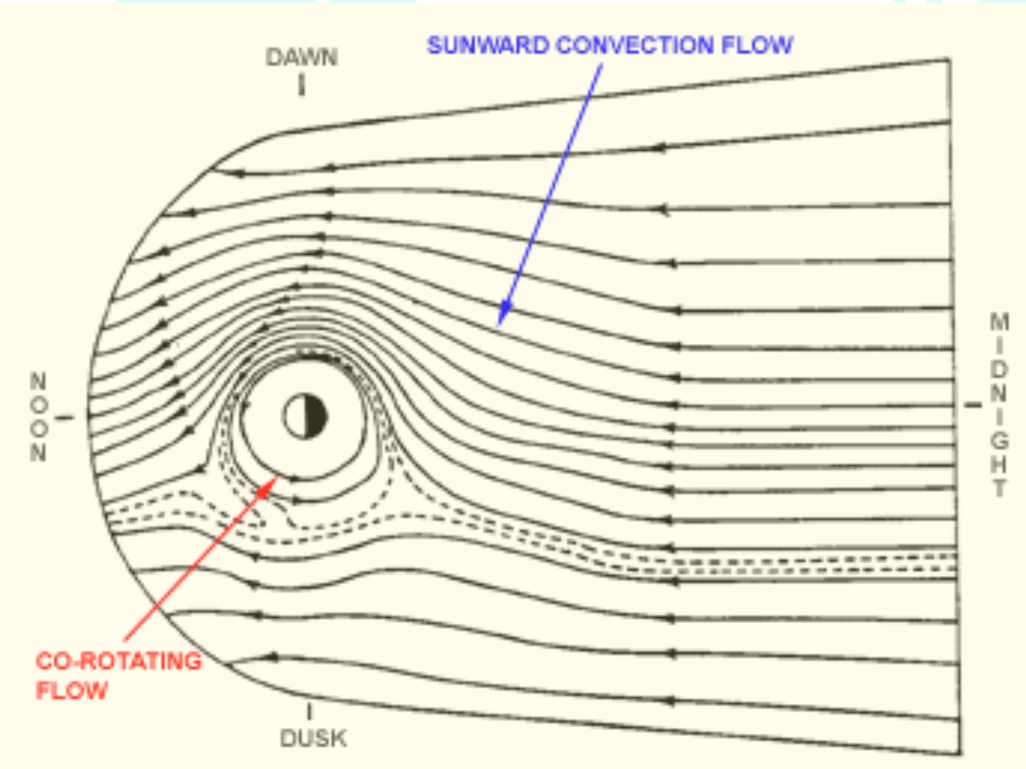
Plasmasphere

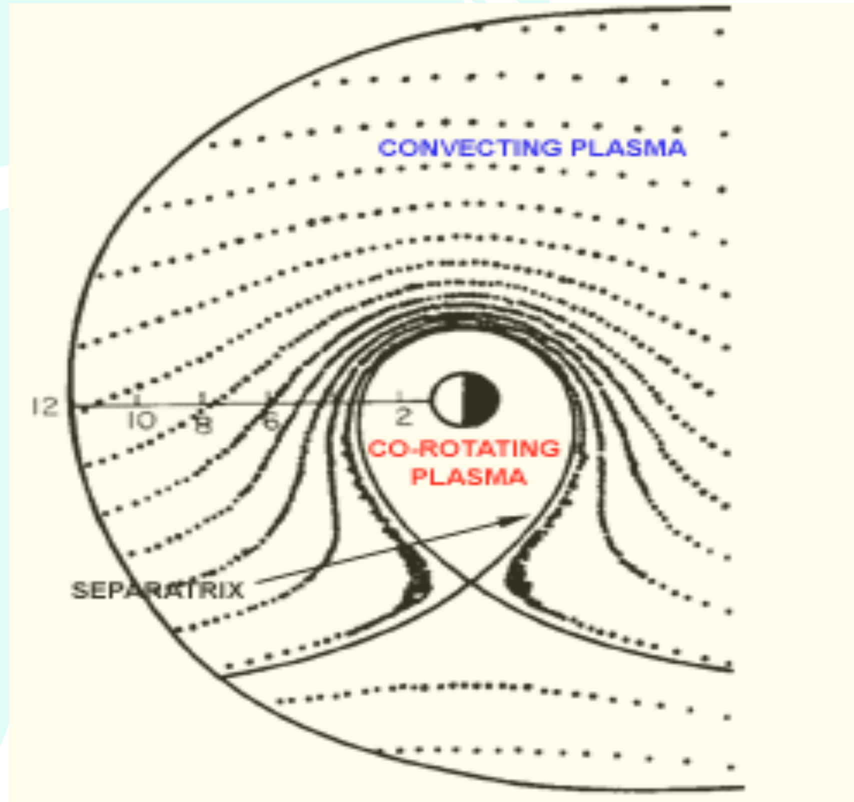


Plasmasphere

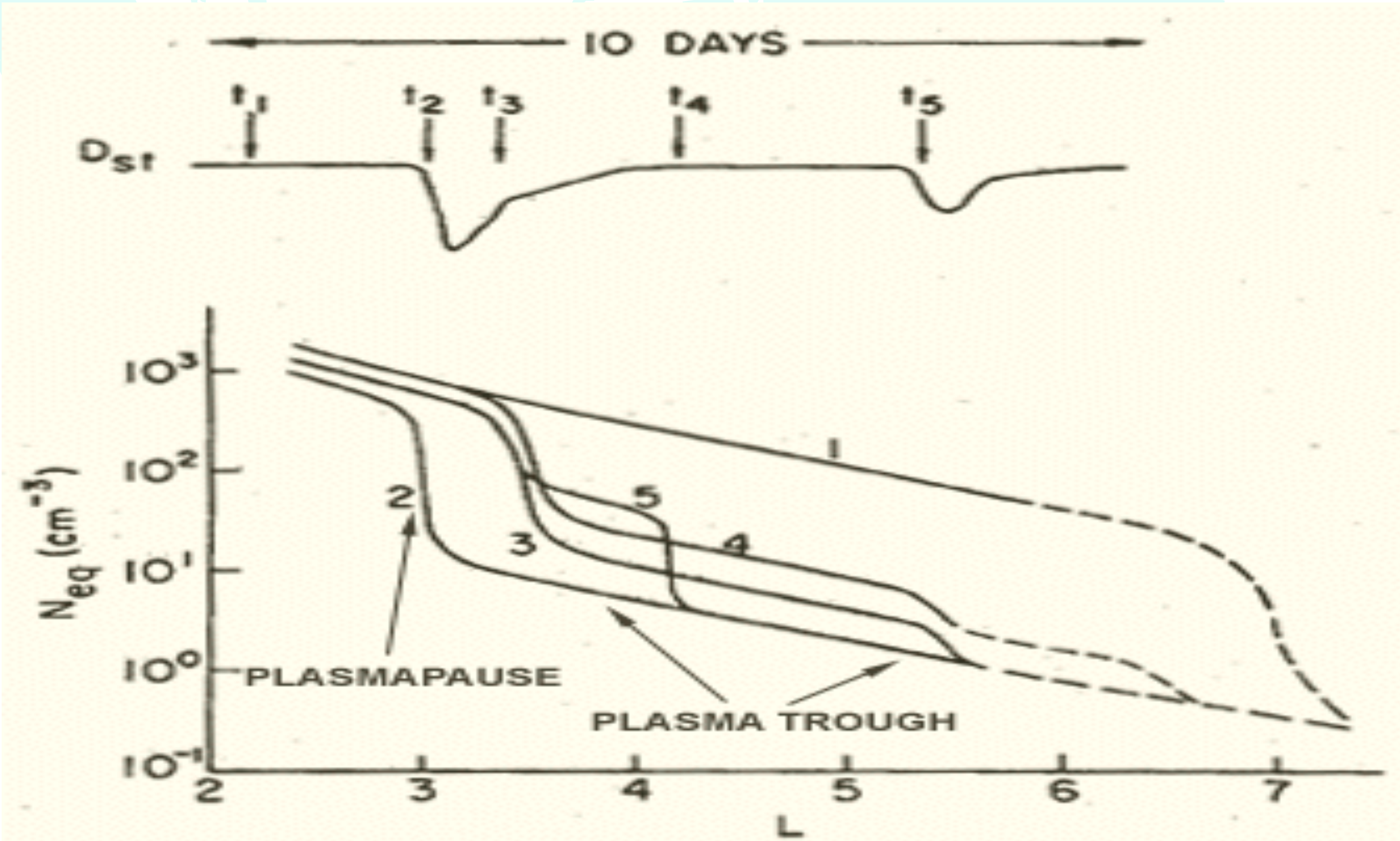
- Unlike the plasma of the central plasma sheet, which in general "convects" (i.e., flows) sunward toward the dayside magnetopause, the cold, dense plasma of the plasmasphere is trapped on magnetic field lines that rotate with the Earth and thus "co-rotates" with them
- It is the competitive interplay between these two flow regimes – one convecting sunward, the other co-rotating – that, together with the outflow of plasma from the ionosphere, determines the size, shape, and dynamics of the plasmasphere, which vary strongly according to the level of magnetospheric activity

