Space Weather Impacts on Satellites/Space Assets

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Acknowledgement:
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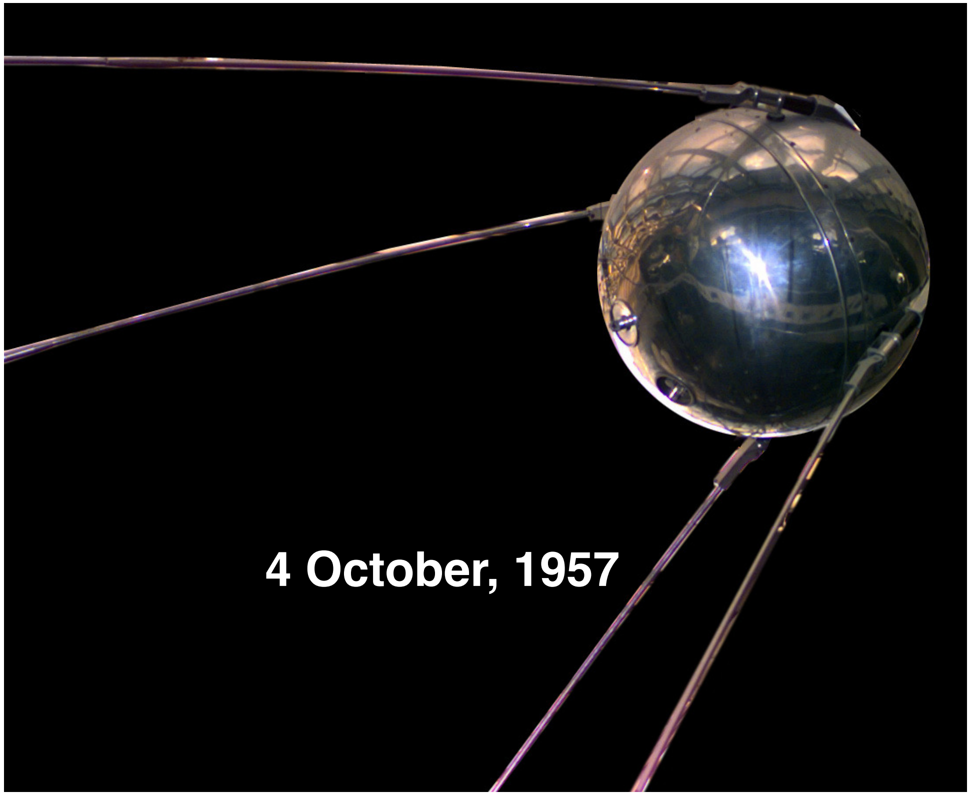
June 7, 2018
Corrected: Feb 9, 2023
with right acknowledgement

Outline

- ✓ Intro of man-made satellites
- ✓ Intro of different orbits
- ✓ Different types of space weather effects on satellites
- ✓ Satellite anomalies from the Oct 2003 and the March 2012 space weather events

1st Satellite Launched Into Space



The world's first artificial satellite, the **Sputnik 1**, was launched by the Soviet Union in 1957.

Marking the start of the Space Age

International Geophysical Year: 1957

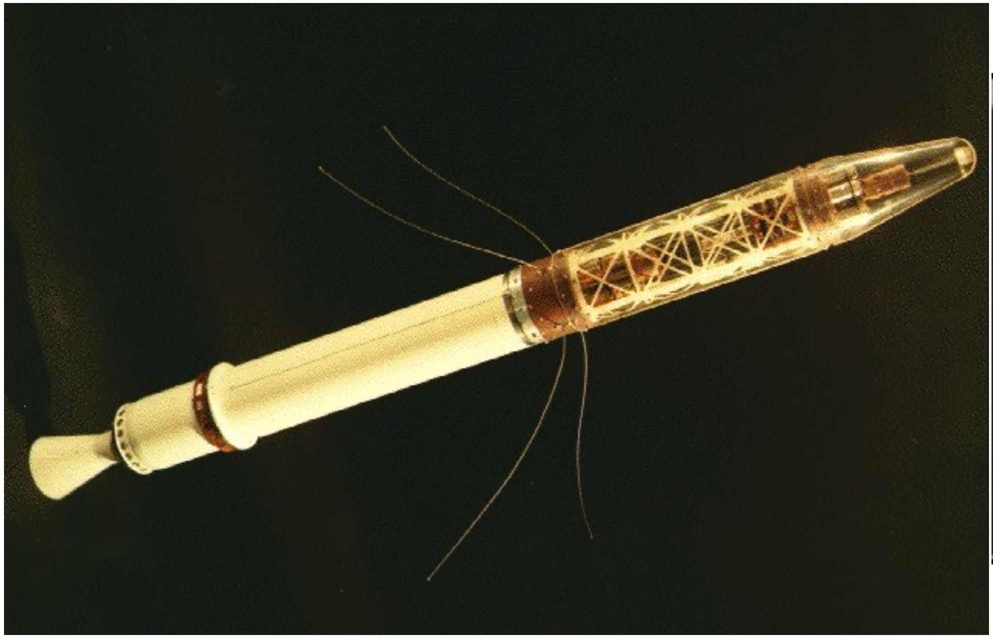
Space dog - Laika

The occupant of the Soviet spacecraft Sputnik 2 that was launched into outer space on November 3, 1957

Paving the way for human missions

Explorer I – 1st U.S. Satellite

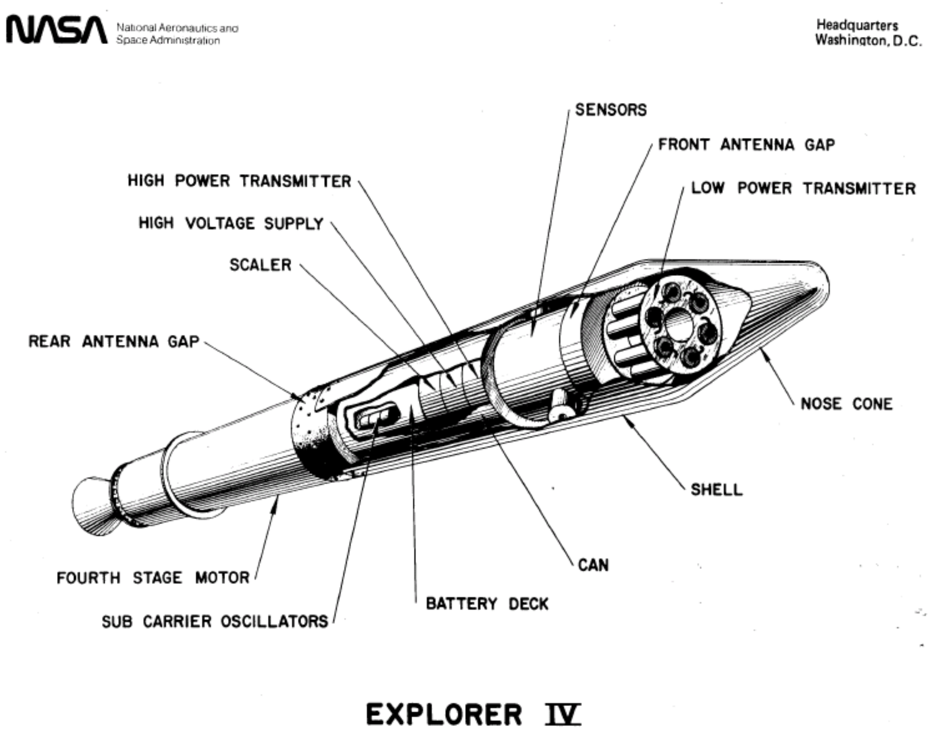
- was launched into Earth's orbit on a Jupiter C missile from Cape Canaveral, Florida, on January 31, 1958 - Inner belt discovery



Explorer 1 and 3: discovery of the inner radiation belt

William Pickering (L), James Van Allen (center), Wernher von Braun (right)

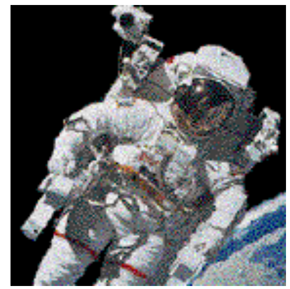
Discovery of the Outer Van Allen Radiation Belt

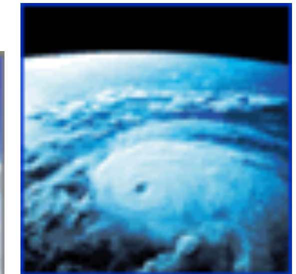
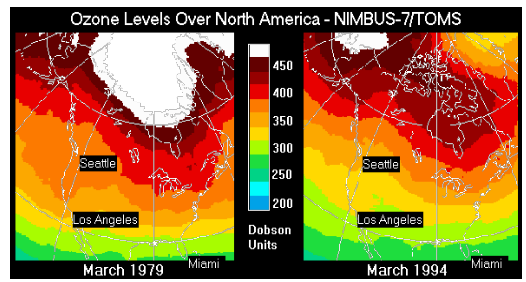


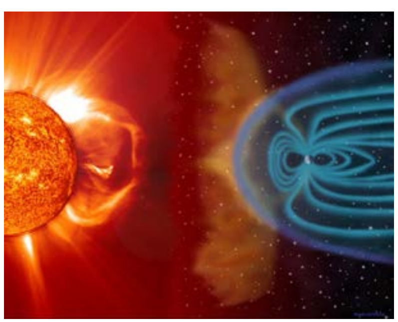
Pioneer 3 (launched 6 December 1958) and Explorer IV (launched July 26, 1958) both carried instruments designed and built by Dr. Van Allen. These spacecraft provided Van Allen additional data that led to discovery **of a second radiation belt**

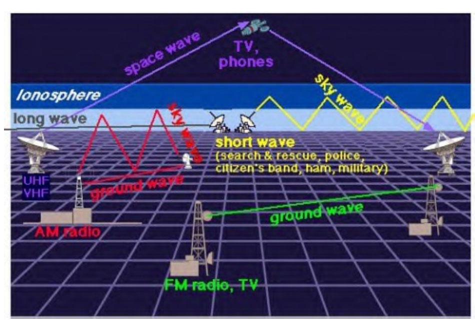
Importance & Our Increasing Reliance on Space Systems

