Space Environments & Effects

Janet L. Barth
NASA/GSFC (Emeritus)

IEEE Nuclear & Plasma Sciences Society
Distinguished Lectures Program

Toulouse Graduate School of Aerospace Engineering
13 September 2018
**Acronyms**

- ALMA Common Software. (ACS)
- Astronomical Unit (AU)
- Command and Data Handling System (C&DH)
- Charge-Coupled Devices (CCDs)
- Communication (Comm)
- Cosmic Ray Effects on Micro-Electronics (CREME)
- Charge Transfer Ratio (CTR)
- Error Eetecation and Correction (EDAC)
- Earth radius (ER)
- Galactic Cosmic Rays (GCR)
- Geostationary orbit or Geosynchronous orbit (GEO)
- Geostationary Operational Environmental Satellite (GOES)
- Goddard Space Flight Center
- Geostationary transfer orbit (GTO)
- Highly elliptical orbit (HEO)
- Hubble Space Telescope (HST)
- Integration and Test (I&T)
- Institute of Electrical and Electronics Engineers (IEEE)
- stable points in interplanetary space
- Low earth orbit (LEO)
- Linear Energy Transfer (LET)
- Microwave Anisotropy Probe (MAP)

- Multiple Bit Upset (MBU)
- Medium earth orbit (MEO)
- National Aeronautics and Space Administration (NASA)
- North American Aerospace Defense Command (NORAD)
- Nuclear & Plasma Sciences Society (NPSS)
- South Atlantic Anomaly (SAA)
- Solar Anomalous and Magnetospheric Particle Explorer (SAMPEX)
- Single Event (SE)
- Single Event Burnout (SEB)
- Single Event Effects (SEEs)
- Single Event Functional Interrupt (SEFI)
- Single Event Gate Rupture (SEGR)
- Single Event Latch-up (SEL)
- Solar Energetic Particles (SEPs)
- Single Event Transient (SET)
- Single Event Upset (SEU)
- Single Event Hard Errors (SHE)
- Solid State Star Tracker (SSST)
- Total Ionizing Dose (TID)
- United States Air Force (USAF)
Outline

• Space Environments & Effects
• Definitions & Units
• High Energy Radiation Environment
  » Solar Protons & Heavier Ions
  » Cosmic Ray Ions
  » Trapped Protons & Electrons (Van Allen Belts)
• Radiation Hardness Assurance
• Summary
Space Environments

- Plasma
- Particle Radiation
- Neutral Gas Particles
- Ultraviolet & X-ray
- Micro-meteoroids & Orbital Debris
- Electromagnetic Radiation, Thermal Environment, Geomagnetic Field, Gravitational Field
Space Environments & Effects

- Plasma
  - Charging
    - Biasing of instrument readings
    - Pulsing
    - Power drains
    - Physical damage
  - Ionizing & Non-Ionizing Dose
    - Degradation of micro-electronics
    - Degradation of optical components
    - Degradation of solar cells
  - Single Event Effects
    - Data corruption
    - Noise on Images
    - System shutdowns
    - Circuit damage
  - Drag
    - Torques
    - Orbital decay

- Neutral Gas Particles
  - Surface Erosion
    - Degradation of thermal, electrical, optical properties
    - Degradation of structural integrity
  - Impacts
    - Structural damage
    - Decompression

- Ultraviolet & X-ray

- Micro-meteoroids & Orbital Debris

To be presented by Janet L. Barth at the Nuclear and Plasma Sciences Society’s Distinguished Lecturer Program, Toulouse, France, September 13, 2018.
Definitions

• Distance
  » Sun to Earth = 1 Astronomical Unit (AU)
  » Earth radius (ER) = 6378.165 km at equator

• Spacecraft Orbits
  » Inclination – Angle between equatorial plane and orbit plane
  » Altitude – Distance from earth’s surface in km

• Orbit Altitude
  » LEO – Low earth orbit < 1000 km
  » MEO – Medium earth orbit 1000 km – 36,000 km
  » GEO – Geostationary orbit = 36,000 km or 6.6 - 7.0 ER
  » GEO – Geosynchronous orbit
  » GTO – Geostationary transfer orbit
  » HEO – Highly elliptical orbit
  » L1, L2, L3, etc. – stable points in interplanetary space
# Units