Plasmasphere formation

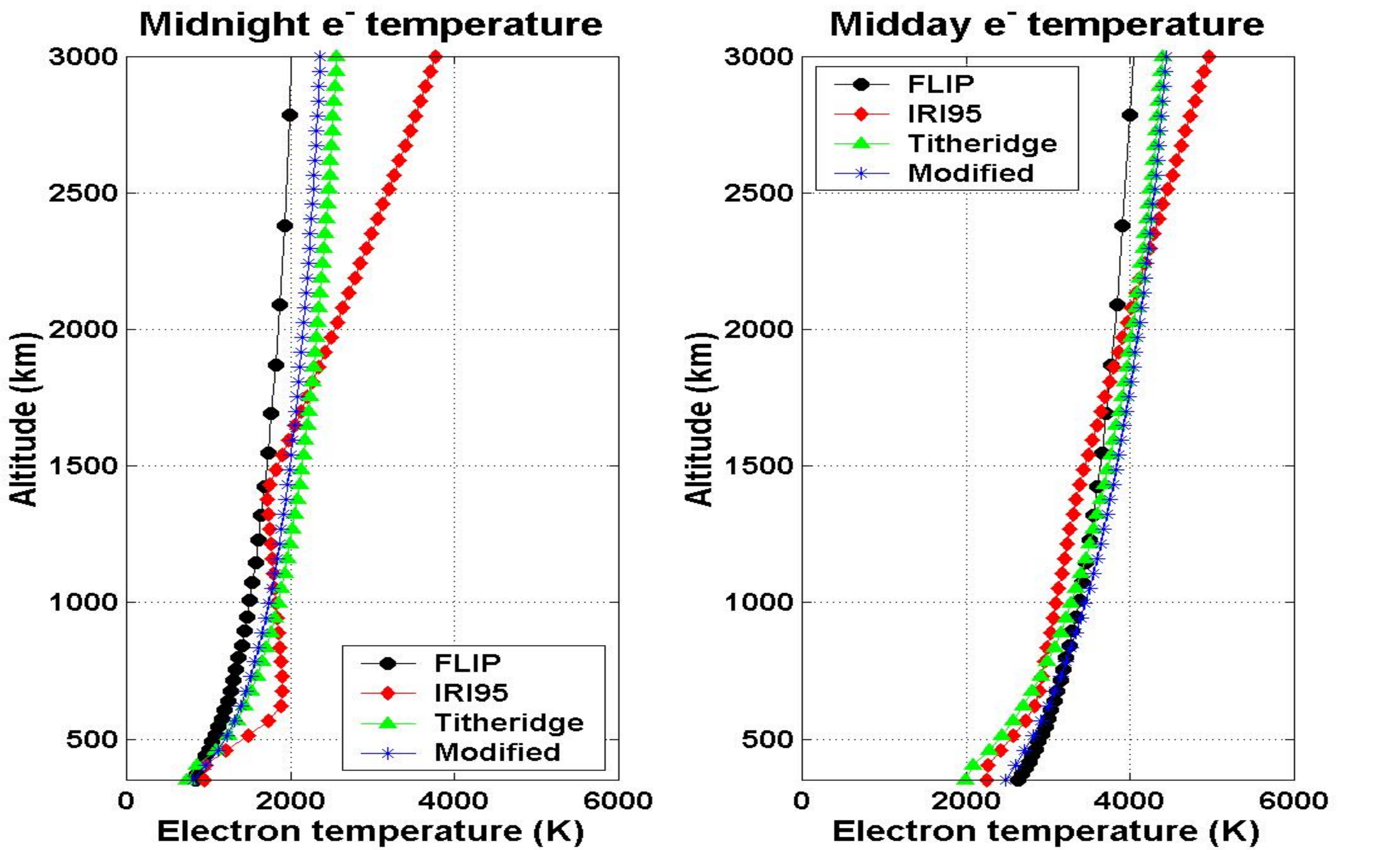




Plasmasphere variability



Plasmasphere temperatures



BREAK

Radiation physics – high energy (MeV) plasma

Radiation-surface interactions

Radiation interactions imply **high energy** (100 keV – 10 GeV) particles and photons as opposed to **low energy** interactions discussed earlier in previous lectures (0.01 eV - 1 keV)

Deep penetration of solid surfaces is only possible with high energy particles and photons

Photons interactions (covered in this lecture)

- Photon absorption
- Radiation damage by photon impact

Credit: Ketsdever

Photon-surface interactions

Photon interactions

Hard X-rays ($0.001 \leq \lambda < 0.1$ nm or 1.24 MeV-12.4 keV)

Gamma-rays ($0.00001 \leq \lambda < 0.001$ nm or 124 MeV-1.24 MeV)

Note: $\text{eV} = 12398.4282 \times \lambda^{-1}$ (λ in Ångstroms)

Photon absorption

1. Photoelectric effect
2. Compton scattering
3. Pair production

Photon absorption

1) Photoelectric effect

Incident photon transfers all of its energy to an atomic electron in the absorbing material

It is the chief energy loss mechanism in surface interactions for X-ray photon energies

Greater atomic number of absorbing material leads to higher photon energy at which effect still persists

The importance of the photoelectric effect *decreases* with increased photon energy

Credit: Ketsdever

Photon absorption

2) Compton scattering

- Incident photon losses part of its energy to an atomic electron and the remaining energy is released in the form of a secondary photon at a longer wavelength (less energy)
- Compton scattering begins to dominate photon-surface interactions when photon energies are in tens of keV when impacting the lighter elements
- Compton scattering *dominates* in heavier elements at 1 MeV energies

Credit: Ketsdever

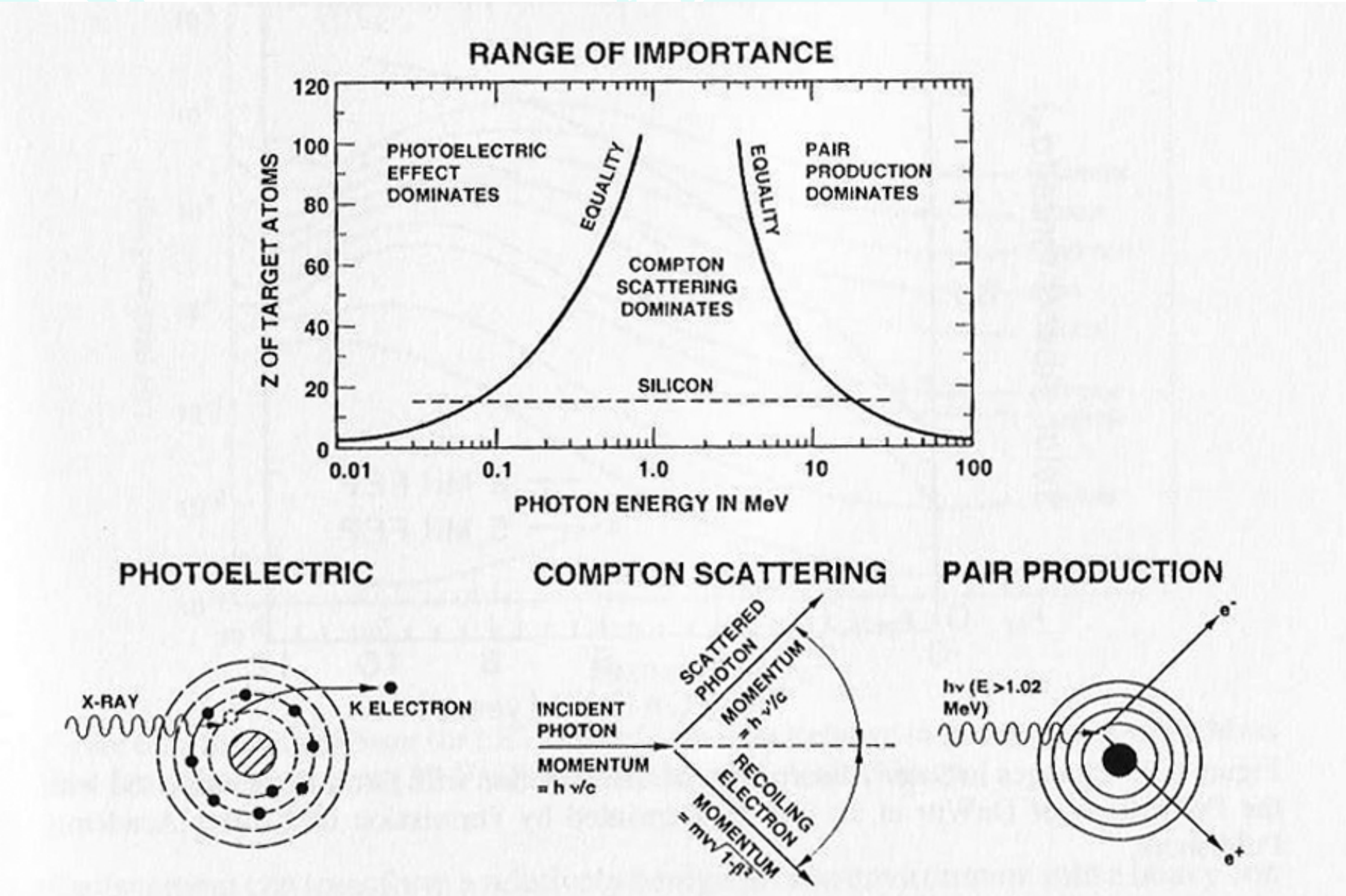
Photon absorption

3) Pair production

- Occurs for photon energies that are high enough (> 1MeV γ-rays) so that incident photon transforms into an electron-positron pair when it passes near an atomic nucleus
- Positron is a positively charged electron (anti-electron)
- Presence of nucleus required for conservation of momentum
- Greater atomic numbers of absorbing material require lower energy for pair production

Credit: Ketsdever

Photon interactions



Photon absorption

Linear attenuation or absorption coefficient

- The intensity, I, of an X-ray or γ-ray beam is equal to the rate at which it transports energy per unit cross-sectional area of the beam
- The fractional energy lost by the beam (-dI/I) in passing through a thickness, dx, of material is

$$-\frac{dI}{I} = n\sigma_{tot}dx \qquad \text{(10-7)}$$

- where n is the absorbing material number density (cm^{-3}) and target cross section is σ_{tot} (cm^2) and

$$I = I_0 \exp(-n\sigma_{tot}x) \qquad \text{(10-8)}$$

Credit: Ketsdever

Photon absorption

Total absorption coefficient

The total absorption cross section of the material atomic nuclei and photon for all 3 processes (photoelectric effect, Compton scattering, pair-production) is written as σ_{tot} (cm^{-2}) where the attenuation coefficient, μ, ($cm^2\ g^{-1}$) is

$$\mu = \frac{n\sigma_{tot}}{\rho} = \frac{N_A \sigma_{tot}}{M_A} \qquad \textbf{(10-9)}$$

and n is the absorbing material number density, ρ is the mass density, N_A is Avogadro's Number, and M_A is the atomic weight

Credit: Ketsdever

Photon absorption

Total absorption coefficient

For a composite material the attenuation coefficient can be written as

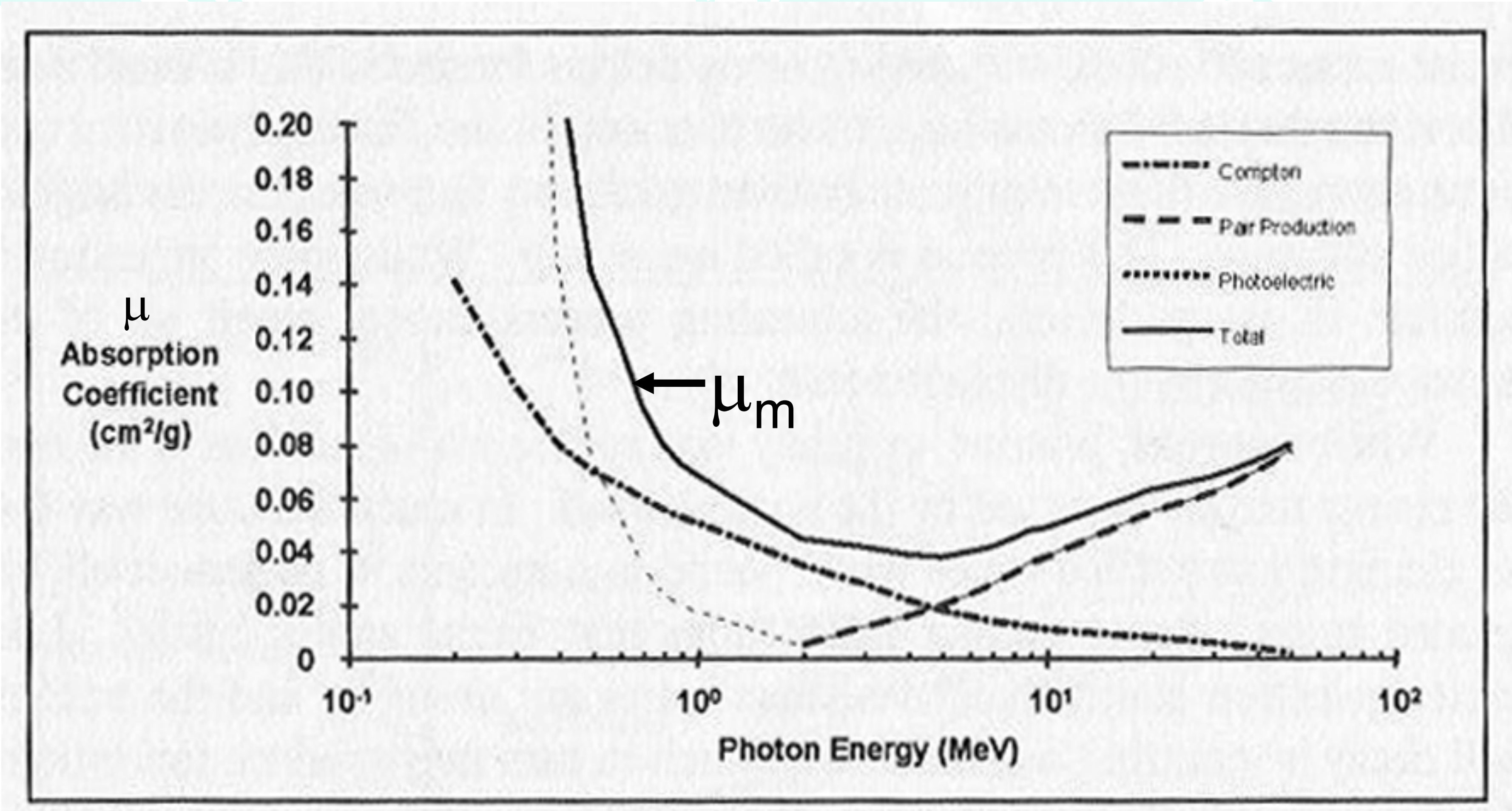
$$\mu_m = \sum_i \frac{n_i \sigma_{tot,i}}{\rho_i} \alpha_i = N_A \sum_i \frac{\sigma_{tot,i}}{M_{A\,i}} \alpha_i \qquad \textbf{(10-10)}$$