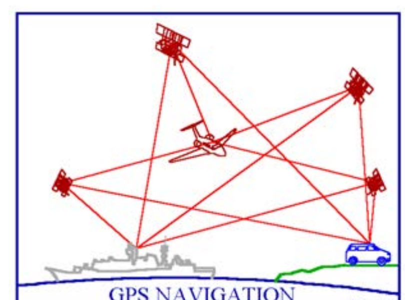
- Scientific Research
  - Space Science
  - Earth Science
  - Human Exploration of Space
  - Aeronautics and Space Transportation
- Navigation
- Telecommunications
- Defense
- Space environment monitoring
- Terrestrial weather monitoring



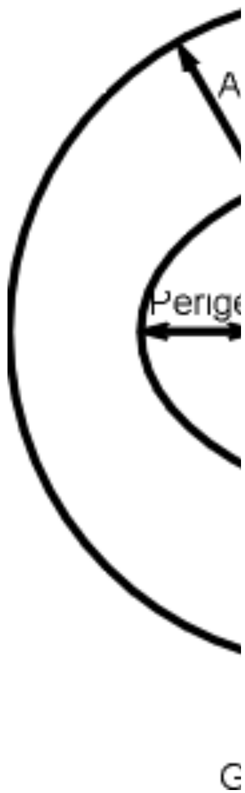







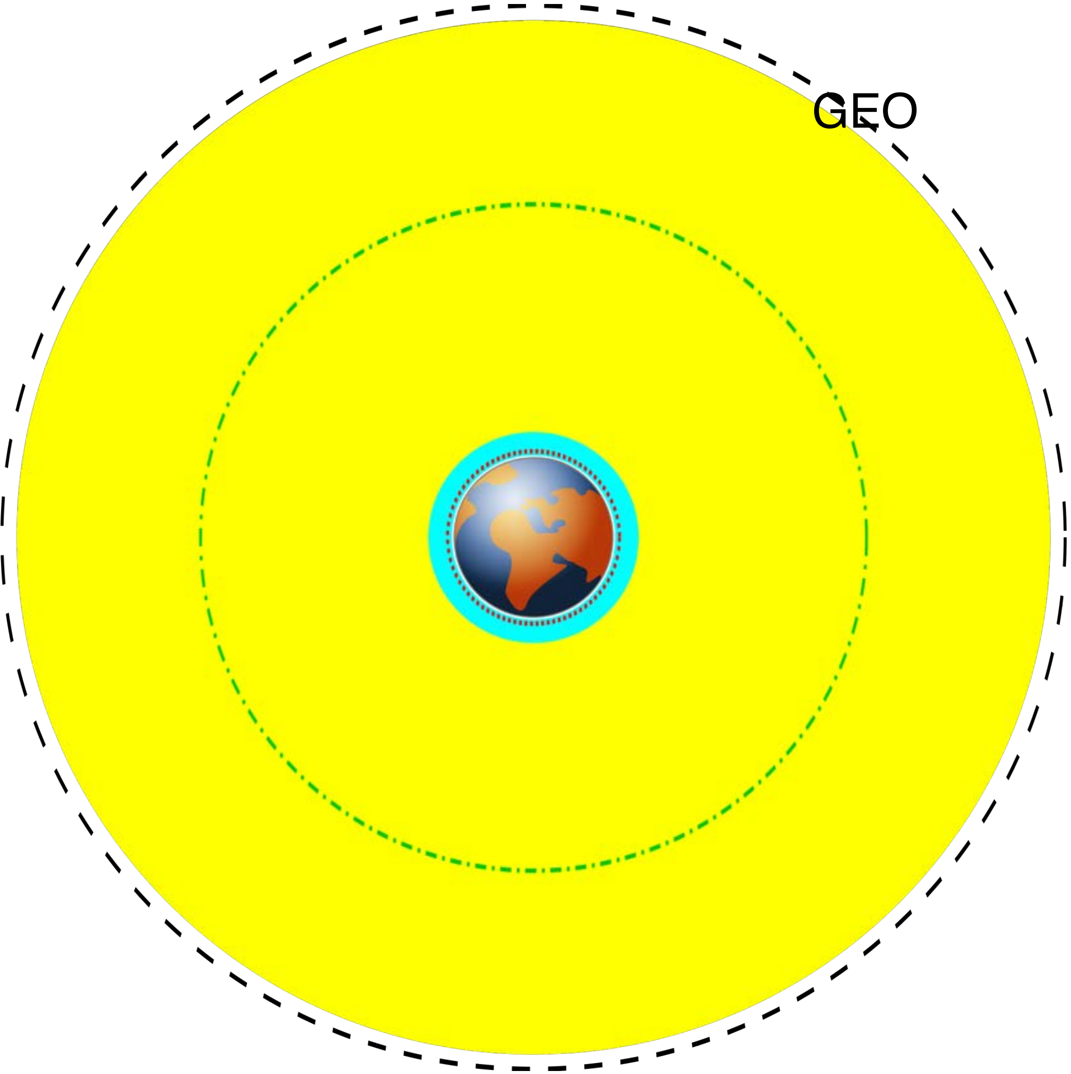
Courtesy: J. Barth (NASA/GSFC, ret.)

Orbits



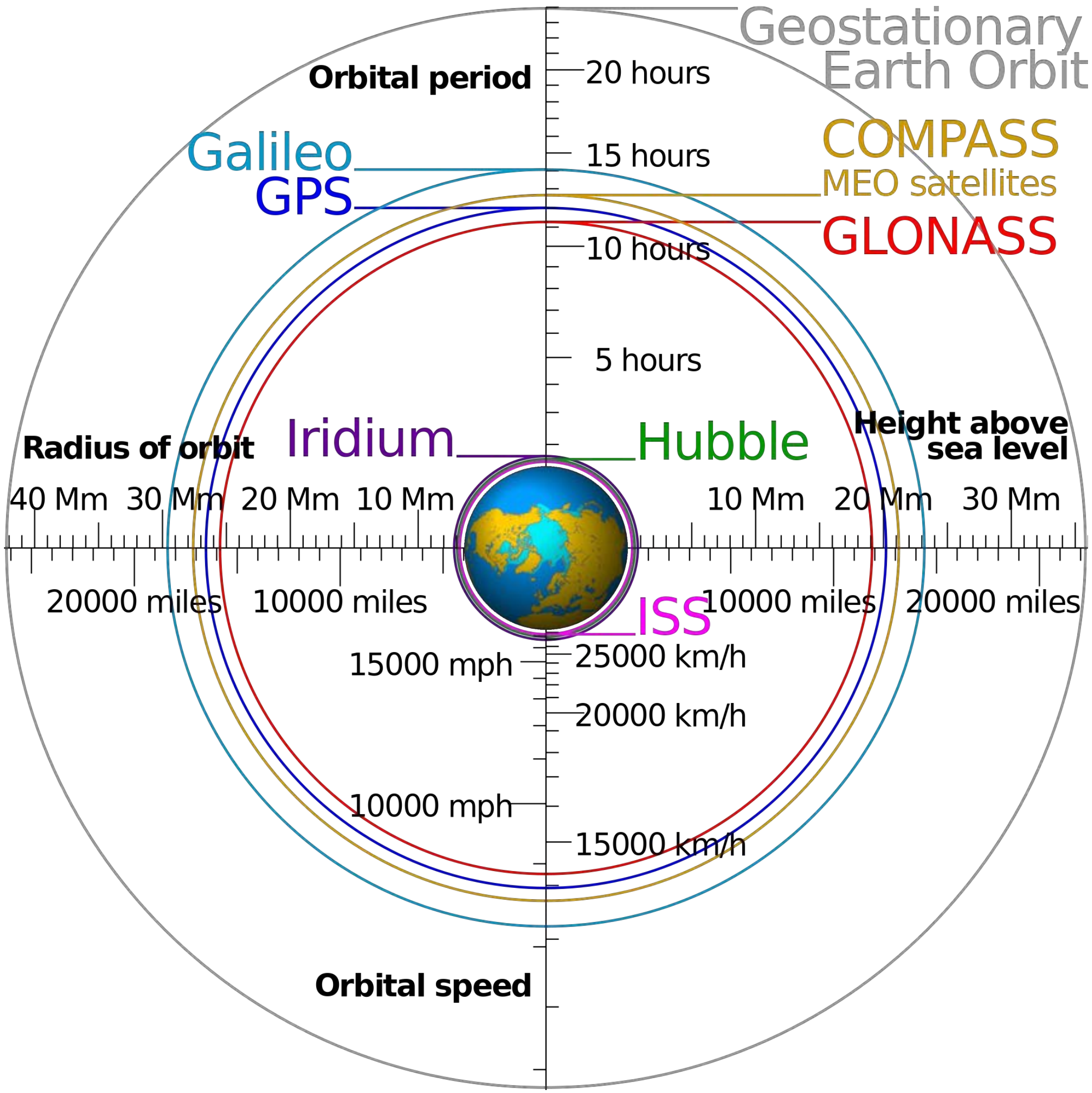
ORBIT NAME	ORBIT INITIALS	ORBIT ALTITUDE (KM ABOVE EARTH'S SURFACE)	DETAILS / COMMENTS
Low Earth Orbit	LEO	200 – 1200	
Medium Earth Orbit	MEO	1200 – 35790	
Geosynchronous Orbit	GSO	35790	Orbits once a day, but not necessarily in the same direction as the rotation of the Earth – not necessarily stationary
Geostationary Orbit	GEO	35790	Orbits once a day and moves in the same direction as the Earth and therefore appears stationary above the same point on the Earth's surface. Can only be above the Equator.
High Earth Orbit	HEO	Above 35790	

