SPACE RADIATION AND ITS EFFECTS ON SPACE SYSTEMS AND ASTRONAUTS

Instructor: Dr. Vincent L. Pisacane

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SOLAR WIND
Introduction

- Solar wind is the flow of plasma from the Sun's corona, the outermost atmosphere of the Sun.

- In vicinity of the Earth the solar wind has:
  - Temperature of ~150,000 K
  - Sonic velocity of ~45 km s\(^{-1}\)
  - Average velocity ~400 km s\(^{-1}\), supersonic
  - Average density ~1-10 particles cm\(^{-3}\)
  - Composition of ~95% electrons and protons in near equal numbers, ~4% helium nuclei (alpha particles), remainder heavy nuclei and is electrically neutral

- Termination Shock at ~95 AU is where the velocity transitions from supersonic to subsonic (Illustrated next slide)

- Heliopause at ~120 AU is the interface between the solar wind and the constituents of the galaxy (Illustrated next slide)

From: http://www.mps.mpg.de/projects/sun-climate/se_body.html
MAGNETIC FIELD and MAGNETOSPHERE
Introduction to Interplanetary Fields

- The interplanetary magnetic field is driven by the Sun

- **Upper Figure**
  - It is essentially a dipole field tilted with respect to the ecliptic plane as illustrated in the upper figure

- **Lower Figure**
  - In the ecliptic plane, the plane of the Earth’s orbit, the interplanetary magnetic field is spiral in shape as illustrated in the figure due to the rotation of the Sun about an axis inclined to within 7.25 degrees of normal to the ecliptic plane
CUTOFF RIGIDITY
Earth Cutoff Contours at 450 km Altitude

- Contour maps of computed vertical cutoff rigidities at 450-km altitude for quiet magnetic conditions ($K_p = 0$ on left), and disturbed ($K_p = 8$ on right)

- Cutoff rigidity contours are in GV increments

- Maximum cutoff rigidities are along the magnetic equator and the minimum cutoff rigidity is at the magnetic poles.

INTRODUCTION
Summary Motion

- Motion of the trapped radiation as illustrated in Figure 6.4 consists of three primary components:
  - Gyration ~ milliseconds
    - Particles rotating around field lines
  - Mirroring ~0.1 – 1.0 s
    - Particles traveling from one hemisphere to the other and back
  - Longitudinal drift ~ 1 – 10 min
    - Particles drifting east or west

Figure 6.4 Motion of charged particles trapped in the Earth’s magnetic field,
GUIDING CENTER MOTION
Motion in Uniform Magnetic Field

- General motion of proton and electron in a constant magnetic field with an initial velocity along the field line results in the direction of the magnetic field results in helical motion.
Equatorial Loss Cone is a cone of velocities of charged particle whose apex is on the equator and axis along a magnetic field line that represents the charged particles that will be lost due to interaction with the atmosphere or the surface in a dipole field.

Loss-cone angle for intersection with the Earth depends solely on $L$-shell value and not on particle mass, charge or energy where

$$\sin\alpha_{lc} = \pm \left(4L^6 - 3L^5\right)^{1/4}$$

http://www-spof.gsfc.nasa.gov/Education/wtrap2.html
AE8 AND AP8 MODELS
Example Electron Flux at Max Sunspot Number

AE-8 MAX integral electron flux >1 MeV at 500 km altitude

AE8 AND AP8 MODELS
Low Altitude Simulation 2/2

- World map of electron and proton fluxes > 1 MeV

Electron flux AE8-Min

Proton flux AP8-Min

Spenvis simulation
CHARACTERISTICS
Gamma Ray Energy Spectrum

- Image is the EGRET gamma ray all-sky survey
- EGRET is instrument on NASA's Compton Gamma Ray Observatory satellite
- Energies > $1 \times 10^8$ eV
- Some cosmic rays interact with the interstellar medium and produce gamma rays

*Picture Credit: NASA, Compton Gamma Ray Observatory*
MODEL EVALUATIONS
Differential Flux Geostationary Spacecraft

- Integral flux comparisons

- Models
  - ISO-15390-Standard Model
  - CREME96 Solar Minimum
  - CREME86 M=2
    - Galactic and anomalous
    - Nymmik et al Solar Minimum

- Mission
  - Altitude 35,786 km
    Geostationary
  - Inclination 0°
  - Eccentricity 0
  - 21 March 2012, 12h UT

Spenvis simulation
CHARACTERISTICS
Anisotropy of SPE

- Upper Figure
  - Particles propagating along the “favorable path” will be anisotropic at Earth