where α_i is the relative (fractional) abundance of the ith element

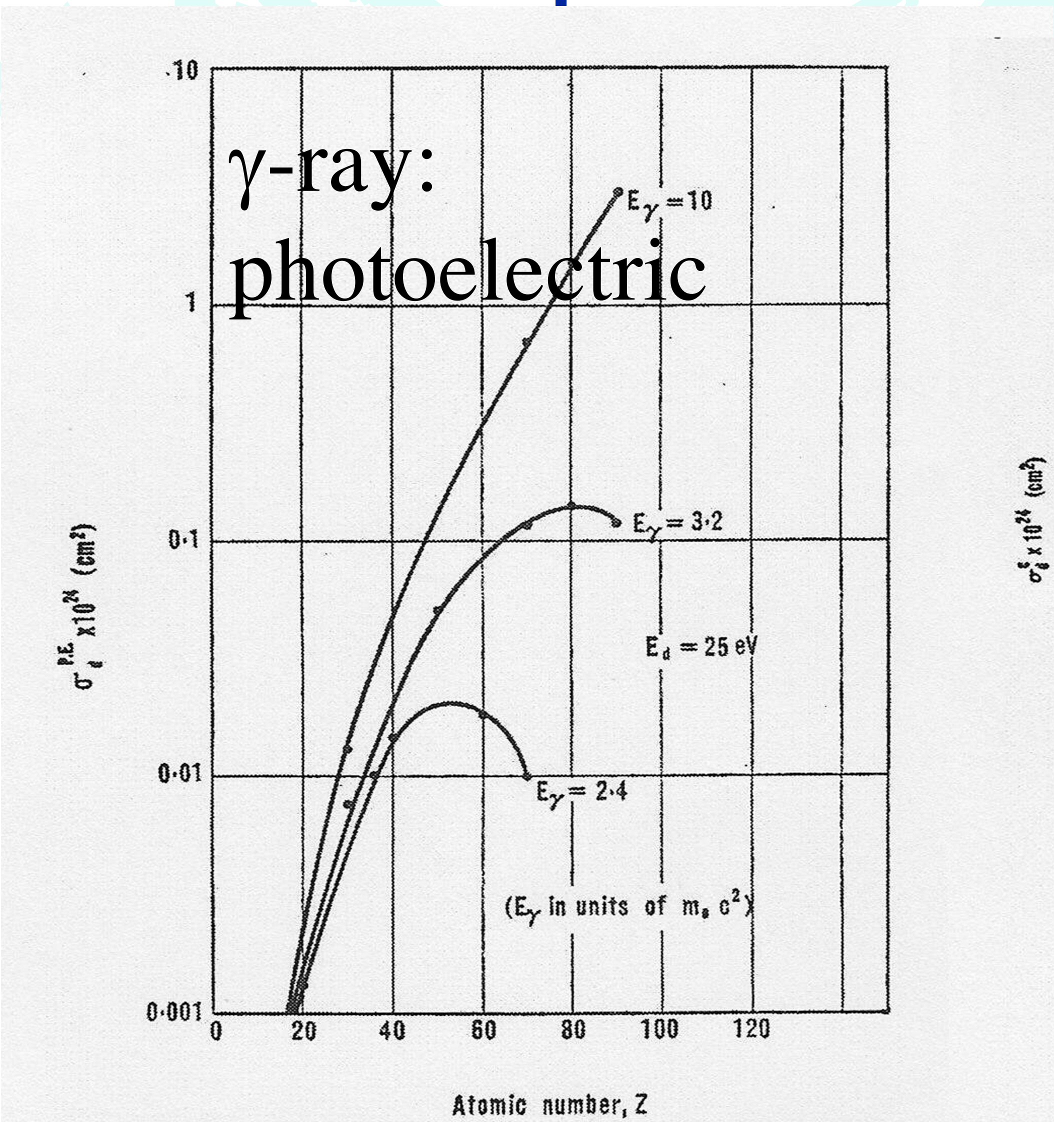
The photon mean free path, or the absorber thickness in g cm^{-2}, of the material is approximately of the inverse of the absorption coefficient, μ^{-1}

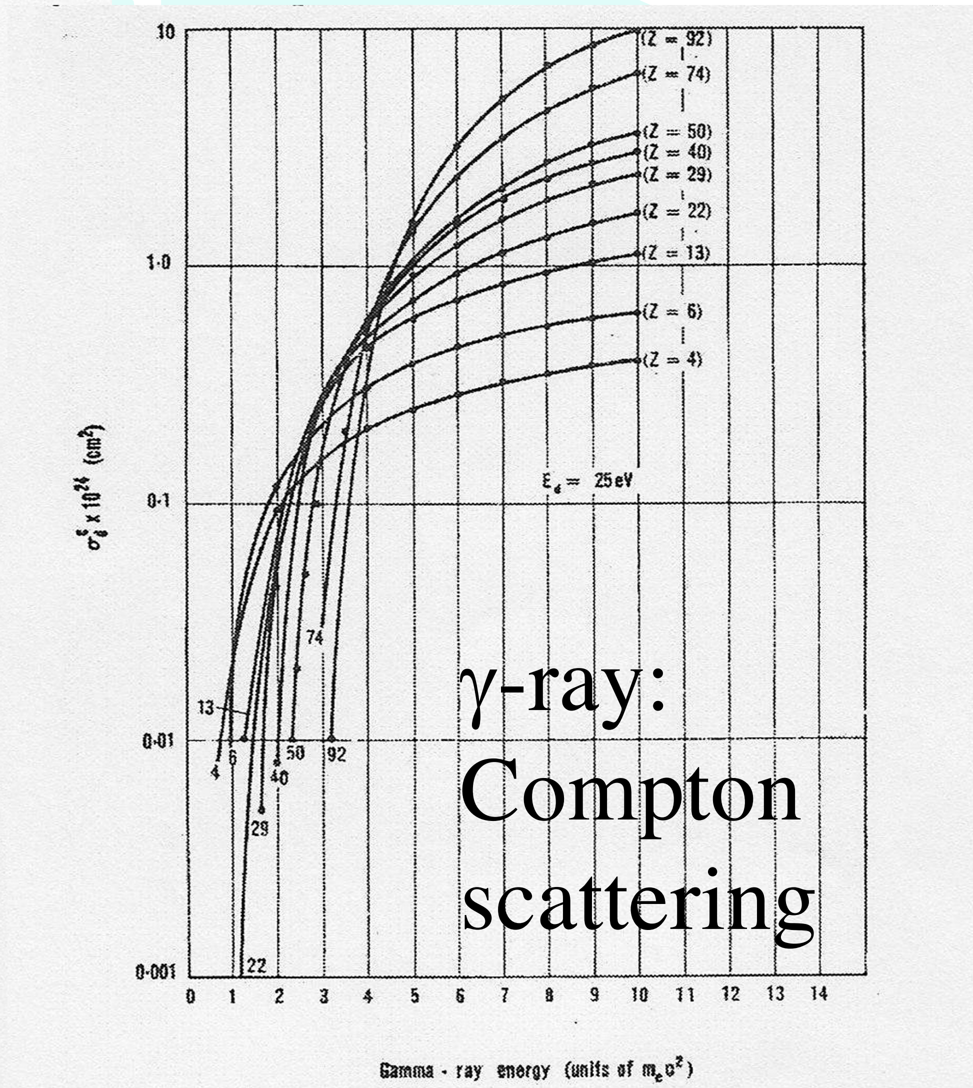
Credit: Ketsdever

Photon absorption



Atomic displacement cross sections





Credit: Ketsdever

Photon radiation damage effects

Photon radiation damage

- **Damage occurs when changes in material persist after removal from radiation source**
  - Usually, this is a result of displacement of atoms in a material lattice
  - Transient radiation effects only occur while material is exposed to radiation source (no permanent change but material performance during exposure may be different)
  - Photon energies > 20 keV can create atomic displacements

Credit: Ketsdever

Photon radiation damage

Atomic displacements

- Incident gamma-rays can produce electrons in a material leading to sufficient energy to create displacements
- >1 MeV electrons can be created by all 3 processes
- Photons alone are usually capable of only dislodging 1-2 heavy material nuclei from their lattice sites and these will have insufficient energy to make further displacements

Credit: Ketsdever

Photon radiation damage

Material hardening

- Point defect sites (displacements) caused by photons usually anneal rapidly except at very low temperatures
- Resistivity in metals exposed to radiation can be affected by concentrations of point defects
- Defects can migrate and combine into clusters which impede motion of dislocations throughout the lattice
- This reduces material flow resulting in hardening and embrittlement

Credit: Ketsdever

Photon radiation damage

Material ionization

- Incident photons strip electrons from atoms in the material and leave positively charged nuclei as well as free electrons
- Break chemical bonds (dissociation)
- For metals, freely mobile electrons make little impact since equilibrium can be maintained
- For inorganic nonmetallic materials, ceramics, composite materials (organics) and semiconductors, the ionizing effect can be very important

Credit: Ketsdever

Photon radiation damage

Nonmetallic inorganic material damage

- Glass and quartz can be damaged by X-ray or γ-ray photons that create color centers (photon-absorbing centers in the material)
- Optical transmission of UV, VIS, IR photons can be affected by discoloration with doses of 10^{10} erg g^{-1} (this was likely cause of GLL UVS failure).
- Thermal annealing can recover optical transmissivity
- Electrical properties affected with decrease in resistivity (reduced insulating ability)
- Thermal conductivity can decrease
- Damages require displacement of at least 1 in 10^7 lattice atoms

Credit: Ketsdever

Photon radiation damage

Organic material damage

- Molecular bonds can be broken (dissociation) and reformed (recombination)
- Atomic nuclei can be displaced
- Annealing not possible with dissociation and recombination
- Long-chain polymers can be broken into smaller and more volatile chains
- Free radicals or trapped gas can be created and molecular weight of material is reduced
- Viscosity and strength can be increased
- Radiation damage to polymers is proportional to total energy absorbed (the dose)