Orbits



Yellow: MEO
Green-dash-dotted line: GPS
Cyan: LEO
Red dotted line: ISS

Orbits

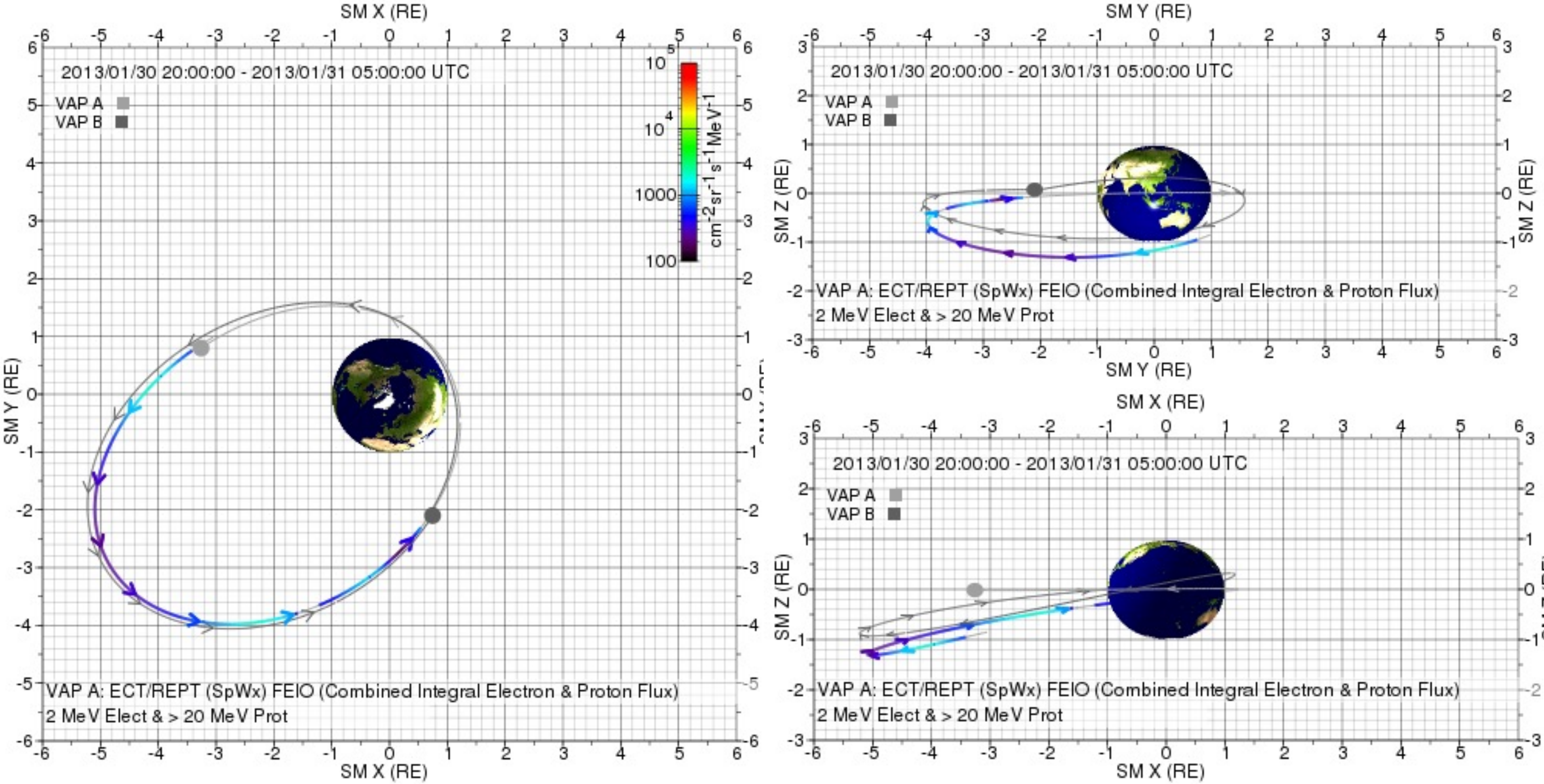


Different observing assets in near-Earth environment

Orbit Classification Based on Inclination

- **Inclined orbit**: An orbit whose inclination in reference to the equatorial plane is not zero degrees.
  - **Polar orbit**: An orbit that passes above or nearly above both poles of the planet on each revolution. Therefore it has an inclination of (or very close to) 90 degrees.
  - **Polar sun synchronous orbit**: A nearly polar orbit that passes the equator at the same local time on every pass. Useful for image taking satellites because shadows will be nearly the same on every pass.
    - DMSP satellites

Van Allen Probes



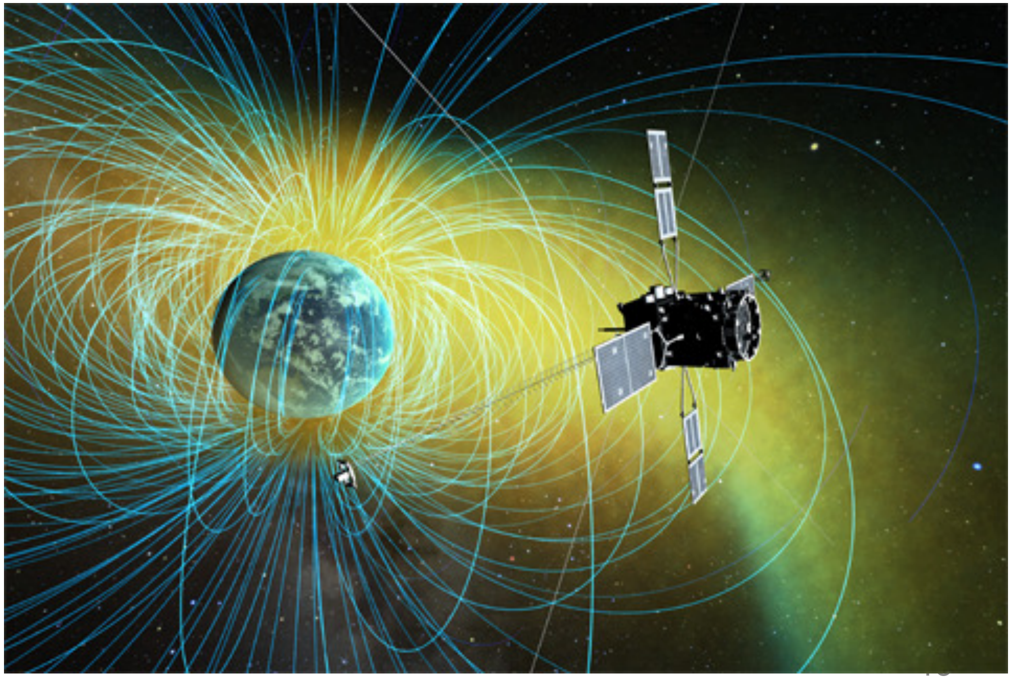
Two Spacecraft In an Elliptical Orbit

ERG/Arase

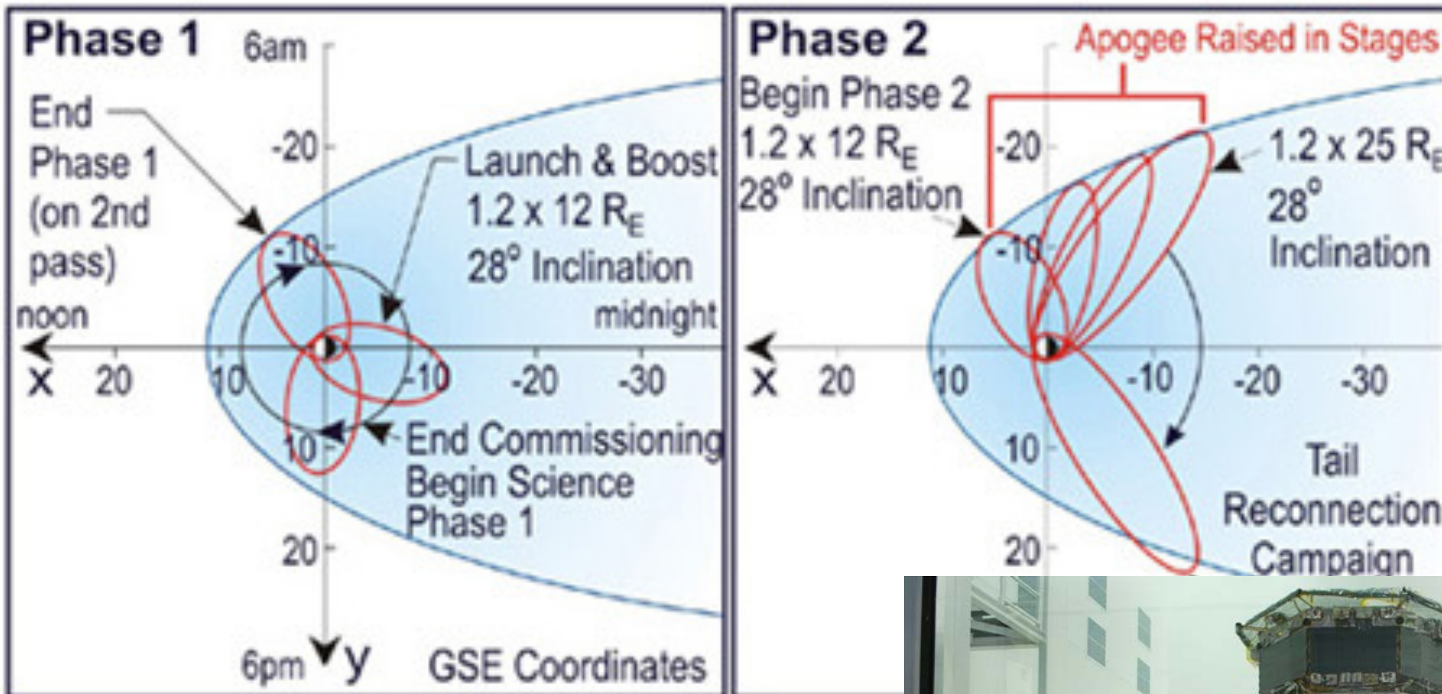
Energization and Radiation in Geospace (ERG)

Japanese satellite of exploring radiation belts
Launched on Dec 20, 2016

- Orbit info
  - Altitude
    - Perigee about 440 km, Apogee: about 32,000 km
  - Inclination
    - 32 degrees
  - Elliptical orbit
  - Period: 570 min



MMS (Magnetospheric Multiscale Mission)



Other Types of Orbits

Heliocentric Orbit: An orbit around the Sun.