- Lower Figure
  - Measured longitude distribution of propagation times of solar particles from coronal mass ejections to Earth
  - The various symbols indicate data from different studies

From Smart and Shea, 1985, and Barouch et al., 1971
CHARACTERISTICS
Observed Solar Proton Spectra

- Solar proton fluence for extremely large solar cycle 22 event on August 1972 and other events
- Dashed line is common interpolation between 8/72 event and the USSR balloon measurement

MARS SURFACE MODEL
Martian Surface Radiation Models

- Martian Energetic Radiation Environment Models (MEREM) developed to simulate the Martian radiation environment
- Two models
  - eMEREM – engineering model
  - dMEREM – more detailed model
- Takes into account
  - Solar minimum and maximum conditions
  - Solar particle events
  - Cosmic rays
  - Secondaries from surface and atmosphere


Spectrum due to GCR protons on Mars surface, for given location and epoch.
INTRODUCTION
Hazards of Radiation

http://holbert.faculty.asu.edu/eee560/spacerad.html
PHOTON RADIATION
Aluminum Mass Attenuation Coefficient

From XCOM available from NIST

aluminum, $\rho = 2.7 \text{ g cm}^{-3}$
CHARGED PARTICLE RADIATION
Proton and Electron Penetration Depth

- Graph showing the range in aluminium (mm) vs. energy (MeV) for electrons and protons.
- The graph indicates that electrons stop at approximately 2 mm at ~1 MeV energy, while protons stop at ~20 MeV energy.
EFFECTS ON ELECTRONICS
Total Ionization Dose (TID) NPN MOSFET

- Example, when gate to source voltage is positive, current flows between drain and source.

- Gate oxide insulates gate from source and drain and is made of silicon dioxide.

- When exposed to radiation, holes not as mobile as electrons, become trapped in the gate oxide.

- With sufficient radiation accumulated trapped holes build to a positive charge that acts the same as if a positive voltage were applied inducing an n+ conducting channel.

- Positive voltage from the trapped holes
  - Changes the operating characteristics
  - Reduces voltage to turn on device
  - Eventually turns device on permanently leading to failure.


Cross section of an NMOS transistor showing the gate oxide and conducting n+ channel formed between the source and drain. The trapped charges shown in the inset are responsible for the threshold voltage shift, ultimately leading to failure.
EFFECTS ON ELECTRONICS
UoSAT-2 Spacecraft Single Event Upsets

Figure 9.20
EFFECTS ON ELECTRONICS
Single Event Latchup (SEL)

- High-energy charged particle can cause an ionized low impedance path between the power lines and ground or between power lines.

- Typically occurs in CMOS circuits with intrinsic Bipolar Junction Transistors as illustrated.

- If power is limited, condition will persist and state will not change, called a Single Event Latchup.

- If power is high or not removed quickly, catastrophic failure may occur due to excessive heating of metallization or bond wire failure.

- Power reset will often correct the problem.

Figures from: Aerospace Corp, http://www.aero.org/capabilities/seet/otherSEE.html

From NASA
### RADIATION GUIDELINES

Steps in Radiation Hardness Assurance Program

<table>
<thead>
<tr>
<th>STEPS</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Identify the radiation exposure</td>
</tr>
<tr>
<td>2</td>
<td>Identify acceptable risk</td>
</tr>
<tr>
<td>3</td>
<td>Determine margins of safety</td>
</tr>
<tr>
<td>4</td>
<td>Identify potentially susceptible parts, maintain parts list</td>
</tr>
<tr>
<td>5</td>
<td>Procure rad-hard parts if possible (availability, cost)</td>
</tr>
<tr>
<td>6</td>
<td>Identify parts still at risk</td>
</tr>
<tr>
<td>7</td>
<td>Establish risk mitigation strategies for parts at risk</td>
</tr>
<tr>
<td>8</td>
<td>Confirm hardness of rad-hard parts by analysis and test</td>
</tr>
<tr>
<td>9</td>
<td>Confirm risk mitigation strategies for parts at risk by analysis and test</td>
</tr>
<tr>
<td>10</td>
<td>Monitor effectiveness of risk mitigation strategies during operations</td>
</tr>
</tbody>
</table>

Table 9.6
RADIATION DAMAGE COEFFICIENTS
EQFLUX Simulation Low Earth Orbit 2/2

Trapped proton equivalent fluences for Pmax as function of cover slide thicknesses

Solar proton equivalent fluences for Pmax as function of cover slide thicknesses

Trapped proton equivalent fluences for Voc as function of cover slide thicknesses

Solar proton equivalent fluences for Voc as function of cover slide thicknesses

Trapped proton equivalent fluences for Isc as function of cover slide thicknesses

Solar proton equivalent fluences for Isc as function of cover slide thicknesses

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INTRODUCTION
DNA Repair

- DNA damage, due to environmental factors and normal metabolic processes inside the cell, occurs at a rate of up to 500,000 DNA modifications per cell per day.