Credit: Ketsdever

Photon radiation damage

Semiconductor material damage

- Electrical properties, thermal conductivity, and carrier mobility are affected by lattice defects and changes in carrier concentration
- Minority carrier lifetime will be reduced by trapping and recombination centers
- In devices with minority carriers (transistors, photoconductors, solar cells) the minority carrier may not be able to drift across the junction leading to device inoperability
- Charge carrier concentration changes affects conductivity and majority carrier type (heavily bombarded germanium becomes p-type)

Credit: Ketsdever

Photon radiation damage

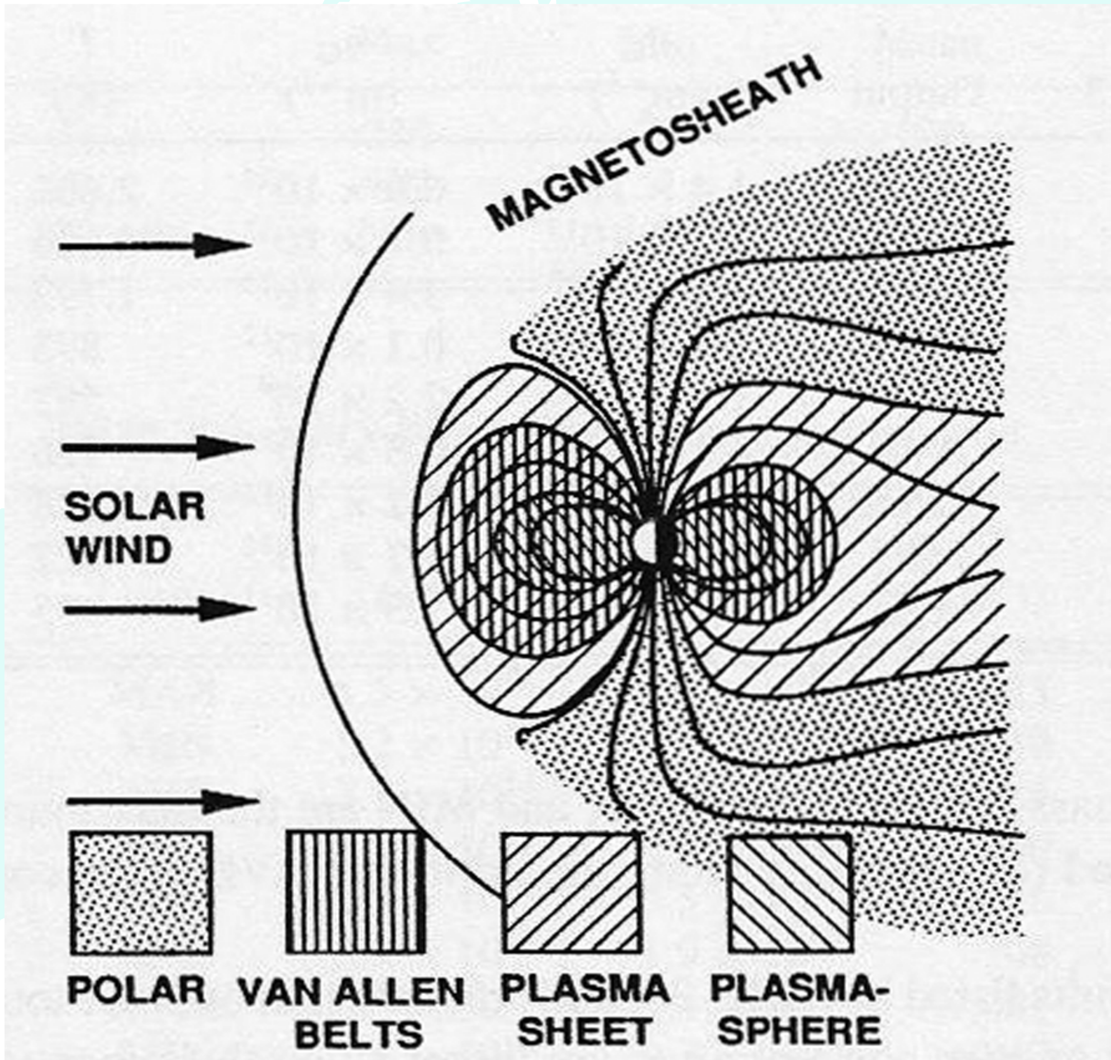
Transient effect damage

- Local ionization does not usually displace many lattice atoms
- However, a burst of charge carriers (free electrons and ions) can be produced
- These decay in a short time but cause a short pulse in device output
- The transient pulse allows the basic circuit current to flow in an unplanned manner causing a change in the state of the circuit
- This is known as a **single event upset** (SEU - transient) or **latch up** (permanent)

Credit: Ketsdever

Radiation environment - the Van Allen Belts

Radiation environment



Radiation environment features

Van Allen radiation belts

- Inner belt - Galactic cosmic rays (GCRs) source
- Outer belt - Magnetotail particle injection source
- New belt(s) - solar wind and anomalous cosmic ray source

Other Sources

- Solar energetic particles (SEPs)
- Nuclear explosions

Credit: Tobiska

Van Allen Radiation Belts

Radiation belt history

- **Inner belt**

  Inner radiation belt discovered by Explorers 1 & 3 (1958)

  Concept of neutrons splashing out of the atmosphere was proposed in 1958 for inner belt formation; confirmed in 1959

  In Jul 1962 the US exploded an H-bomb above Johnston Island which injected high-energy electrons into the stable inner radiation belt; many of them lasted 1-2 years; the intense artificial radiation belt from the H-bomb blast disabled three satellites

Van Allen Radiation Belts

Explorer I

Explorer 1 carried one instrument, a Geiger counter, designed to observe cosmic rays. The experiment worked well at low altitudes but counted no particles at high altitudes.

Explorer 3 tape recorded continuous data and revealed that high altitude zero counts actually represented a very high level of radiation (detector saturation).

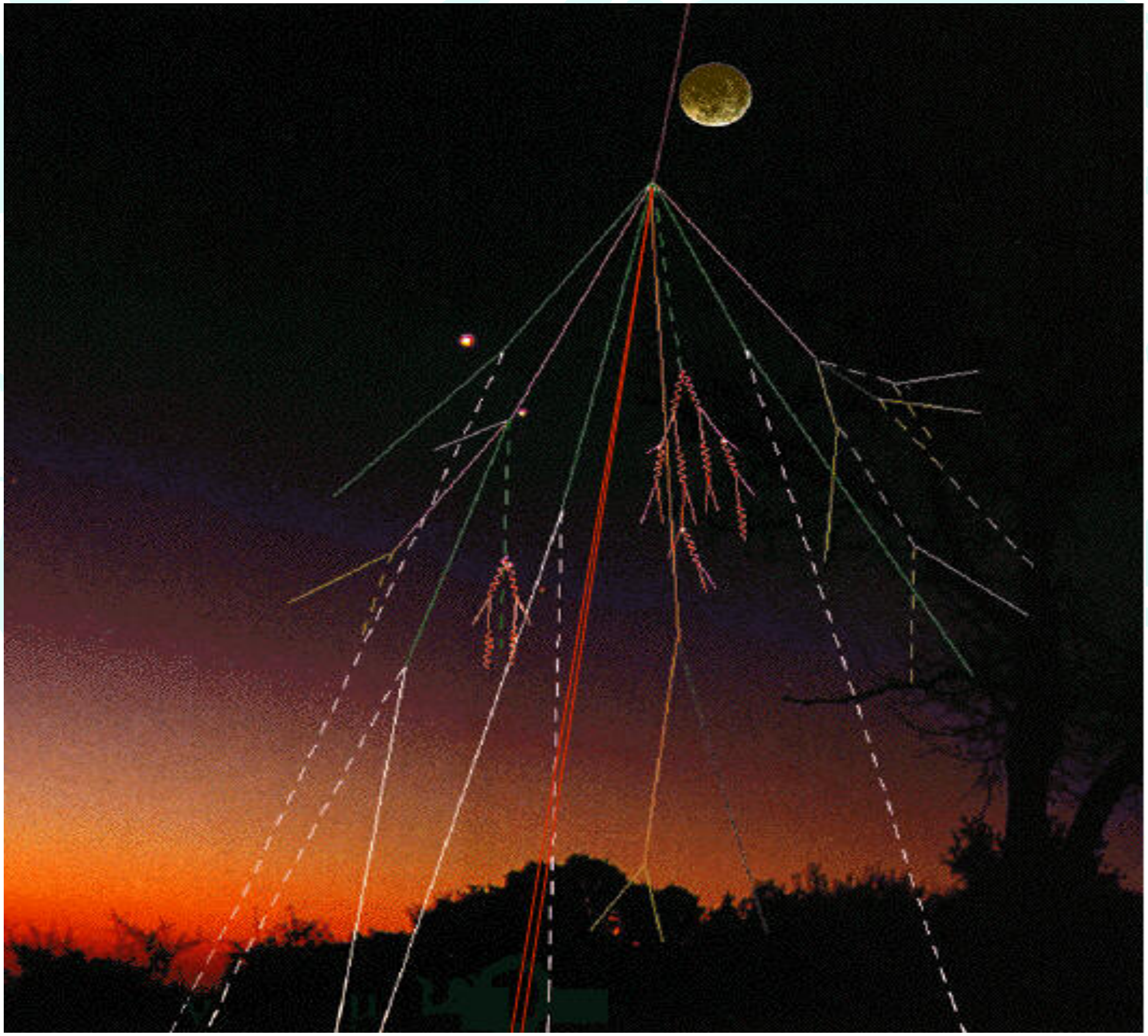
Galactic Cosmic Rays

Galactic cosmic rays (GCRs) (Lecture 3)

- GCRs bombard Earth region from all directions
- Their numbers are small but the energy of each particle is high
- Collisions with atmospheric gases cause fragments to scatter in all directions
- Most GCR collision-produced fragments are absorbed by the atmosphere or by the ground but some of the charged particles end up in the inner radiation belt