STEREO A and STEREO B

Interplanetary space

At different planets (in reference to a planet)

Unit in terms of Rs (solar radii) or AU (Astronomical Unit)

Orbit/Mission Design

- New Horizon to Pluto

Closest approach to Pluto: 7:49:57 a.m. EDT (11:49:57 UTC) on July 14, 2015

http://www.jhu.edu/jhumag/1105web/pluto.html

Dr. Yanping Guo, a mission design specialist at APL

Reduced the journey by at least three years

For more information about New Horizon
http://www.nasa.gov/mission_pages/newhorizons/main/index.html

Space Weather and Spacecraft Operations

- The primary approach for the spacecraft industry to mitigate the effects of space weather is to design satellites to operate under extreme environmental conditions to the maximum extent possible within cost and resource constraints

  "Severe Space Weather Events--Understanding Societal and Economic Impacts Workshop Report," National Academies Press, Washington, DC, 2008 http://www.nap.edu/catalog/12507.html

- **This technique is rarely 100% successful and space weather will typically end up impacting some aspect of a space mission**
  - Some space weather issues are common to all spacecraft, e.g., space situational awareness is one example
  - Specific details of space weather interactions with a spacecraft are often unique because spacecraft systems are unique, there is no "standard" space weather support to mission operations
  - Miniaturization of space assets makes them more vulnerable

Space Weather impacts on spacecraft operation

Space Environment Model Use in Mission Life Cycle

Mission Concept
Mission Planning
Design
→ **Space Climatology** — Minimize Risk

Launch
Operations
→ **Space Weather** — Manage Residual Risk

Anomaly Resolution → **Both**

NASA Space Weather services

Models: big variety including assimilative ones

Courtesy: J. Barth (NASA/GSFC, ret.)

Effects of Space Weather on Technology Infrastructure, Proceedings of the NATO ARW on Effects of Space Weather on Technology Infrastructure, Rhodes, Greece, from 25 to 29 March 2003. Editors: Ioannis A. Daglis, Part of the book series: NATO Science Series II: Mathematics, Physics and Chemistry (NAII, volume 176), "Prevention of Spacecraft Anomalies — The Role of Space Climate and Space Weather Models," Janet L. Barth, Pages 123-145.

Space Climatology and Space Weather

- Space Climatology:
  - Variability over months to years
  - Space environment effects on both satellites and launch vehicles are best mitigated by good design
- Space Weather
  - Variability over minutes to days
  - Effects mitigated by design or operational controls
  - Design satellites to withstand mean, extreme space weather events that may occur during time on orbit

Space Environment & Effects (1)

Mechanism	Effect	Source
Total Ionizing Dose (TID)	• Degradation of microelectronics	• *Trapped protons* • *Trapped electrons* • *Solar protons*
Displacement Damage Dose (DDD)	• Degradation of optical components and some electronics • Degradation of solar cells	• *Trapped protons* • *Trapped electrons* • *Solar protons* • *Neutrons*
Single-Event Effects (SEE)	• Data corruption • Noise on images • System shutdowns • Electronic component damage	• *GCR heavy ions* • *Solar protons and heavy ions* • *Trapped protons* • *Neutrons*
Surface Erosion	• Degradation of thermal, electrical, optical properties • Degradation of structural integrity	• *Particle radiation* • *Ultraviolet* • *Atomic oxygen* • *Micrometeoroids* • *Contamination*

Adapted from a chart by J. Barth

Space Environment & Effects (2)

Mechanism	Effect	Source
Surface Charging	• Biasing of instrument readings • Power drains • Physical damage	• *Dense, cold plasma* • *Hot plasma (ring current, aurora population) (few eV to 10s keV)*
Deep Dielectric Charging	• Biasing of instrument readings • Electrical discharges causing • physical damage	• *High-energy electrons (>300 keV)*
Structure Impacts	• Structural damage • Decompression	• *Micrometeoroids* • *Orbital debris*
Satellite Drag	• Torques • Orbital decay	• *Neutral thermosphere*

Adapted from a chart by J. Barth

Space Environment & Effects

another way (a previous bootcamp participant)

Total Ionizing Dose (TID) — **Trapped protons, Trapped electrons, Solar protons**
- Degradation of microelectronics

Displacement Damage Dose (DDD) — **Trapped protons, Trapped electrons, Solar protons, Neutrons**
- Degradation of optical components and some electronics
- Degradation of solar cells

Single-Event Effects (SEE) — ***GCR heavy ions, Solar protons and heavy ions, Trapped protons, Neutrons***
- Data corruption
- Noise on images
- System shutdowns
- Electronic component damage

Surface Erosion — ***Particle radiation, Ultraviolet, Atomic oxygen, Micrometeoroids, Contamination***
- Degradation of thermal, electrical, optical properties
- Degradation of structural integrity

Surface Charging — **Dense, cold plasma, Hot plasma**
- Biasing of instrument readings
- Power drains
- Physical damage

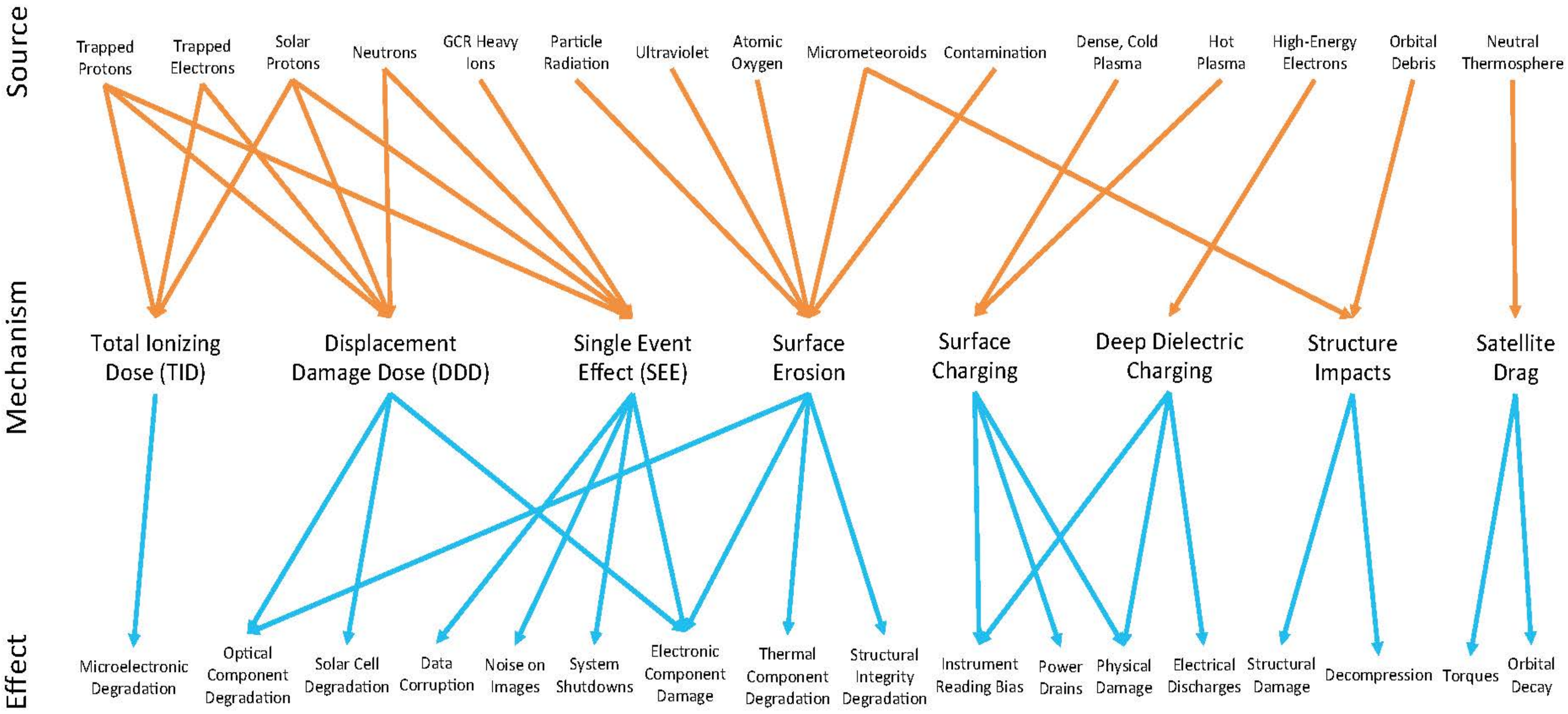
Deep Dielectric Charging — **High-energy electrons**
- Biasing of instrument readings
- Electrical discharges causing
- physical damage

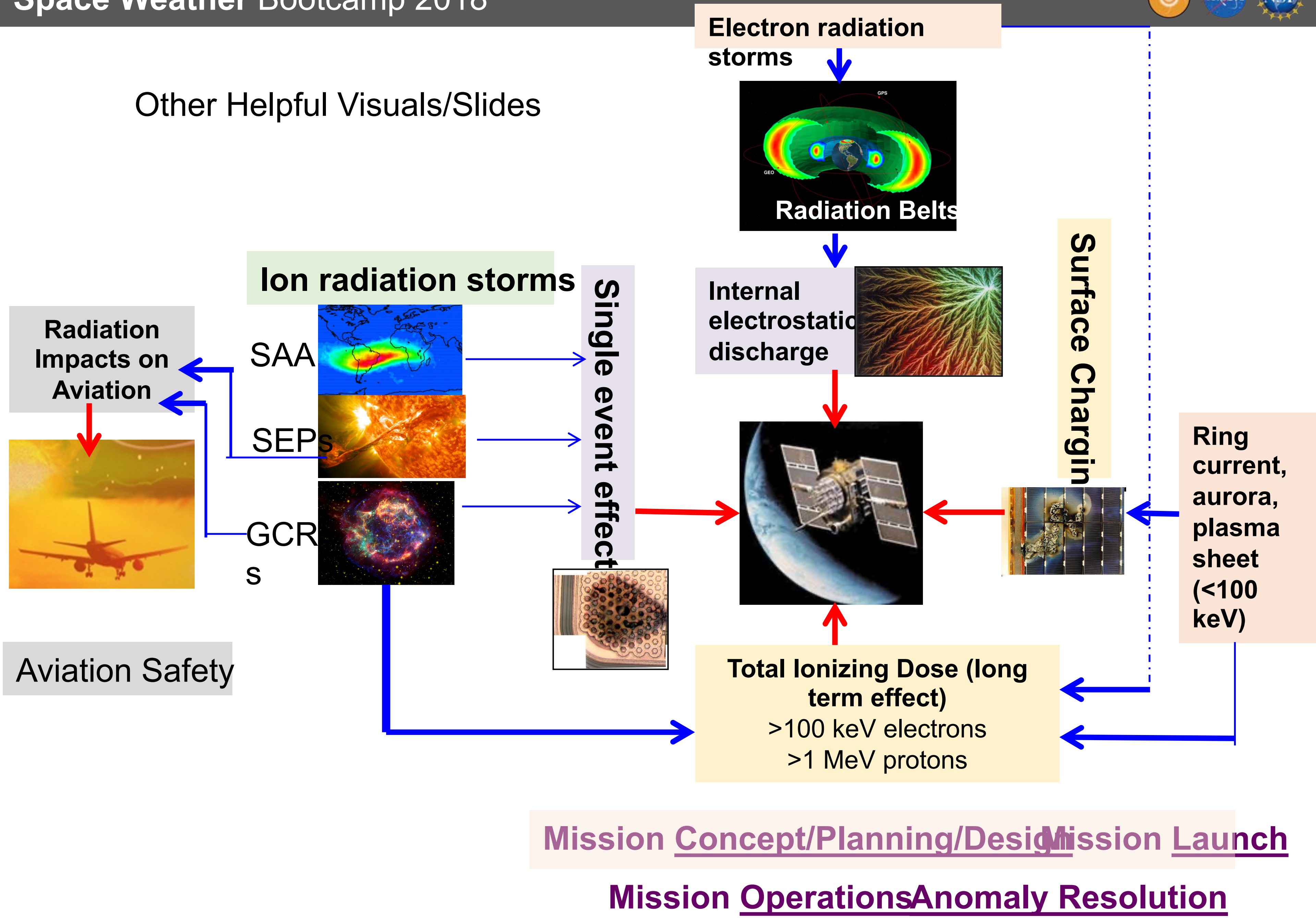
Structure Impacts — ***Micrometeoroids, Orbital debris***
- Structural damage
- Decompression