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle Energy, $E$</td>
<td>eV, MeV, GeV</td>
<td>Electron volt - the amount of work done on an electron when it moves through a potential difference of one volt</td>
</tr>
<tr>
<td>Particle Flux Density, $\phi$</td>
<td>$# \text{ cm}^{-2} \text{ s}^{-1}$</td>
<td>Transfer of particles per unit time across a unit area form either side</td>
</tr>
<tr>
<td>Particle Fluence, $\Phi$</td>
<td>$# \text{ cm}^{-2}$</td>
<td>Time rate of particle fluence</td>
</tr>
<tr>
<td>Ionizing Dose, $D$</td>
<td>Rads, seiverts</td>
<td>The amount of radiation that deposits 0.01 joule of energy in 1 kg of material</td>
</tr>
<tr>
<td>Linear Energy Transfer, LET</td>
<td>Fluence/material density, MeV cm$^2$ mg$^{-1}$</td>
<td>$dE/dX$ – mean energy lost by a charged particle in electronic collisions per unit length of its trajectory</td>
</tr>
</tbody>
</table>
High Energy Radiation

Galactic Cosmic Rays

Solar Protons
&
Heavier Ions

Trapped Particles

Nikkei Science, Inc. of Japan, by K. Endo
Characteristics of the Radiation Environment

• High energies
  » Electrons – 10s of MeV
  » Protons – 100s of MeV
  » Heavier Ions – 1000s of MeV

• Solar variability drives population levels
  » Long term solar cycle
  » Solar rotation
  » Solar storms, magnetospheric storms

• Magnetosphere filters galactic and solar particles
  » Polar, low-earth orbits are exposed to interplanetary levels during passes over the poles

• Trapped population has complex spatial distribution
Surface Charging

- Induced charge on surface
  - Low energy plasma & photoelectric currents
  - “Hot” plasma (LEO vs. GEO)

- Orbits with high risk
  - LEO – maybe
  - MEO - ? probably
  - GEO - generally a greater concern
  - GTO

- Risk factors
  - Geomagnetic substorms resulting in injection of keV electrons
  - Passage from eclipse to sunlight – positive charge surface due to photoelectron emission
  - Large spacecraft
  - High voltage power system
Deep Dielectric Charging

• Process
  » High energy electrons penetrate into dielectric materials (circuit boards and cables).
  » Charge builds up and gives rise to intense electric fields.
  » When charge exceeds the breakdown potential, discharge occurs.

• Missions affected
  » Any spacecraft spending long periods in Van Allen belt electron regions
  » MEO, GEO, GTO, Phasing loops
  » Jovian

• Risk factors
  » Accumulation of $> 10^{10}$ E $> 1$ MeV electrons within 10 hours
  » Accumulation of $> 3 \times 10^8$ E $> 2$ MeV electrons/day for 3 consecutive days
  » Accumulation of $> 10^9$ E $> 2$ MeV electrons in a single day
Displacement Damage Dose (DDD)

- Cumulative long term non-ionizing damage
- Effect:
  - Production of defects which result in charge transfer ratio (CTR) degradation
  - Optocouplers, solar cells, CCDs, linear bipolar devices
- Shielding has some effect
  - Solar cell cover glasses and mounting panels
  - Only for some orbits
Total Ionizing Dose (TID)

- Cumulative long term ionizing damage
- Strongly dependent on mission duration, orbit, and shielding
- Effects
  - Threshold Shifts
  - Leakage Current
  - Timing Skew
  - Functional Failures
- Can reduce with shielding
  - Low energy protons
  - Electrons
**Single Event Effects (SEEs)**

- Event caused by a single charged particle
- Effects:
  - Non-destructive: SEU, SET, MBU, SEFI, SHE
  - Destructive: SEL, SEGR, SEB
- Severity is dependent on:
  - type of effect
  - system criticality
- Shielding has little effect
Solar Activity Cycle

- Caused by reversal of solar magnetic field
- Many indicators of the cycle
  - Sunspot count
  - $F_{10.7}$ radio flux
  - Atmospheric density

Little Ice Age in 1645 to 1715

Length varies from 9 - 13 years
Recent solar cycles – 10 years
Interplanetary Particles – Galactic Cosmic Ray Heavy Ions (GCRs)

- 1913 - Victor Hess’ Balloon experiments
- 1960’s - Light flashes in astronauts’ eyes
- 1975 - Binder et al. documented logic upsets on spacecraft