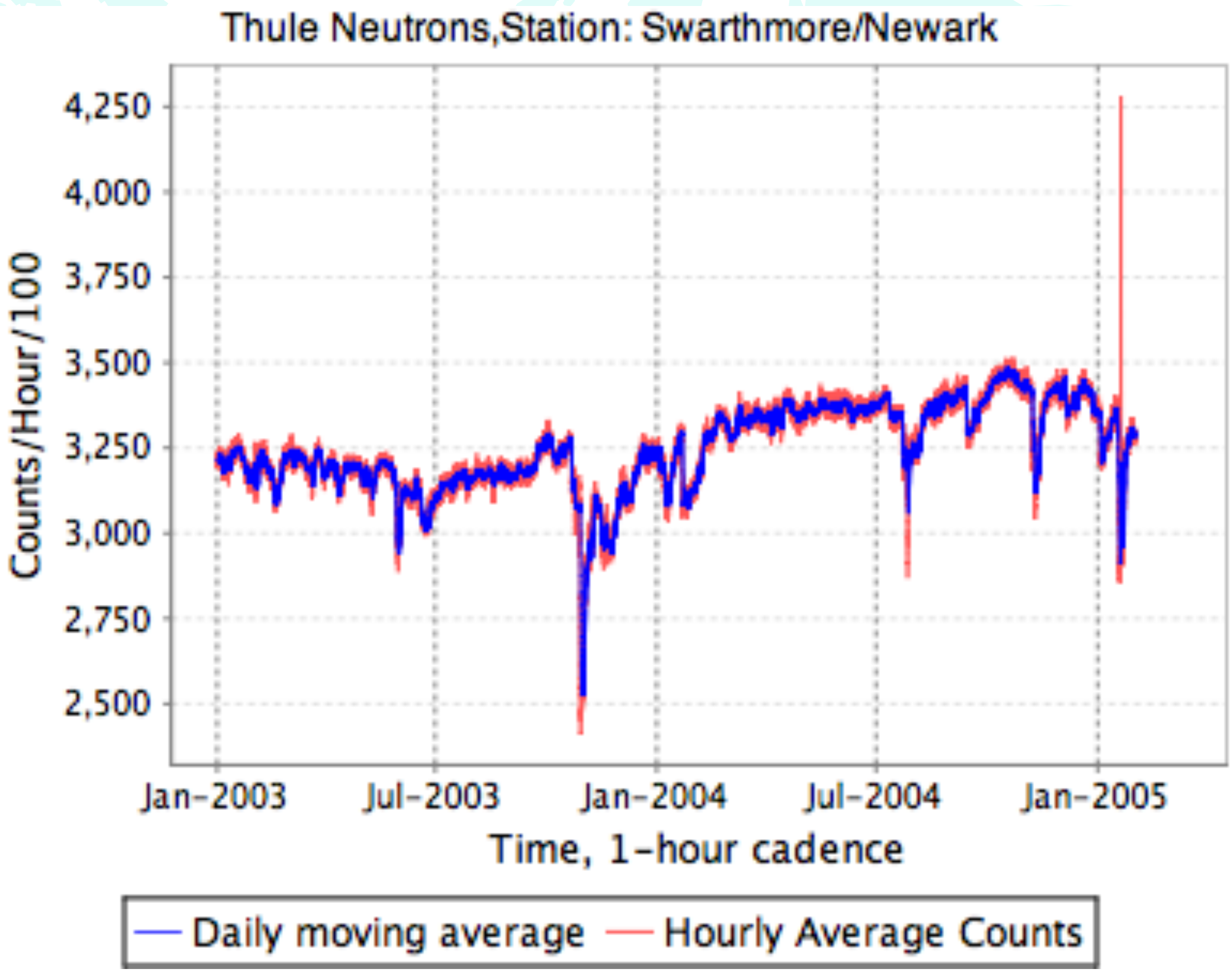
Credit: Tobiska

GCRs at Earth



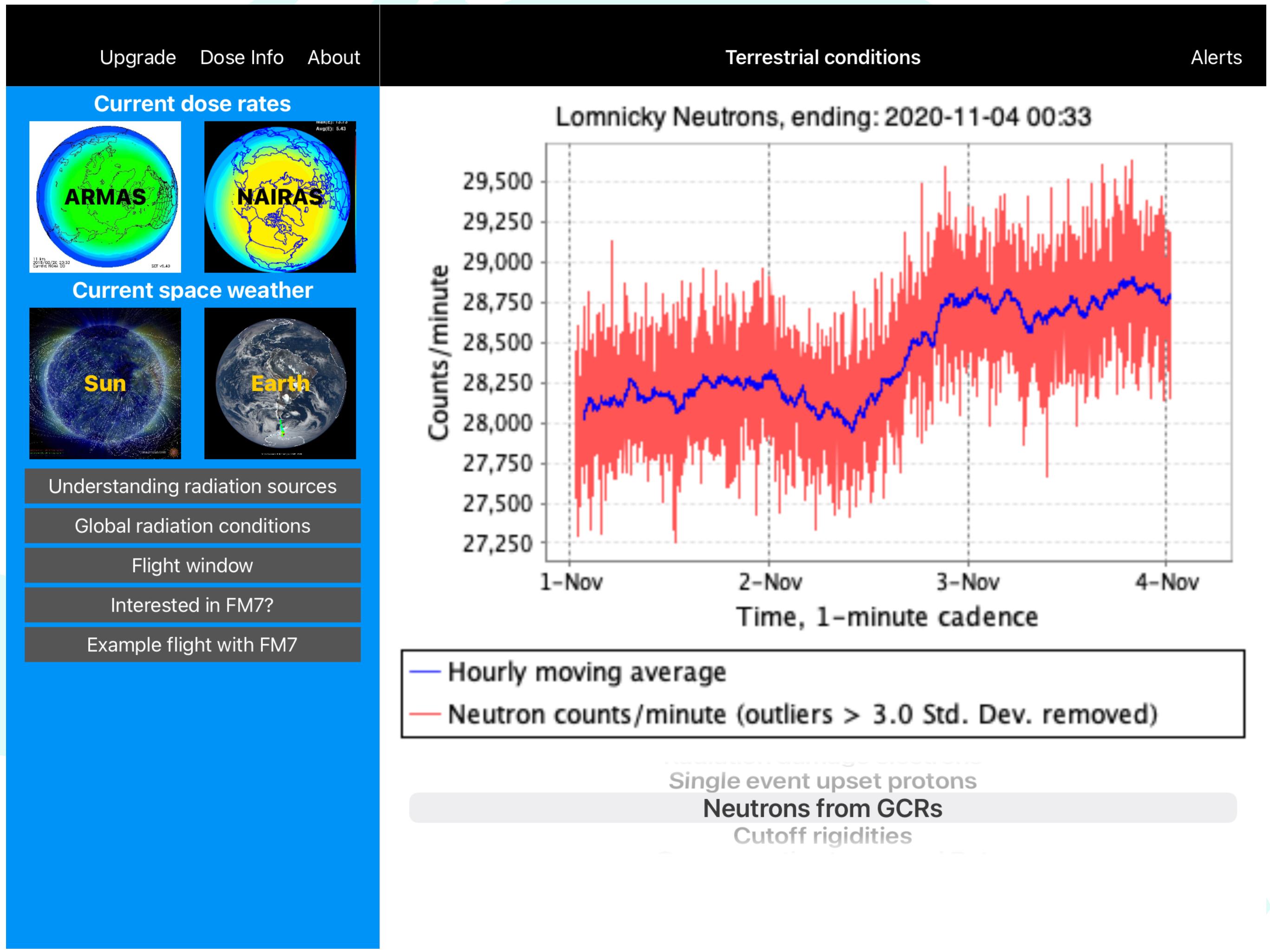
Credit: J. Schombert

Neutron monitors



Lomnicky real-time neutrons

ARMAS app



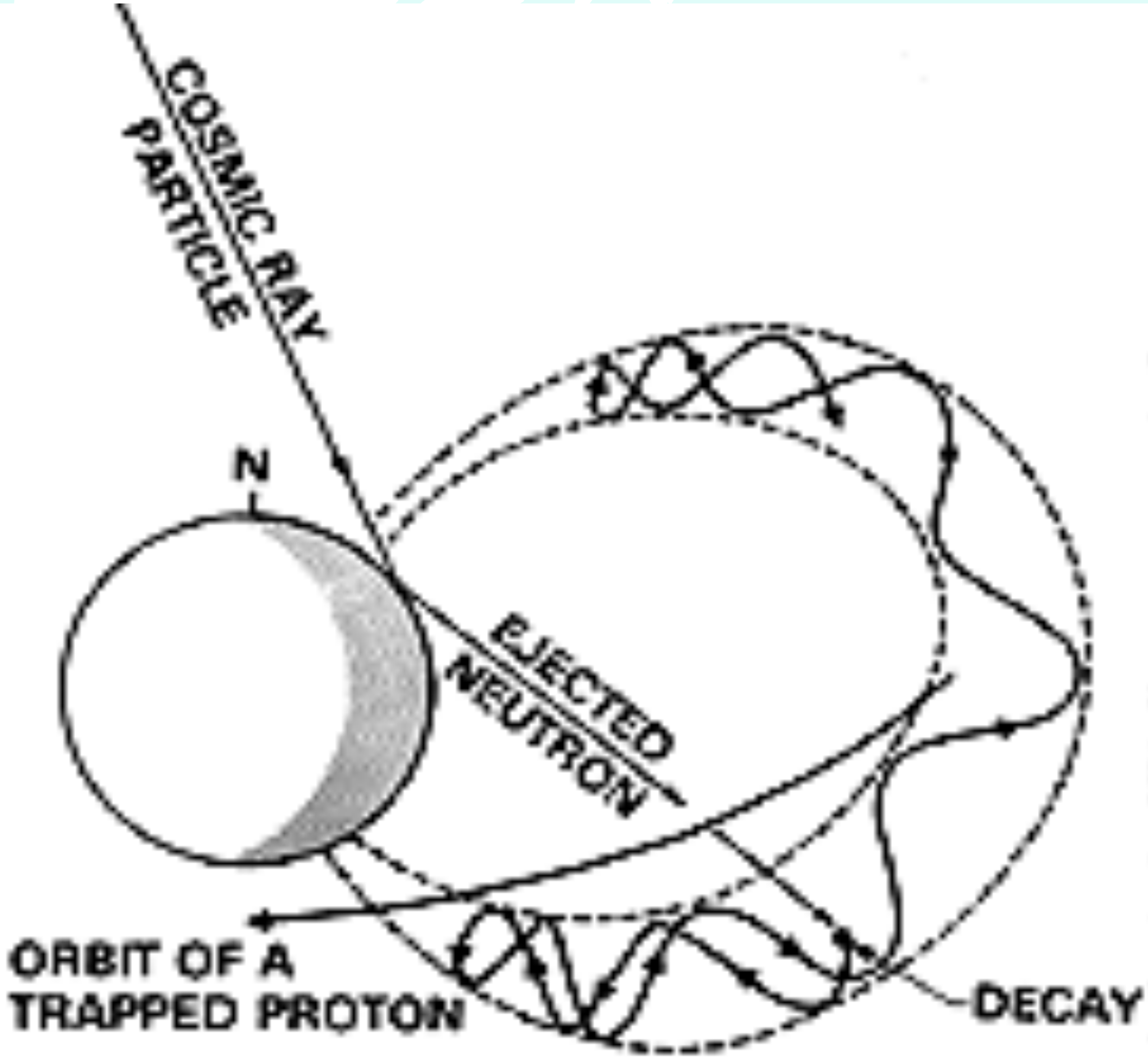
Inner radiation belt

- Inner belt particles in trapped orbits must sooner or later enter the atmosphere again
- Some of the fragments are **neutrons** (no electric charge - half the weight of a typical atomic nucleus)
- Neutrons are not affected by the Earth's magnetic field and can move too fast for gravity to hold them; they usually escape into space
- The free neutron is radioactive (contains unstable energy states) - within about 10 minutes it breaks up into a proton, which captures most of the energy, an electron, and a massless neutrino

Inner radiation belt

- Ten minutes is a fairly long time for a fast particle, time enough for many neutrons to get halfway to Mars' orbit (0.25 AU ~ 37,500,000 km (1000 times further than GEO) or <1 second to GEO)
- However, decay times are spread out statistically, and while 10 minutes is the average, a few neutrons decay quite soon, while still inside the Earth's magnetic field, i.e., decay times of <0.6 seconds (<GEO)
- The energetic protons are grabbed by the Earth's magnetic field and are often on trapped orbits which do not return to the atmosphere