Satellite Drag — ***Neutral thermosphere***
- Torques
- Orbital decay

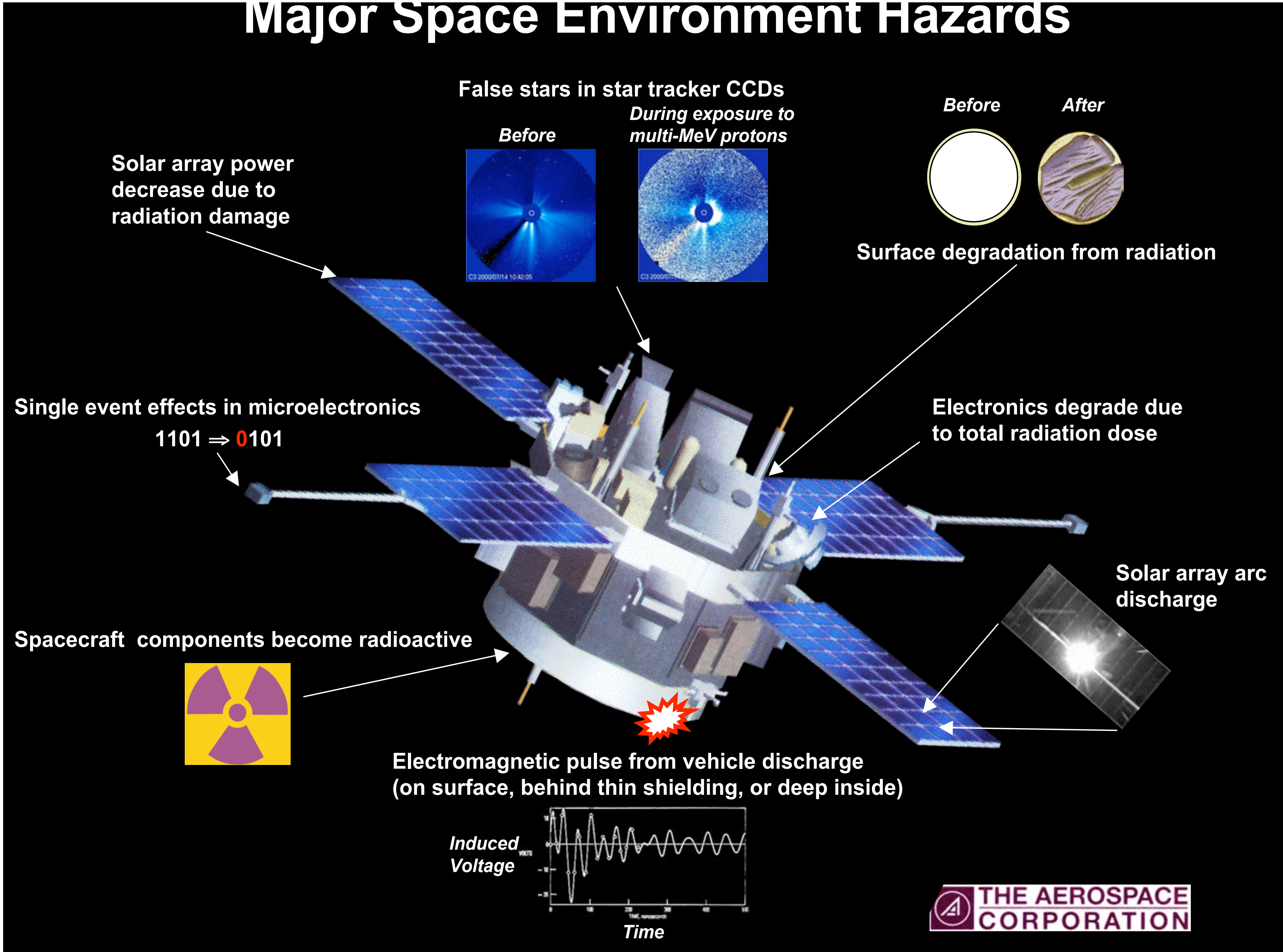
another way (Beryl Hovis-Afflerbach)

Space Environment & Effects




Other Helpful Visuals/Slides
Electron radiation storms
Radiation Belts
Internal electrostatic discharge
Surface Charging
Ring current, aurora, plasma sheet (<100 keV)
Ion radiation storms
Single event effect
SAA
SEPs
GCRs
Radiation Impacts on Aviation
Aviation Safety
Total Ionizing Dose (long term effect)
>100 keV electrons
>1 MeV protons
Mission Concept/Planning/Design
Mission Launch
Mission Operations
Anomaly Resolution

Visual Representation of Space Environment Hazards



Space Environment Effects/Anomalies

Space Environmental Impacts on Space Systems			
Anomaly Diagnosis	Koons et al, 2000	NGDC DB, 2006	Satellite Digest, 2014
ESD-Internal, surface, and indeterminate	54%	31%	10%
SEU (GCR, SPE, SAA, etc.)	28%	17%	5%
Radiation Dose	5%	---	---
Meteoroids and Orbital Debris	3%	---	5%
Atomic Oxygen	< 1%	---	---
Atmospheric Drag	< 1%	---	---
Design	---	---	25%
Other or Unknown	8%	52%	55%

McKnight 2015

Space Environment Impacts/Anomalies

- According to a study by the Aerospace Corporation the 2 most common types of spacecraft anomalies by far are due to electrostatic discharge (ESD) and single event effects (SEE)
- Reported results*:

Anomaly Type:	Number of Occurrences:
ESD	162
SEE	85
Total Dose and Damage	16
Miscellaneous	36

* H.C. Koons et al., 6th Spacecraft Technology Conference, AFRL-VS-TR-20001578, Sept. 2000

A few types of space weather impacts on spacecraft

Surface Charging (1)

Surface charging: which can lead to electrostatic discharges (ESD)

ESD: can lead to a variety of problems, including component failure and phantom commands in spacecraft electronics [Purvis et al., 1984].

Purvis, C. K., H. B. Garrett, A. C. Wittlesey, and N. J. Stevens (1984), Design guidelines for assessing and controlling spacecraft charging effects, NASA Tech. Pap. 2361

https://standards.nasa.gov/documents/detail/3314877

Surface Charging (2)

Substorm injections (Aurora)

Commercial satellite anomaly

More often in the midnight to morning sector

<100 keV e- distribution: similar behavior as spacecraft anomalies

=> Surface charging might be the main cause of the anomalies.

Choi, H.-S., J. Lee, K.-S. Cho, Y.-S. Kwak, I.-H. Cho, Y.-D. Park, Y.-H. Kim, D. N. Baker, G. D. Reeves, and D.-K. Lee (2011), Analysis of GEO spacecraft anomalies: Space weather relationships, Space Weather, 9, S06001,doi:10.1029/2010SW000597.

Surface Charging Hazards Distribution

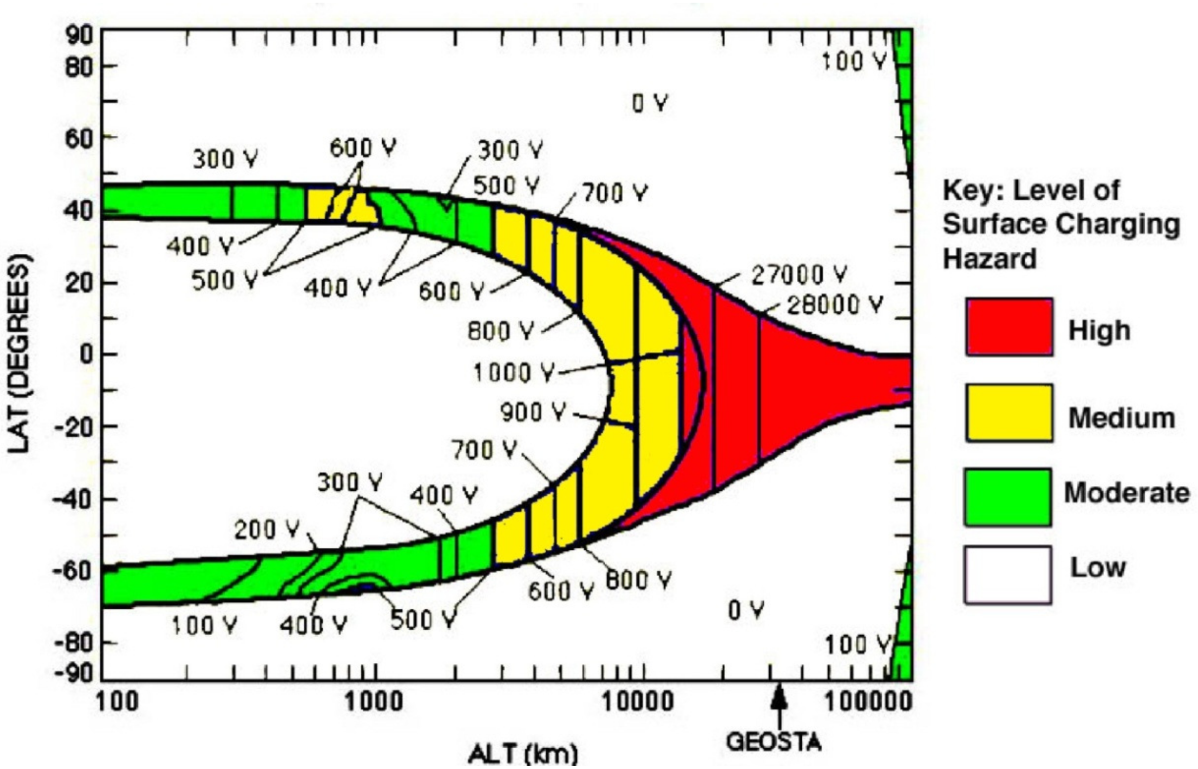


Figure 1—Earth Regimes of Concern for On-Orbit Surface Charging Hazards for Spacecraft Passing Through Indicated Latitude and Altitude (Evans and others (1989))