Properties
  - All elements in Periodic Table
  - Energies in TeVs
  - Found everywhere in interplanetary space
  - Omnidirectional
  - Filtered by the magnetosphere
  - Mostly fully ionized

Effects
  - Astronaut dose
  - Single event effects
GCRs: Nuclear Composition

Energy = 2 GeV/n, Normalized to Silicon = 10^6
Solar Cycle Effects: Heavy Ions

CNO - 24 Hour Averaged Mean Exposure Flux

![Graph showing CNO flux over time with labels for different components: Background Galactic Cosmic Rays, Storms Solar Heavy Ions.]
GCRs: Shielded Fluences - Fe

Solar Minimum, 100 mils (2.54 mm) Al

Particles (#/cm²/day/MeV/n)

Energy (MeV/n)

- 0 deg/36,000 km
- 18 deg/360 x 36,000 km
- 51 deg/10,000 km
- 98 deg/705 km
- 29 deg/600 km

CREME 96
Interplanetary Particles – Solar Energetic Particles (SEPs)

- 1946 - Scott Forbush
- Increased levels of protons & heavy ions due to SEP events
- Properties
  - Protons - 100s of MeV
  - Heavy ions - 100s of MeV
  - Abundances dependent on radial distance from Sun
  - Partially ionized
  - Number & intensity of events increase dramatically during “solar active” periods
- Effects
  - Degradation
  - Single event effects (protons & heavy ions)
Solar Cycle Effects: Solar Protons

Protons from Solar Energetic Particle Events $E > 10$ MeV

Date

Protons (#/cm$^2$/s)

Yearly Sunspot #

1 AU
SEPs: Proton Event Spectra

Total Integral Proton Fluence Measured by GOES

![Graph showing the total integral proton fluence measured by GOES, with labels for different dates: 20 March 1991, 4 June 1991, 27 September 1991, 20 February 1994, August 1972, and 19 October 1989.](image)
SEPs: Shielded Fluences

Solar Proton Levels Averaged Over Worst Day

Protons (#/cm²/sec/MeV) vs. Energy (MeV)

- 0 deg/36,000 km
- 98 deg/705 km
- I=60° deg/H=800 km
- 29 deg/600 km

CREME 96
Trapped Particles

- Cosmic ray detector on Explorer I, 31 Jan 1958
  » “Zero” levels on instrument
- Highlight of US participation in IGY

- 1895 - Birkeland theorizes particle trapping
- 1904 – Stöermer calculations support theory of particle trapping around the Earth
- 1958 – James Van Allen

Properties
- Omnidirectional
- Protons: $E \sim 1 \text{ keV} - 500 \text{ MeV}$
- Electrons: $E \sim 1 \text{ keV} - 10 \text{ MeV}$
- Heavy Ions: Low E (non-problem for electronics)
- Complex distribution based on energy & solar conditions

Effects
- Degradation – protons and electrons
- Single event effects – protons
- Surface charging, Deep dielectric charging - electrons
Trapped Particle Motions

Spiral, Bounce, Drift

Proton Drift

Flux Tube

Mirror Point

Conjugate Mirror Point

Electron Drift

Magnetic Field Line

after Hess

To be presented by Janet L. Barth at the Nuclear and Plasma Sciences Society’s Distinguished Lecturer Program, Toulouse, France, September 13, 2018.
Trapped Radiation Belts

Van Allen Probes Mission

NASA/LWS Program, Johns Hopkins University Applied Physics Laboratory
Trapped Protons

South Atlantic Anomaly (SAA) & Belt Region

E > 30 MeV (#/cm²/s) - Solar Minimum

To be presented by Janet L. Barth at the Nuclear and Plasma Sciences Society’s Distinguished Lecturer Program, Toulouse, France, September 13, 2018.
Trapped Proton Spectra

- Energy range
  - 0.04 - 500 MeV
- Range in Al:
  - 30 MeV ~ .17 inch
- Effects:
  - Total dose
  - Single event effects
  - Solar cell damage

Integral Proton Fluences

Energy (>MeV) vs. Fluence (#/cm²/day)

- MEO
- GTO
- EOS
- LEO
- GEO
Trapped Electrons

SAA & Outer Zone Electrons

E > 0.5 MeV (#/cm²/s) - Solar Minimum
**Trapped Electron Spectra**

- **Energy range**
  - 0.04 - 7 MeV

- **Range in Al:**

- **Effects:**
  - Total dose
  - Surface charging
  - Deep dielectric charging
  - Solar cell damage