Inner radiation belt



Credit: D.P. Stern

Inner radiation belt

- The inner radiation belt extends from 650-6300 km; strongest between 2,000 and 5,000 km (inside L=2)
- Forms a ring mostly concentrated in equatorial plane
- Consists mostly of very stable protons on the order of 10-50 MeV with particle lifetimes of up to 10 years
- Also contains electrons, low-energy protons, and oxygen atoms with energies of 1-100 keV
- When these electrons strike the atmosphere they cause polar aurora
- The inner radiation belt comes nearest to Earth's surface (250 km) at the South Atlantic Anomaly

Outer radiation belt

Radiation belt history

- **Outer belt**

  Outer radiation belt was discovered by Pioneer 3 (Mar 1958)

  It consists of a wide belt of trapped particles (electrons and ions) beyond the inner belt

  Solar wind proposed by Parker (1958) and solar wind-magnetosphere link proposed in 1961

  In Oct-Nov 1959 the USSR exploded three atomic bombs in the outer belt region; their electrons persisted for a number of weeks; nuclear explosions in space were banned in 1967 by international treaty

Outer radiation belt

- Outer belt ions and electrons come from the magnetotail (stretched magnetic field lines on the night side of the magnetosphere)
- Magnetic storms drive tail plasma Earthward into the near-Earth magnetosphere
- Electric fields help tail particles break into trapped orbits and to drive them to higher energies
- When the magnetic storm ends and the electric field dies away, the particles find themselves locked in trapped orbits of the ring current and the outer radiation belt

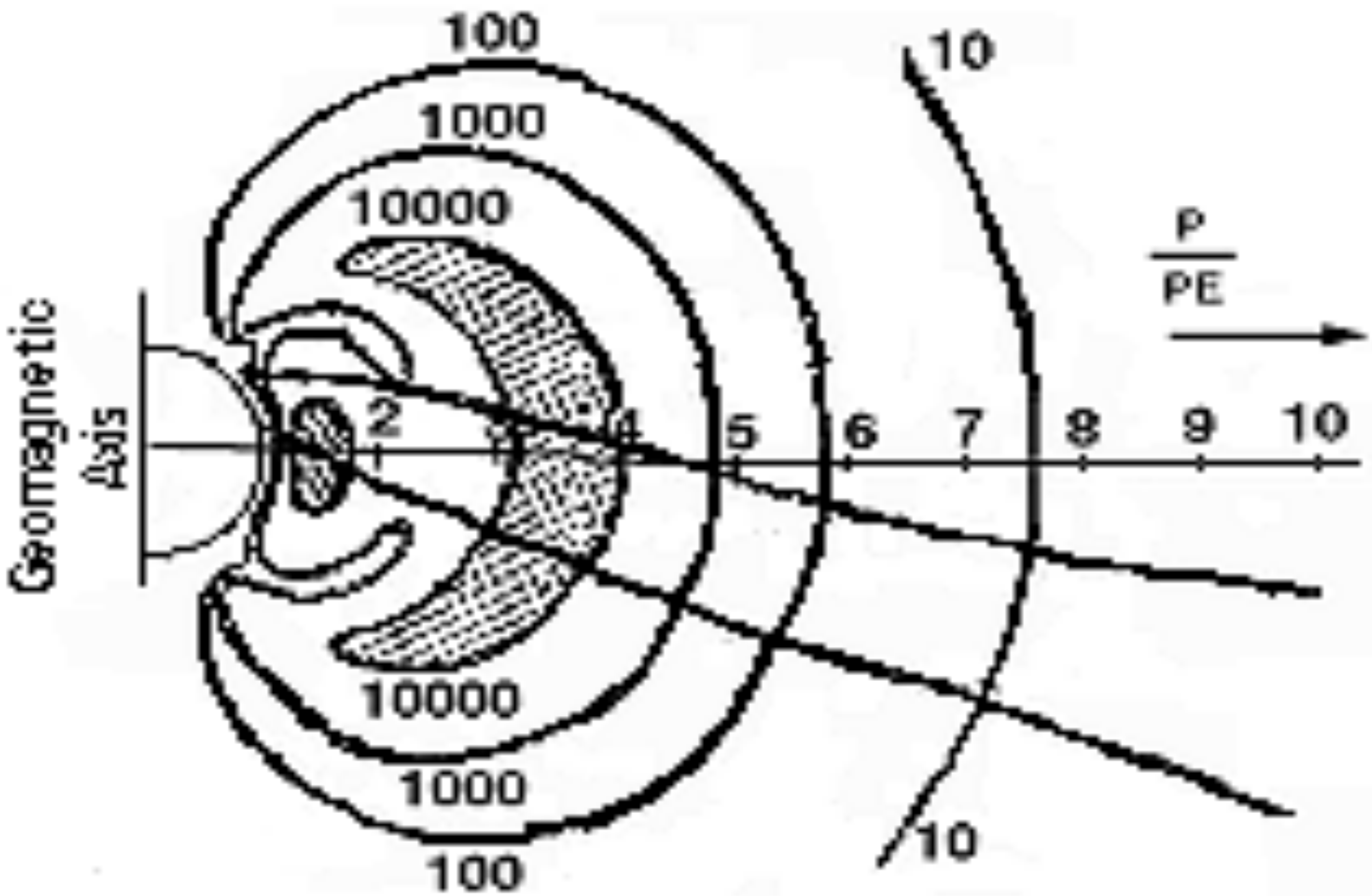
Outer radiation belt

- Sooner or later the particles are lost by collision with the atmospheric constituents (polar thermosphere)
- Magnetospheric substorms occur frequently and inject new particles into the ring current and the outer belt causing them to constantly change
- The outer belt is larger and more diffuse than the inner, surrounded by a low-intensity region known as the ring current
- The electric fields which inject the new particles can also draw oxygen ions upwards from the ionosphere; the ring current contains such ions, typically a few percent of the total, more during magnetic storms

Outer radiation belt

- Outer radiation belt extends from 10,000-65,000 km; greatest intensity is between 14,500-19,000 km (L=3-4)
- The electrons have energies > 40 keV along the outer edge and can drop to normal interplanetary levels within about 100 km (a decrease by a factor of 1000) as a result of the solar wind
- Unlike the inner belt, the outer belt's particle population fluctuates widely and is generally weaker in intensity (less than 1 MeV), rising when magnetic storms inject fresh particles from the magnetotail and then falling off again

Outer radiation belt



New radiation belts

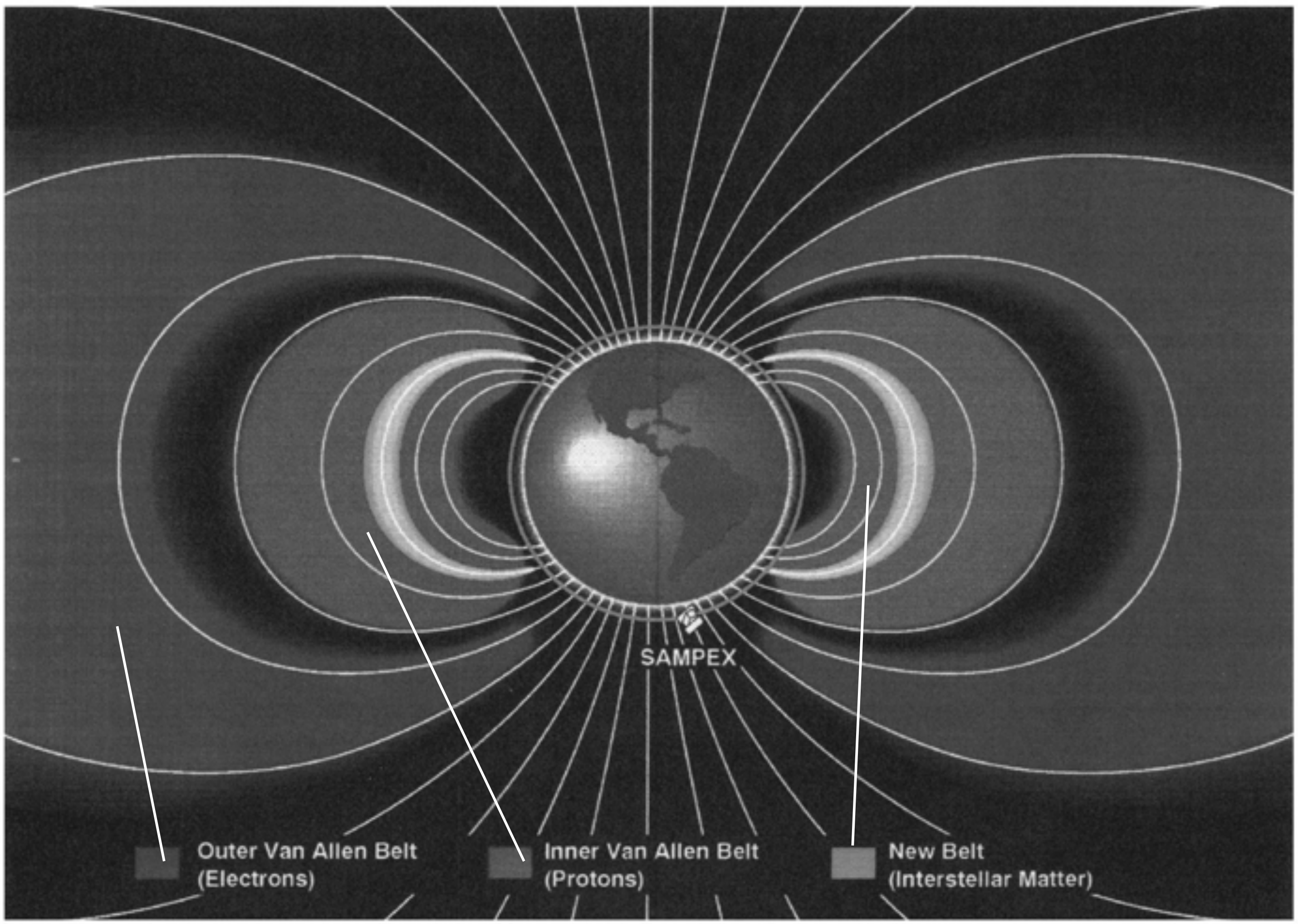
Radiation belt history

- **New belt #1 discovery**
  - On Mar 24, 1991 a strong a solar CME created a large interplanetary shock
  - The shock wave shock hit the Earth's magnetosphere and greatly compressed it
  - Trapped electrons and ions rode this shock and within a minute or so created a new radiation belt just **outside** the inner belt containing both electrons and protons of high energy (15-20 MeV)
  - It disabled the MARECS-I satellite and degraded GOES-7