NASA Document on Mitigating Charging Effects

Title: Mitigating In-Space Charging Effects-A Guideline

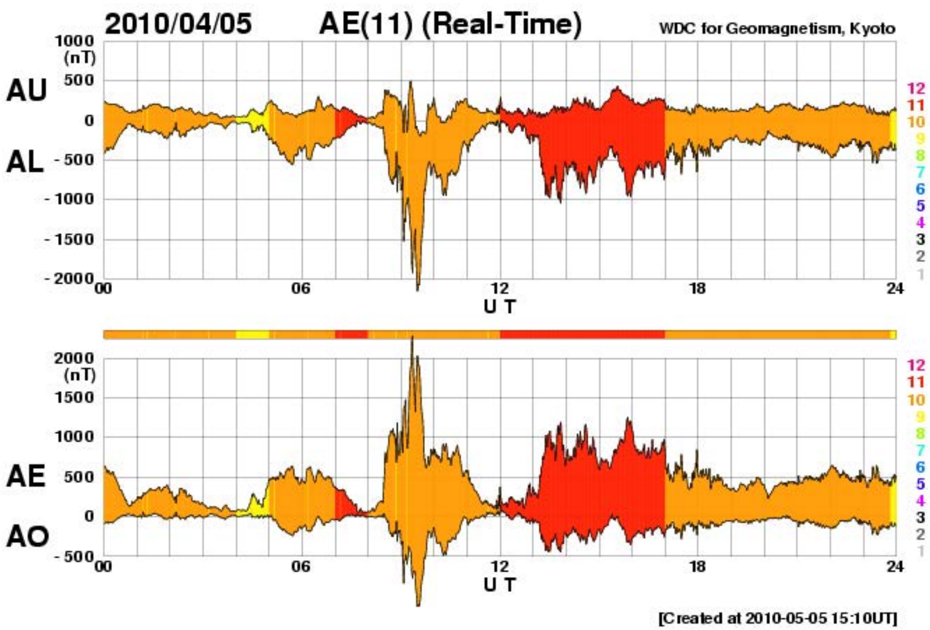
Document Date: 2011-03-03

Revalid and Reaffirmed Date: 2016-03-03

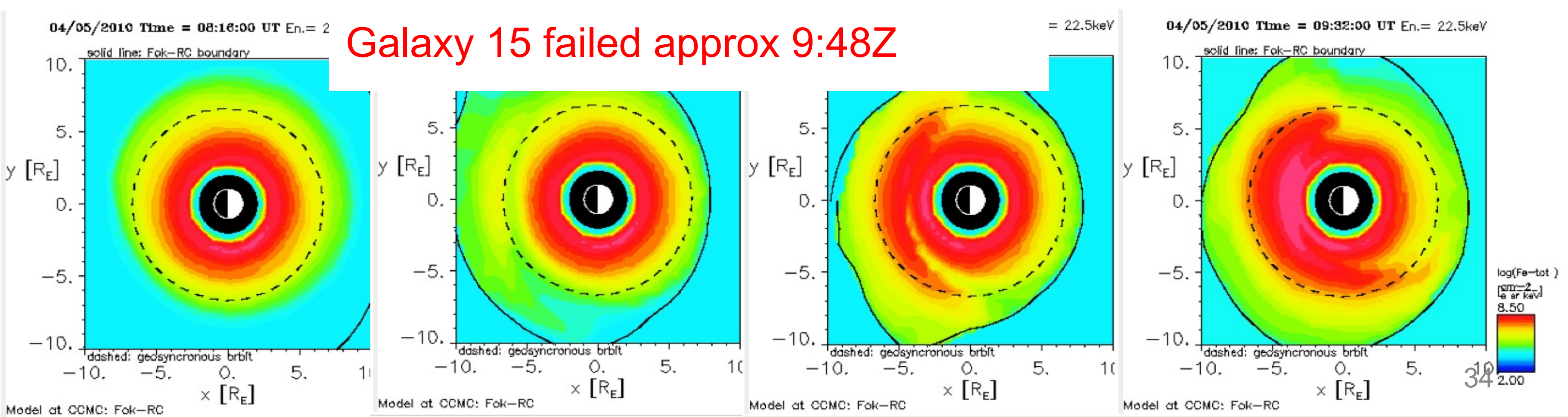
Revision: A

Organization: NASA

Surface Charging?!: Galaxy 15 failure on April 5, 2010



22keV electrons 4/5, 8:16-9:32Z

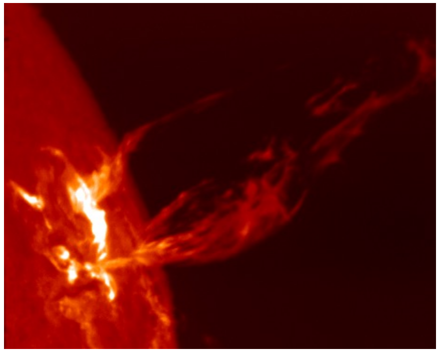


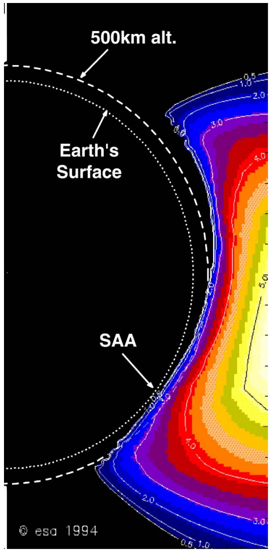
Single Event Effects: Source in Space

High Energy Particle Radiation

- Galactic Cosmic Rays
- Solar Particle Events (flare/CME)
- Trapped Particles (SAA)

High energy neutrons





Most unpredictable

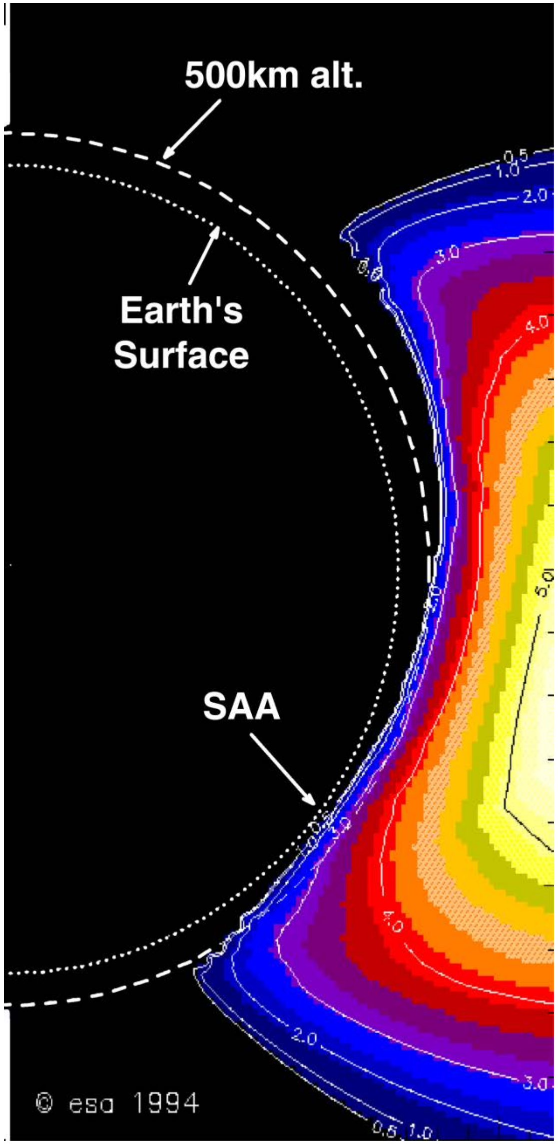
Galactic Cosmic Rays

- Galactic cosmic rays (GCR) are high-energy charged particles that originate outside our solar system.
- Supernova explosions are a significant source