- If the rate of DNA damage exceeds the capacity of the cell to repair it, the accumulation of errors can overwhelm the cell and result in early apoptosis, senescence, or cancer.

- Normal apoptosis results in about one million cells dying every second in an adult.

- Definitions
  - Senescence
    - An irreversible state in which the cell no longer divides
  - Apoptosis
    - Programmed cell death

- DNA Repair
  - Successful repair
  - Unsuccessful repair
    - Mutations
    - Replication errors
    - Persistent DNA damage
    - Genomic instability

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COUNTERMEASURE READINESS LEVELS

Introduction

9. Countermeasure fully flight-tested and ready for implementation.
8. Validation with human subjects in actual operational space flight, demonstrate efficacy/operational feasibility.
7. Evaluation with human subjects in controlled laboratory simulating operational space flight environment.
6. Laboratory/clinical testing of potential countermeasure in subjects to demonstrate efficacy of concept.
5. Proof of concept testing and initial demonstration of feasibility and efficacy.
4. Formulation of countermeasures concept based on understanding of phenomenon.
1. Phenomenon observed and reported. Problem defined.
BACKGROUND EXPOSURE
Growth In Exposure to Ionizing Radiation in USA

# BACKGROUND EXPOSURE
Radiation Exposure in the US from NCRP-160

## Magnitude of Changes in Collective Effective Dose and Effective Dose per Individual in the U.S. Population Between the Early 1980s (NCRP Report No. 93) and 2006 (NCRP Report No. 160)

<table>
<thead>
<tr>
<th>Exposure Category</th>
<th>Collective Effective Dose (person-Sv)</th>
<th>Effective Dose per Individual in the U.S. Population (mSv)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(1) 2006</td>
<td>(2) Early 1980s</td>
</tr>
<tr>
<td>Ubiquitous background</td>
<td>933,000</td>
<td>690,000</td>
</tr>
<tr>
<td>Medical</td>
<td>899,000</td>
<td>123,000</td>
</tr>
<tr>
<td>Consumer</td>
<td>39,000</td>
<td>12,000 – 29,000</td>
</tr>
<tr>
<td>Industrial, security, medical, educational</td>
<td>1,000</td>
<td>200</td>
</tr>
<tr>
<td>and research</td>
<td>1,400</td>
<td>2,000</td>
</tr>
<tr>
<td>Total</td>
<td>1,870,000</td>
<td>835,000</td>
</tr>
</tbody>
</table>

*a* The quantities used in NCRP Report No. 93 were expressed in effective dose equivalent.

*b* Not listed; disparate aggregated sources.

Collective effective dose = Total radiation dose incurred by a population

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[http://NCRPonline.org](http://NCRPonline.org)
[http://NCRPPublications.org](http://NCRPPublications.org)
Figure 9.25 Historical radiation doses recorded by astronauts ▲ and estimates of effective doses ● for all NASA mission through December 1999, from Cucinotta et al, [2002],
PARTICLE ACCELERATORS
Synchrotron

- Synchrotron is a cyclotron where magnetic field is increased as energy increase to maintain constant radius to account for mass increase as speed of light is approached

- Formed from straight sections interspaced with bending magnets, accelerating cavities, and drift tubes

- Diagram
  - Group of particles enter at A
  - Interspaced magnets M bend trajectory
  - Interspaced acceleration gap G accelerates particle
  - Magnetic field at M increases as particle energy increases to maintain constant radius

- Proton Synchrotron at CERN in Geneva
  - Orbit diameter of 172 m
  - Deflecting magnets of 1.4 T
  - Accelerates protons to 28 GeV
  - Each pulse contains ~ 10^11 protons
  - Protons travel ~80,000km during acceleration

http://www.schoolphysics.co.uk/age16-19/Nuclear%20physics/Accelerators/text/Synchrotron_/index.html
NASA SPACE RADIATION LABORATORY
NSRL Site Pictures

NSRL Entrance

Tunnel populated

Tunnel under development