New radiation belts

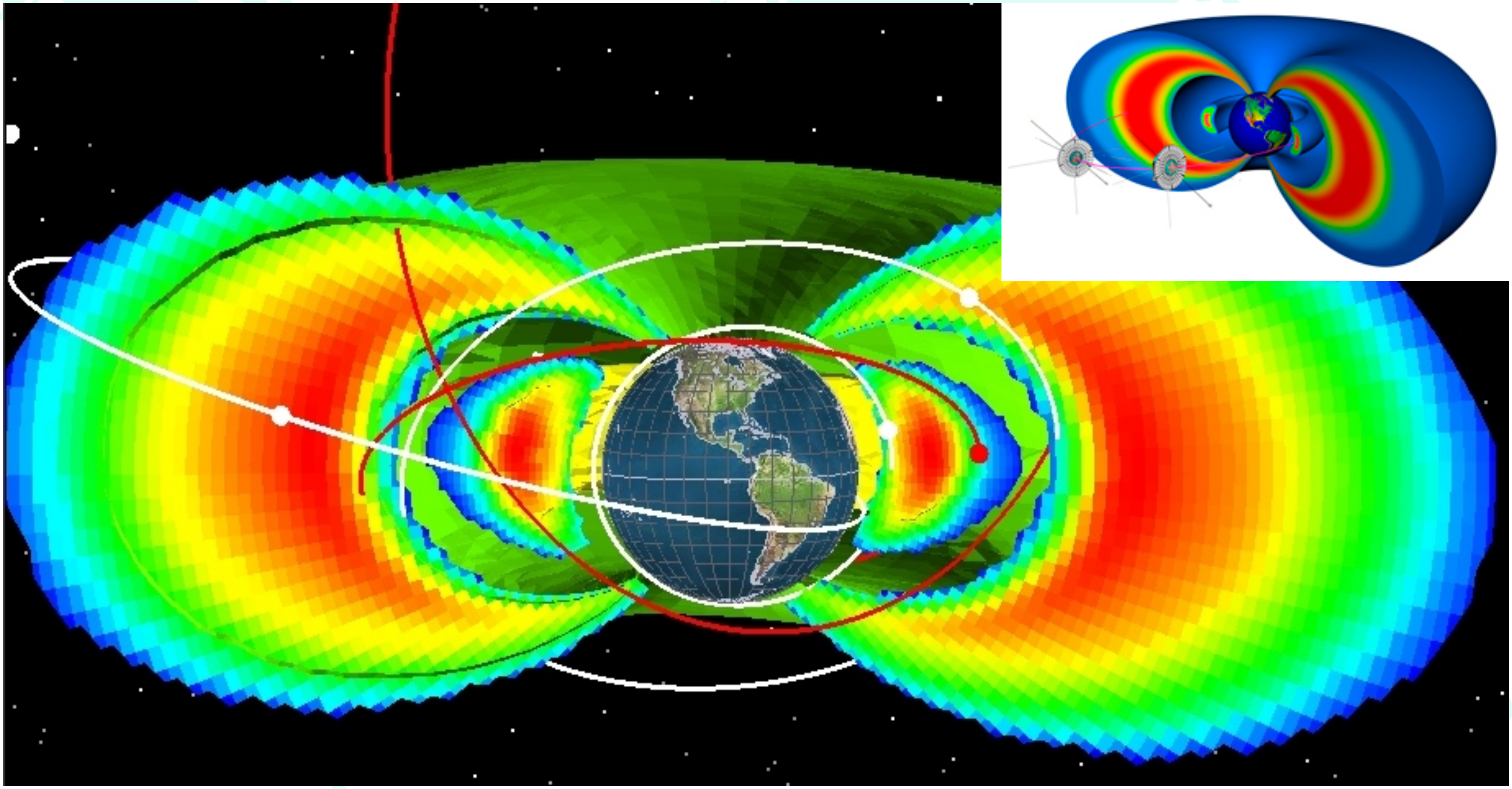
- Another new belt (#2) has been found **within** (below) the inner belt
- It contains heavy nuclei (mainly oxygen, but also nitrogen and helium, and very little carbon) with energies below 50 MeV/nucleon
- The source of these particles are the so called "anomalous cosmic rays" (ACRs) of interstellar origin

Earth's Radiation Belts



Credit: D. Vassiliadis

AE9/AP9 Earth's Radiation Belts

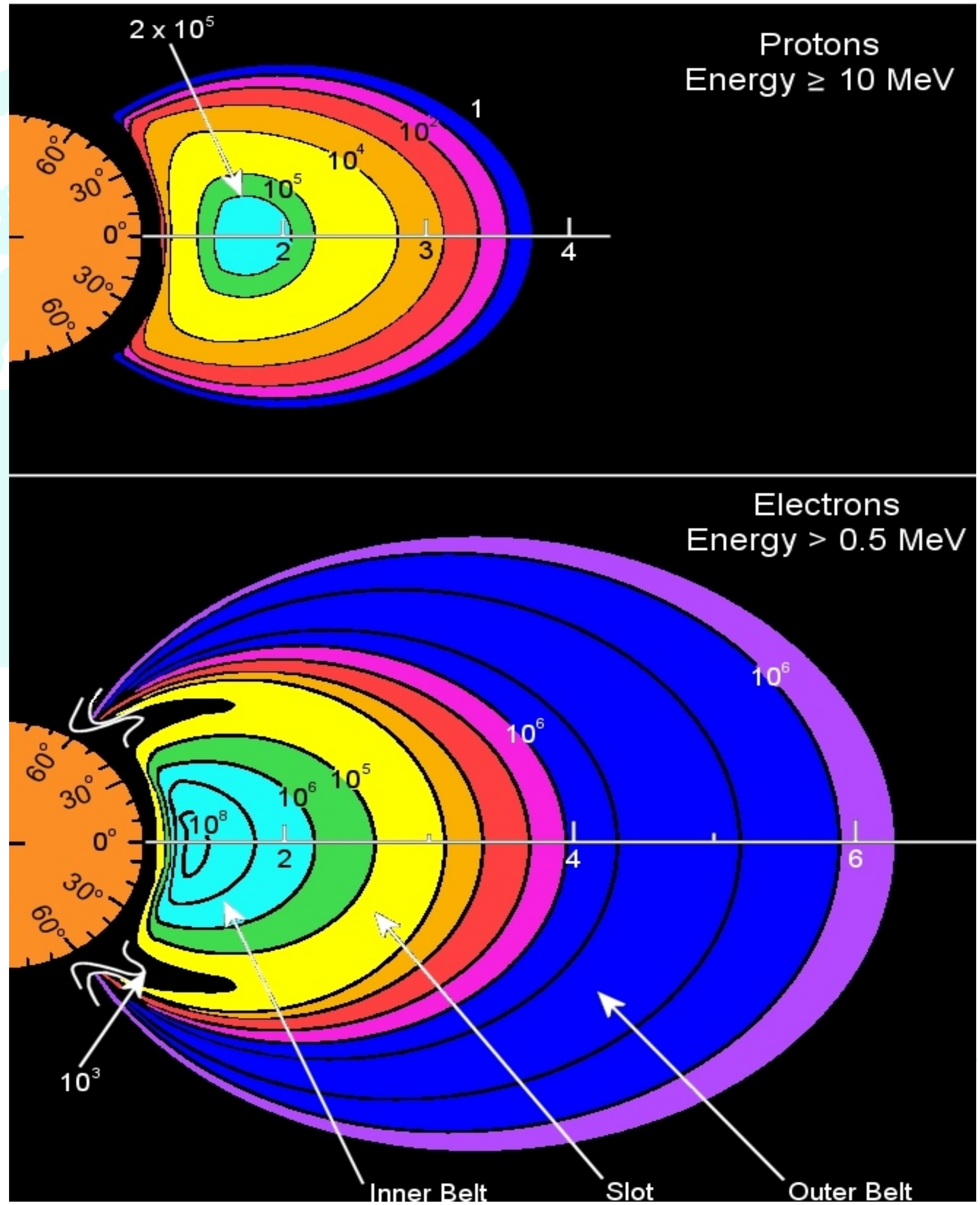


Credit: P. O'Brien

Contours of the omnidirectional flux (particles per square centimeter per second) of **protons** with energies greater than 10 MeV

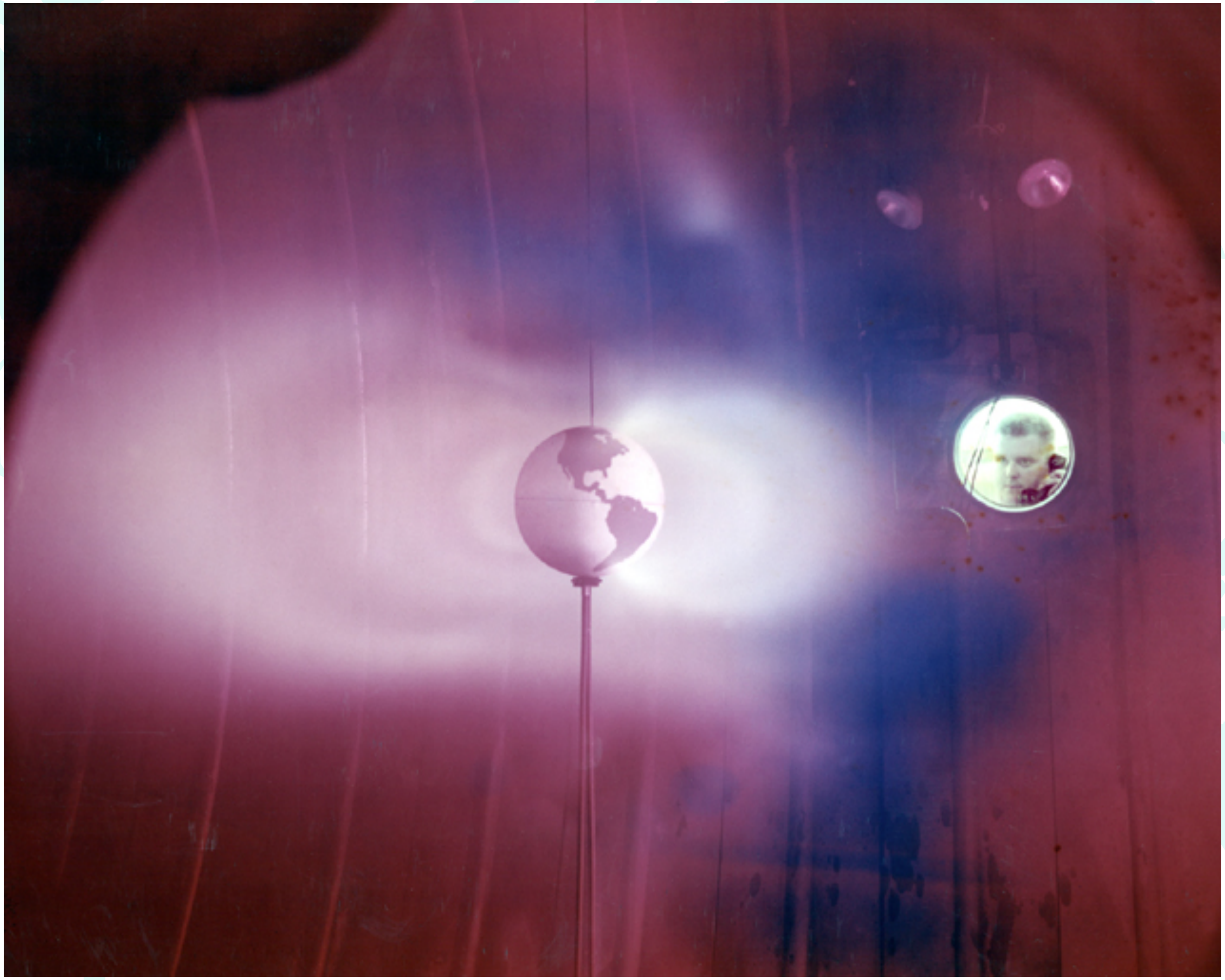
Earth's Radiation Belts

Contours of the omnidirectional flux of **electrons** with energies greater than 0.5 MeV