Anticorrelation with solar activity
More pronounced/intense during solar minimum

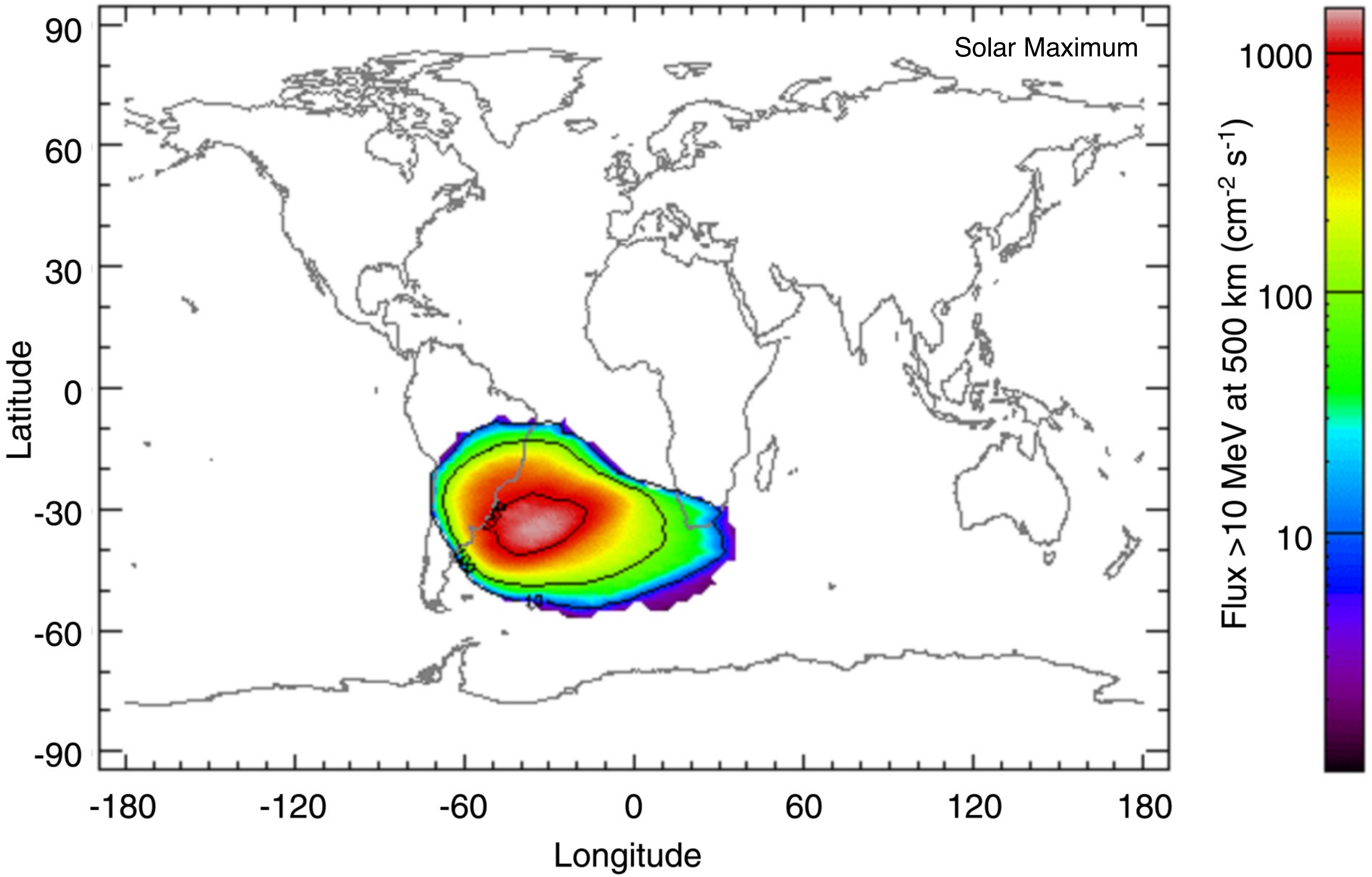
South Atlantic Anomaly

- Dominates the radiation environment for altitudes less than about 1000 km.
- Caused by tilt and shift of geomagnetic axis relative to rotational axis.
- Inner edge of proton belt is at lower altitudes south and east of Brazil.



E.J. Daly et al., IEEE TNS, April 1996

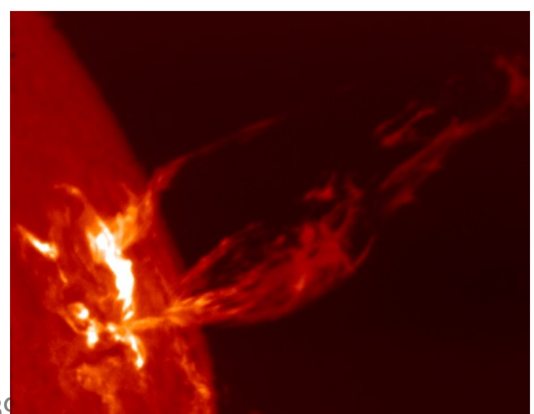
South Atlantic Anomaly

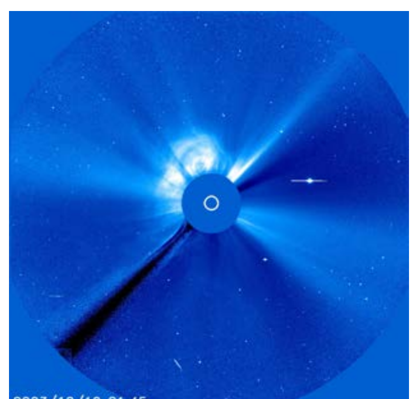


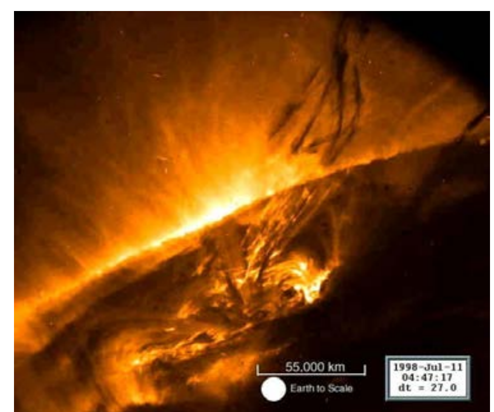
From SPENVIS, http://www.spenvis.oma.be/

Characteristics of SEPs

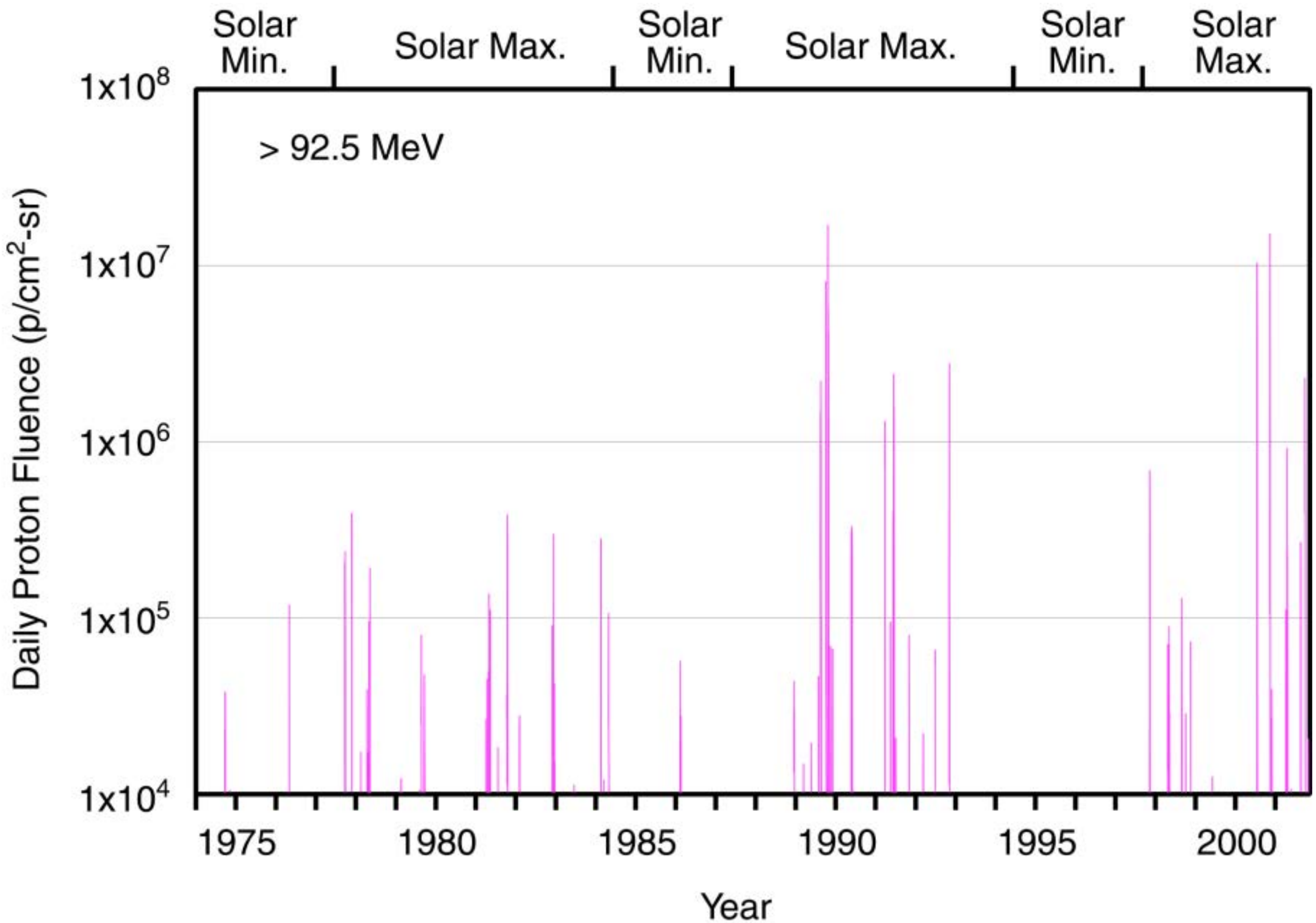
- Elemental composition* (may vary event by event)
  - 96.4% protons
  - 3.5% alpha particles
  - 0.1% heavier ions (not to be neglected!)
- Energies: up to ~ GeV/nucleon
- Event magnitudes:
  - > 10 MeV/nucleon integral fluence: can exceed 10^9 cm^{-2}
  - > 10 MeV/nucleon peak flux: can exceed 10^5 $cm^{-2}s^{-1}$







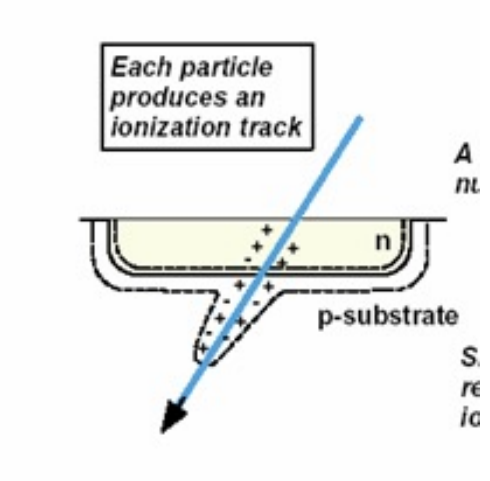
Solar Cycle Dependence

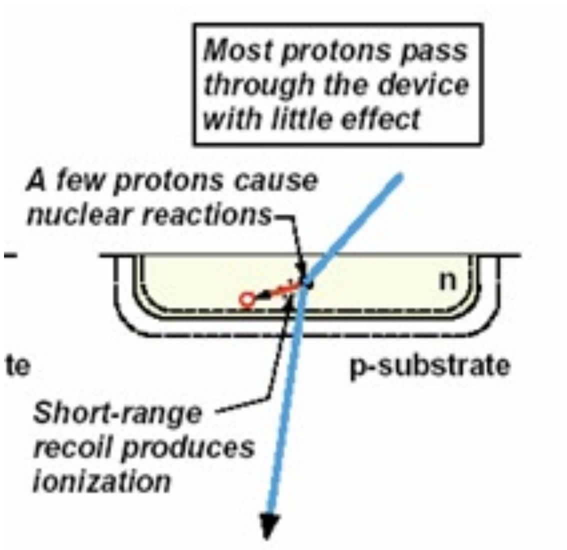


Most unpredictable

Single Event Effects (SEE)