---

**Integral Electron Fluences**

- **Fluence** (#/cm²/day)

- **Energy** (>MeV)

- **Graph** showing integral electron fluences for different orbits (GTO, MEO, GEO, EOS, LEO) across energy ranges.
Effect of Solar Storms on Trapped Protons – CRRES Measurements

Don Brautigam, AF Phillips Laboratory, SPD/GD, used by permission

March 1991

E = 47 MeV
Effect of Solar Storms on Trapped Electrons – SAMPEX Measurements

2–6 MeV Electrons

- Electron belt changes during Oct 2003 solar storm events
- Daily-averaged particle flux data from the SAMPEX satellite.

**Threshold** = 100 e⁻

**Threshold** = 1 e⁻

---

*To be presented by Janet L. Barth at the Nuclear and Plasma Sciences Society’s Distinguished Lecturer Program, Toulouse, France, September 13, 2018.*
Single Event Upsets on Seastar Solid State Recorder

Orbit: 705 km, 98deg, Duration: 4 years

Harvey Saffron, Orbital Sciences, work performed for NASA GSFC
Radiation Environment Levels

**Low: < 10 krads**
- Moderate single event effects environment
- Low displacement damage environment

**Moderate: 10-100 krads**
- Intense single event environment
- Moderate displacement damage environment

**High: >100 krads**
- Intense single event effects environment
- Intense displacement damage environment

**Examples**

- Low altitude/low inclination (HST, Shuttle, XTE)
  - If Short mission duration

- Low altitude/high inclination (EOS, GLAS)
  - L1, L2, GEO
  - Medium mission duration

- Europa, GTO, MEO, << 1 AU
  - or Long mission duration

*after LaBel*
Radiation Hardness Assurance

• Space radiation penetrates spacecraft shielding and interacts with components to produce a broad range of effects.
• A rigorous methodology is needed to ensure that the radiation environment does not compromise the functionality and performance of the electronics.
Single Event Effects on Missions

- Equator-S – SE Latchup on processor & redundant processor
- HST – SE Transients on an optocoupler
- Terra – Single particle events on the solid state star tracker (SSST)
- Flight Data Recorders – SE upsets
  - HST
  - SAMPEX
  - Seastar
- MAP – SE Transient on a voltage comparator
Janet’s Top 5 Quotes About Harness Assurance

5. “I hired radiation specialists from ACME, and I need you to fix their calculations for my program review tomorrow.”

4. “I called to get the radiation environment for my mission. I need the number now so I’ll wait while you look it up in your table.”

3. “Extra overhead like radiation engineering is not part of our program philosophy.” (followed with 2 weeks of 3-page emails with questions about radiation)

2. “Well, my radiation plan was to add some spot shielding after the board is built.”

1. “Hello, you don’t know me but I’m launching next week and I need you to sign these waivers.”
**Hardness Assurance Methodology**

- **Definition**
  - Activities undertaken to ensure that the electronic piece parts placed in the space system perform to their design specifications after exposure to the space radiation environment.

- **Goal**
  - A system tolerant to the radiation environment within the level of risk that is acceptable for the mission.
Typical Project Organization

- Project Management
- Science Team

- Safety & Mission Assurance
- Mission Systems Engineering

- Instrument Systems Management
- Observatory Management: ACS, I&T, Propulsion, C&DH, Comm., Power, Mechanical, Electrical, etc.
- Ground Systems & Mission Operations Management

Radiation Hardness Assurance
Hardness Assurance Methodology

- Step 1 - Describe the mission radiation environment and define the radiation levels within the spacecraft
- Step 2 - Assess the radiation sensitivity of the parts based on radiation databases and relevant radiation tests
- Step 3 – Perform Worst Case Analysis (WCA) of the impact of the radiation effect taking into account the system and circuit design
- Step 4 – Categorize parts for acceptability
- Step 5 – If needed, develop Risk Management Plan
Spacecraft Charging – System Hardening

- Two distinct problems
  - Surface charging
  - Deep-dielectric charging
- Risk Avoidance
  - Assume there will be a problem
  - Evaluate with NASCAP 2K
  - Follow accepted design practices
    - Grounding
    - Shielding
    - Material selection
    - Circuit design
TID - System Hardening

- Risk avoidance
  - Component selection
  - Shielding strategies
    - May need more accurate knowledge of component shielding