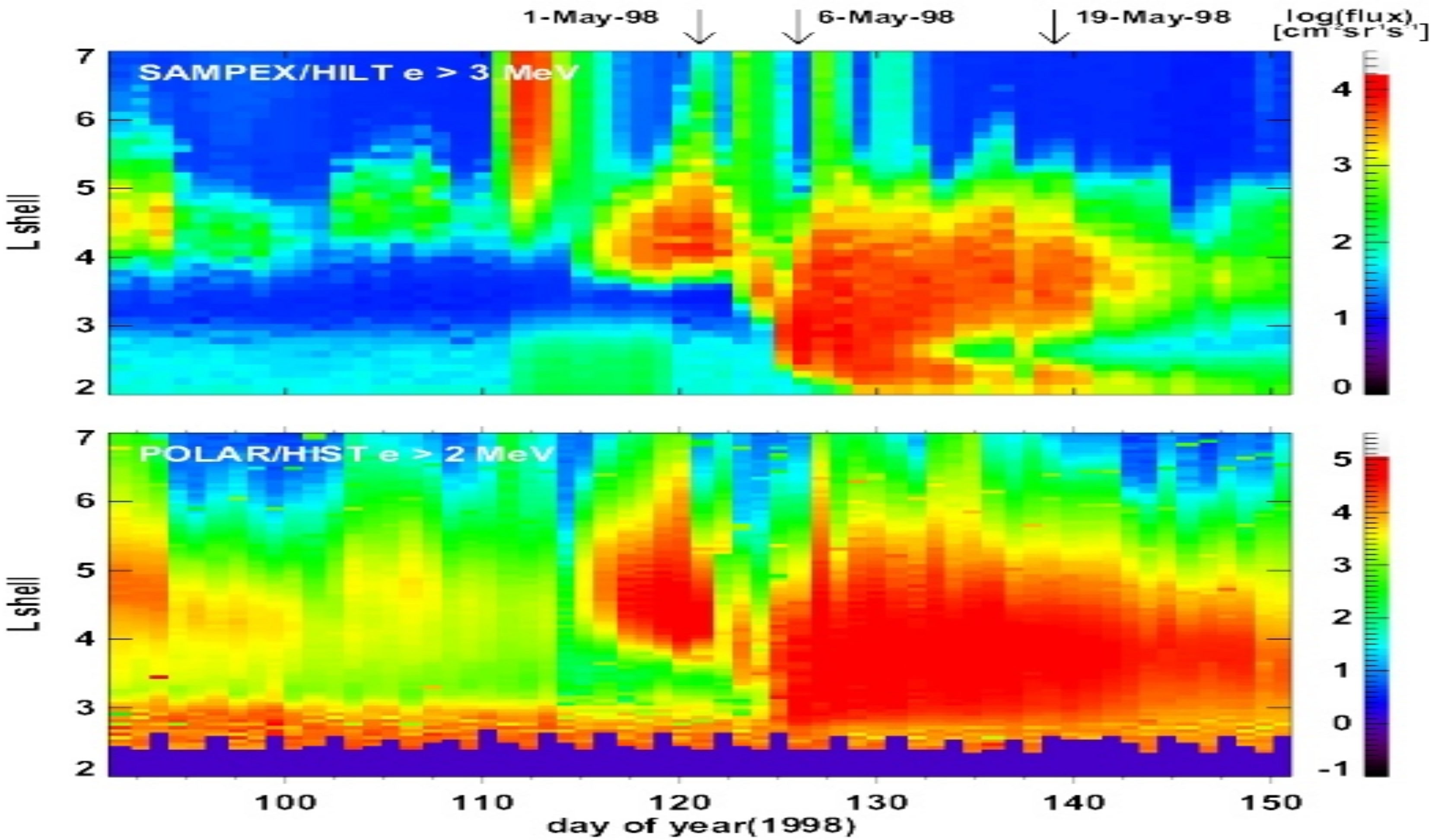
Credit: D.N. Baker

Simulated environment



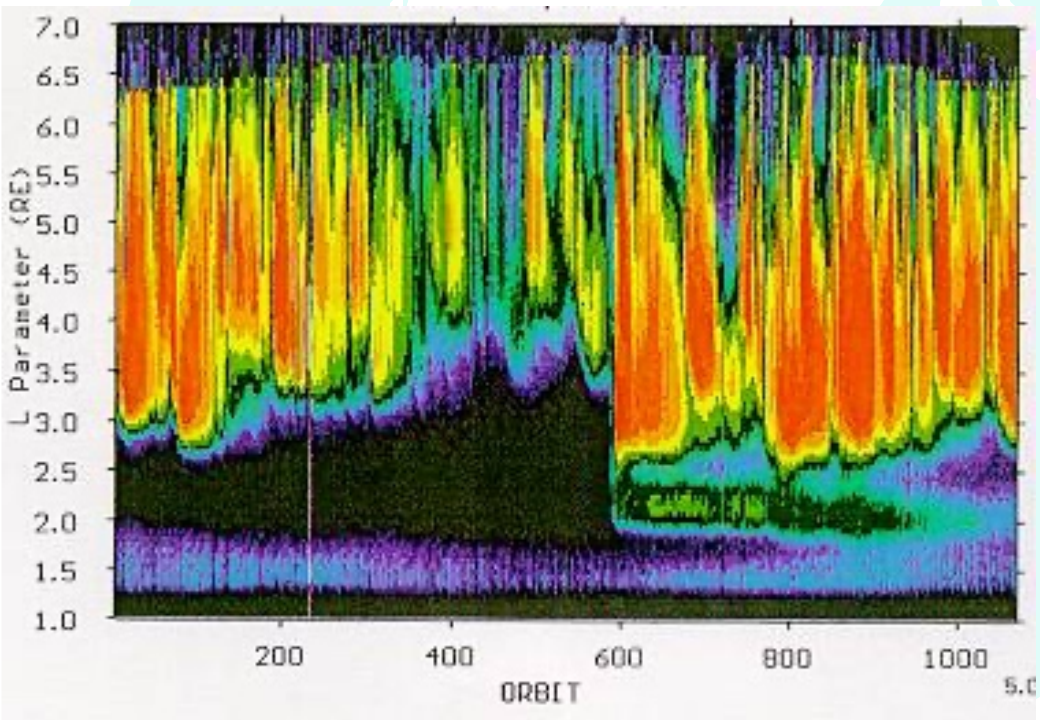
Credit: unknown

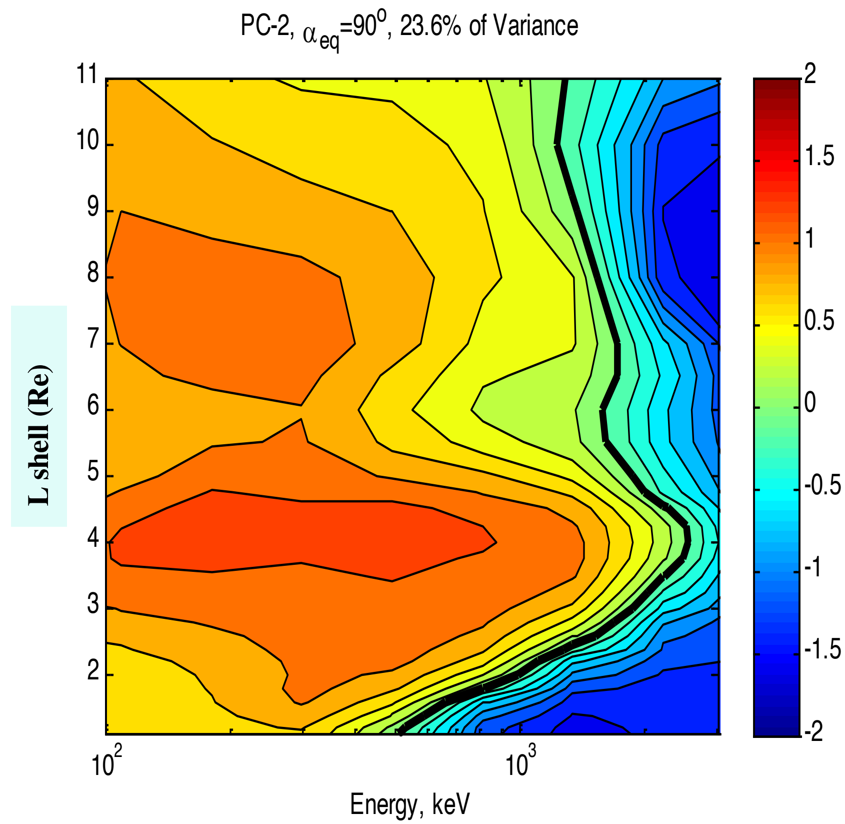
Particles injected into the radiation belts by solar activity



Credit: D.N. Baker

Radiation belt activity





Standards and guidelines

Resources

- IS 15390:2004 - Galactic Cosmic Rays
- IS 21348:2007 - Solar irradiances
- IS 22009:2009 - Earth's magnetosphere
- ISO WD 16695 - Earth's main field
- TS 16457 - Earth's ionosphere and plasmasphere
- TS 12208 Observed Proton Fluences over long duration at GEO and Guideline for selection of confidence level in statistical model of Solar Proton Fluences
- IS 15856 – Radiation exposure for non-metallic materials
- Electrostatic Discharge Association http://www.esda.org/
- AIAA G-083-1999 - Earth's trapped radiation
- MIL-STD-1541A section 6.7 - how to test an electronic assembly's susceptibility to ESD
- AE9/AP9 released Sep 10, 2012 http://lws-set.gsfc.nasa.gov/radiation_model_user_forum.html

IS 15390:2004 GCR standard

- specifies a model for estimating the radiation impact of galactic cosmic rays (GCR) on hardware and on biological and other objects when in space.
- can also be used in scientific research to generalize the available experimental evidence for GCR fluxes.
- establishes the model parameters and characteristics of variations in the 101 MeV to105 MeV GCR particles (electrons, protons, and $Z = 2$ to 92 nuclei in the near-Earth space beyond the Earth's magnetosphere)

AIAA G-083-1999

- **Guide to Modeling Earth's Trapped Radiation Environment**
- Topics covered:
  - Basic concepts of the space radiation environment
  - The trapped radiation environment
  - Geomagnetic field
  - Basic particle motion
  - AE8 and AP8 models
  - Solar cycle effects
  - Magnetospheric heavy ions
  - Shielding
  - Photon and charged particle interactions
  - Recommendations
  - References

AE9/AP9 status

- Algorithms have been released for AE9/AP9 v1.20.004
- GPS, LANL-GEO, HEO, ICO, TSX-5 data are ingested
- TEM-2 & TPM-2 Monte Carlo algorithms are implemented in Matlab
  - TEM-2 derived from: S3-3, SCATHA, CRRES, Polar
  - TPM-2 derived from: SIZM (Selesnick Inner Zone Model)
  - Improved data tables can be utilized without changes to code
- Standard solar cycle
  - Example electron standard solar cycles exist but have not been implemented as part of AE9/AP9 (TEM-2 Reanalysis, DREAM, Salammbo)
  - Proton standard solar cycle will be built from SIZM or Salammbo

Summary

- **Planetary space environment (Plasmasphere and radiation belts)**
  - Magnetosphere
    - BL coordinate system, L-shells, magnetic rigidity
  - Plasmasphere
    - Ionosphere topside, composition, formation, variability
  - Radiation physics
    - Radiation-surface interactions (photons: photoelectric effect, Compton scattering, pair production)
    - Linear attenuation
    - Radiation damage effects
  - Radiation environment - the Van Allen Belts
    - Inner, outer, new belts and their sources
  - Standards and guidelines