- Risk management
  - Plan for graceful degradation
  - Requires accurate knowledge of how device will respond in the space environment
    - System criticality
    - Application
    - Characterization of device response
      - Parametric degradation
      - Enhanced low dose rate
DDD - System Hardening

- Risk Avoidance
  - Not possible for all technologies
  - Protons are difficult to stop with shielding
  - Hardening techniques are not effective
  - Hardness changes with processing

- Risk Management
  - Reduce effect with shielding
  - Plan for degradation
  - Knowledge of radiation environment at detector
  - May require on-ground simulation
  - Models are not validated – need test flights
  - Mitigation through software
SEEs – System Hardening

• Risk avoidance
  » Rad-hard does not always imply SEE hard.
  » Shielding is not an effective mitigator.
  » System should be hard to latchup.
    - Is not always possible to find replacement part
  » Performance requirements push designers to use sensitive technologies.

• Risk management
  » Typical for non-destructive events - EDAC
  » Destructive - rate prediction for assessment of level of risk
  » Both require accurate knowledge of how device will respond in the space environment
    - Type of effect & system criticality
    - Definition of peak & average environments
    - Characterization of device response to particle hits
**Summary**

- The radiation environment has complex spatial distribution and solar variability
  - Environment definition for Project “A” will not work for Project “B”
- Start early in the program – avoid retrofitting & redesign
  - Mission concept – identify show stoppers
  - Mission planning – trade studies
  - Mission design – detailed analyses, quantify residual risk
  - Launch & operations – manage residual risk
- Radiation hardness assurance is a system issue – not a component issue
- Shielding is not a “cure-all”.
References


J.L. Barth, “Modeling Space Radiation Environments,” Notes from the 1997 IEEE Nuclear and Space Radiation Effects Short Course, Snowmass, CO.
Thank you!

IEEE Nuclear & Plasma Sciences Society

Distinguished Lectures Program
Chapter Grants
Awards
Child Care at Conferences
Women in Engineering Events
Young Professionals Events
Backups
Earth’s Magnetosphere

adapted from T. W. Hill by P.H. Reiff
**Trapping Mechanisms**

- **Sources**
  - Outer zone - Solar wind & ionospheric electrons & ions
  - Inner zone - Cosmic ray albedo neutron decay (CRAND)
  - Trapped heavy ions - Interplanetary particles
  - Others
    - *In situ* acceleration
    - Artificial, e.g. Starfish explosion

- **Losses**
  - Collisions
    - Earth’s atmosphere
    - H in the exosphere
    - Particles in the plasmasphere

- **Stable over long periods of time**
  - Inner belts – Years
  - Outer belts - Minutes
TID - Compare Missions

Solid Aluminum Spheres for 1 Year

- Europa Mission
- I=0°, H=3000/3000 km
- I=0°, H=6000/6000 km
- I=18°, H=360/3600 km
- Geostationary
- I=98°, H=705/705 km
- I=30°, H=600/600 km

MEO, GEO, GTO Missions

LEO Missions
Space Environment Model Use in Spacecraft Life Cycle

Mission Concept
Mission Planning
Design
Launch
Operations
Anomaly Resolution

Both + in situ measurements

Space Climate
Minimize Risk

Space Weather
Manage Residual Risk
Pre-Launch Phases: Climatology

• Mission Concept
  » Observation requirements & observation vantage points
  » Development and validation of primary technologies

• Mission Planning
  » Mission success criteria, e.g., data acquisition time line
  » Architecture trade studies, e.g., downlink budget, recorder size
  » Risk acceptance criteria

• Design
  » Component screening, redundancy, shielding requirements, grounding, error detection and correction methods
Launch & Post-Launch: Space Weather

• Launch & Operations
  » Asset protection
    - Shut down systems
    - Avoid risky operations, such as, maneuvers, system reconfiguration, data download, or re-entry

• Anomaly Resolution
  » Lessons learned need to be applied to all phases
The Solar Cycle

- **Ascending Phase**
  - Sunspots appear
  - Solar wind flow is increasingly perturbed by coronal mass ejections
  - Atmospheric heating increases

- **Solar Maximum**
  - Intensity and frequency of solar energetic particle (SEPs) events increase
  - Magnetic storms associated with solar event activity increase

- **Declining Phase**
  - Coronal holes expand (non-polar) resulting in high velocity solar wind streams → Recurrent magnetic storms (& electron storms in belts)

- **Solar Minimum**
  - Solar wind flow not disturbed due to minimal SEP event occurrence
  - Atmospheric heating decreases
Planetary Atmospheres

- GCRs enter atmosphere & collide with matter
  - Secondary particles are produced - Important product is neutrons
  - Earth
    - Magnetic field causes a latitude dependence
    - GCRs enter atmosphere & collide with O & N
  - Mars
    - No magnetic field – Primary cosmic rays are important component
    - Thin atmosphere - Products from interactions with Mars atmosphere and surface materials are also important
Atmospheric Radiation

1951 – Serge Korff
- Collisions between cosmic rays & atmospheric O & N
  - Product - High energy neutrons
- 1990’s – Neutron induced effects in aircraft avionics & ground systems
- Effects
  - Single Event Upsets (Low Earth orbits, aircraft, ground)
  - Passenger & crew exposure in aircraft

Serge Korff
- Balloon observations, high elevations, rockets, high-flying aircraft
- Published study included effects of altitude and latitude dependence

U. J. Schrewe
Neutron Flux Measurements

1-10 MeV & 10-100 MeV Energy Ranges

Normalized to Peak

Altitude (km)

Ait/Ouamer
10-100 MeV

Mendell/Holt
1-10 MeV

Preszler/Saxzena
10-100 MeV
Solar Cycle Effects: Trapped Protons

Solar Cycle Variation: 80-215 MeV Protons

TPM-1 Model

Proton Flux (#/cm²/s)

Radio Flux F 10.7

Date

Huston et al.
Boeing Neutron Model

1-10 MeV Neutron Flux (n/cm²/s)

Latitude (degrees)

Altitude (thousands of feet)

Differential Flux

Energy (MeV)
Solar Cycle Effects: Ground Neutrons

Climax Neutron Monitor

Year

Monthly Sunspot Number

Monthly Count/100


0 100 200 300

3000 3200 3400 3600 3800 4000 4200 4400
Meteoroid/Orbital Debris

• Meteoroids
  » Primarily remnants of comet orbits
    - Several times a year - Earth intersects a comet orbit
    - Other planets
  » Asteroid belt
    - Daily - Sporadic particles released

• Debris
  » Operational payloads, spent rockets stages, fragments of rockets and satellites, other hardware and ejecta
  » USAF Space Command tracks over 7,000 > 10 cm objects in LEO
  » Tens of thousands smaller objects
Satellite & Debris Tracking

USAF
Space Command
NORAD Tracking
Micro-meteoroid & Orbital Debris Effects

- Damage and decompression threat
  - Hypervelocity impacts from larger particles
  - Surface erosion from collisions with smaller objects
- Surface effects on thermal, electrical, and optical properties
- Increases contamination

Impact into solar-cell cover glass. Such impacts can degrade the power producing ability of such devices.

Penetration through an aluminized Mylar foil.

Penetrations, and commonly associated ringed structure, in silver-Teflon thermal blanket.
Neutral Gas/Thermosphere

• Definition
  » Neutral portion of the atmosphere
  » Composed of neutral gas particles
  » 90 – 600 km

• Variations
  » Altitude - Atomic mass
    - Lower altitude – Atomic oxygen (AO) (200 - 400 km)
    - Higher altitude – Hydrogen & Helium
  » Heating
    - Solar cycle effects due to absorption of solar extreme ultraviolet radiation (EUV)
    - Proxy measurement with 10.7-cm radio flux (F10.7)
  » Solar storms
Neutral Gas Effects

- Degradation of surface materials
  - Atomic oxygen in synergy with plasma and UV
- Spacecraft drag
- Spacecraft glow
Plasmasphere
Plasma Environments

• Energy < 100 keV - No radiation effects
• Ionized gas where electron and ion densities are approximately equal
• Sources
  » Ionosphere
    - Electrically charged portion of the atmosphere
    - Low energy (eV)/High Density
  » Plasmasphere - Magnetosphere
    - Source - ionosphere and solar wind
    - High energy (keV)/Low density
    - Storms - Geomagnetic substorm activity
  » Solar Wind
    - Sun’s corona
    - Seen at > 10 Billion km from the Sun by Pioneer 10
Plasma Effects

- Surface charging – can be destructive
- Solar array coupling to plasma
  - Current drain
- Contamination
  - Dense pressure of atmosphere in LEO
- Generation and emission of plasma waves