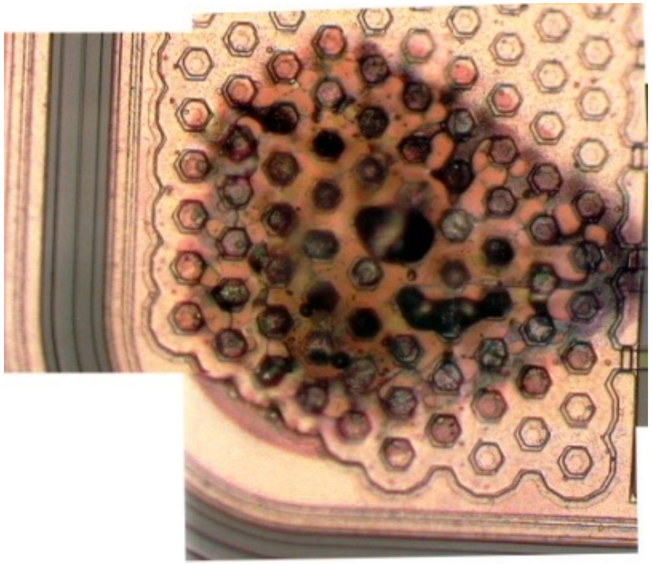
- **Single event effect (SEE) :** current generated by ion passing through the sensitive volume of a biased electronic device changes the device operating state
- **SEE Generated by Heavy Ions (Z=2-92)**
- High linear energy transfer (LET) rate of heavy ions produces ionization along track as ion slows down
- Dense ionization track over a short range produces sufficient charge in sensitive volume to cause SEE
- SEE is caused directly by ionization produced by incident heavy ion particles
- **SEE Generated by Protons (Z=1)**
- Proton LET is too low to generate SEE, but secondary heavy ions are produced in nuclear reactions with nuclei of atoms (usually silicon) inside electronics. Energy is transferred to a target atom fragment or recoil ion with high LET and charge deposited by recoil ion(s) is the direct cause of SEE.
- Only a small fraction of protons are converted to such secondary particles (1 in 10^4 to 10^5).





What is a Single Event Effect?

- Single Event Effect (SEE) – any measureable effect in a circuit caused by single incident ion
  - Non-destructive – SEU (Single Event Upset), SET (single event transients), MBU (Multiple Bit Upsets), SHE (single-event hard error)
  - Destructive – SEL (single event latchup), SEGR (single event gate rupture), SEB (single event burnout)



Destructive event in a COTS 120V DC-DC Converter

Single Event Upsets

- SEUs: are soft errors, and non-destructive. They normally appear as transient pulses in logic or support circuitry, or as bitflips in memory cells or registers.

Destructive SEEs

- Several types of hard errors, potentially destructive, can appear:
- Single Event Latchup (SEL) results in a high operating current, above device specifications, and must be cleared by a power reset.
- Other hard errors include Burnout of power MOSFETS (Metal Oxide Semiconductor Field-Effect Transistor) , Gate Rupture, frozen bits, and noise in CCD (Charge-Coupled Device)s.

Note: anomalies during the March 2012 SWx events: SEEs dominate

Quite a few NASA spacecraft experienced anomalies, majority of which are SEEs. Some of them required reset/reboot.

Internal Charging

- energetic electrons in the outer radiation belt

CIR HSS geomagnetic storm
CME geomagnetic storms

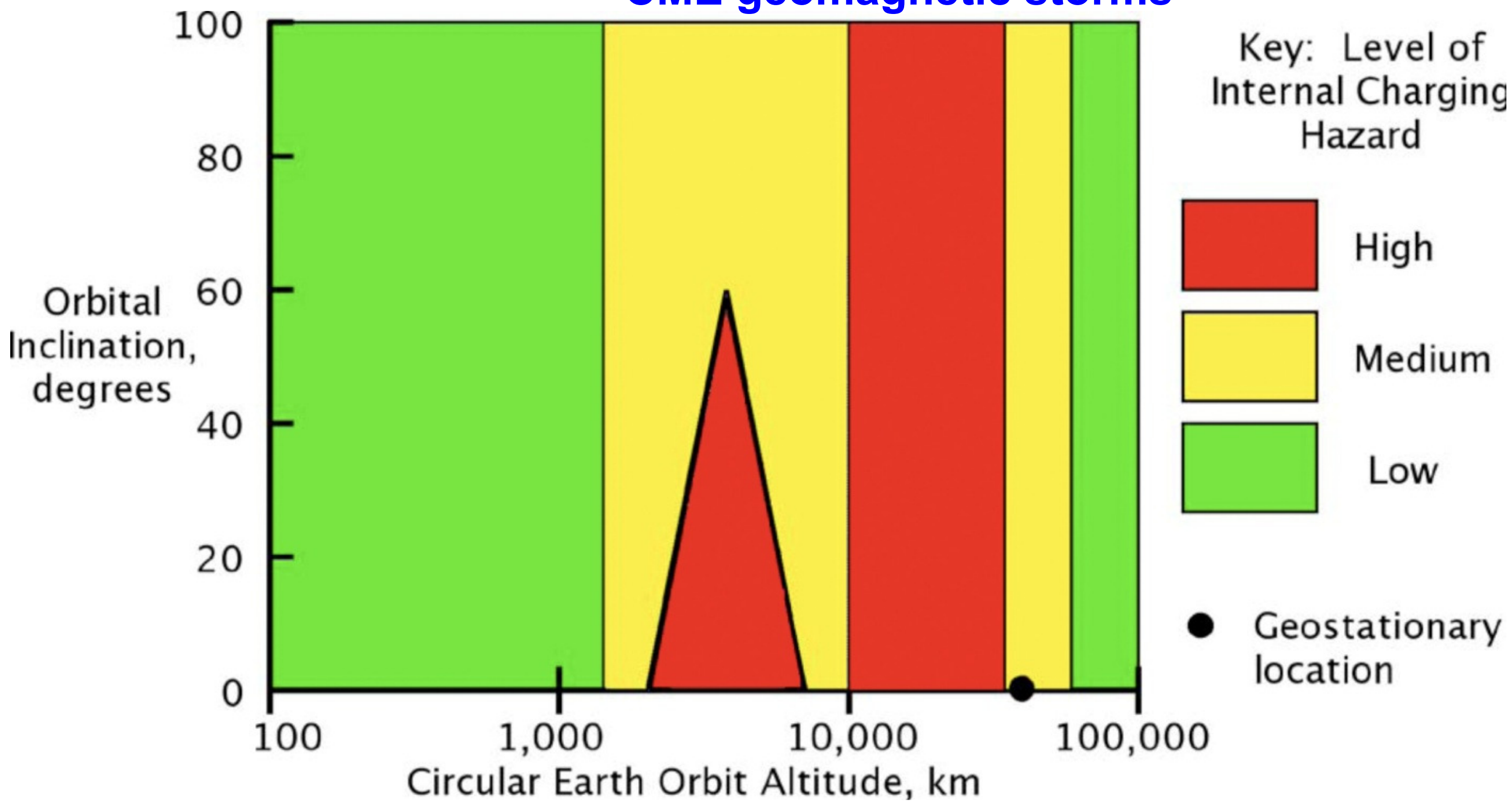
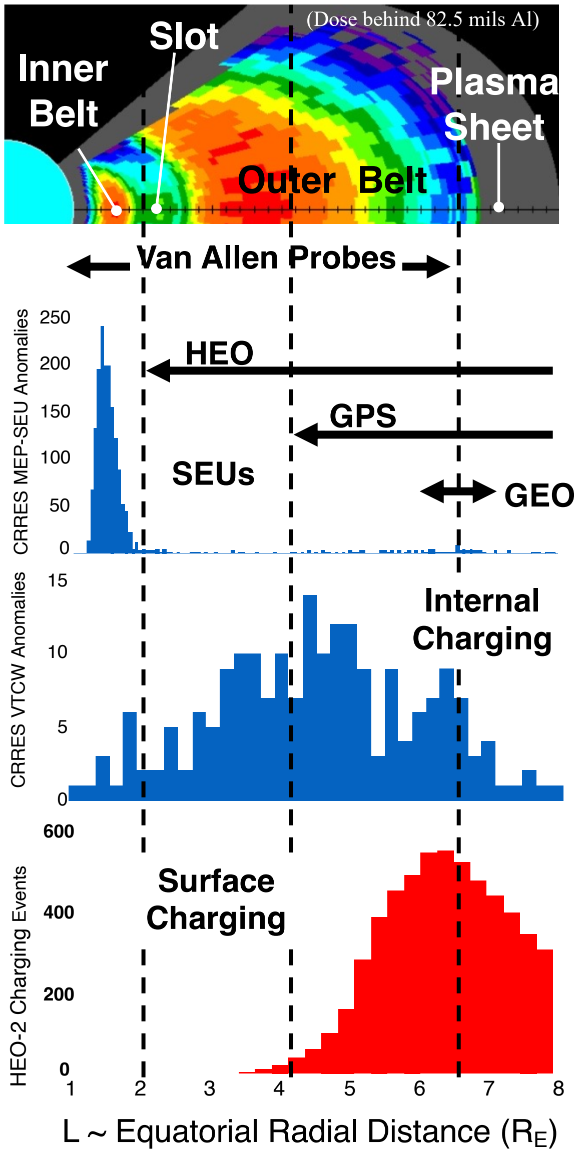


Figure 2—Earth Regimes of Concern for On-Orbit Internal Charging Hazards for Spacecraft with Circular Orbits

Space Environment Hazards (different types of charging) for Spacecraft in the near-Earth environment



Courtesy: Paul O'Brien

- **Single Event Effects tend to occur in the inner (proton) belt and at higher L shells when a solar particle event is in progress.**

- **Internal electrostatic discharges (ESD) occur over a broad range of L values corresponding to the outer belt, where penetrating electron fluxes are high (300 keV – few MeV electrons)**

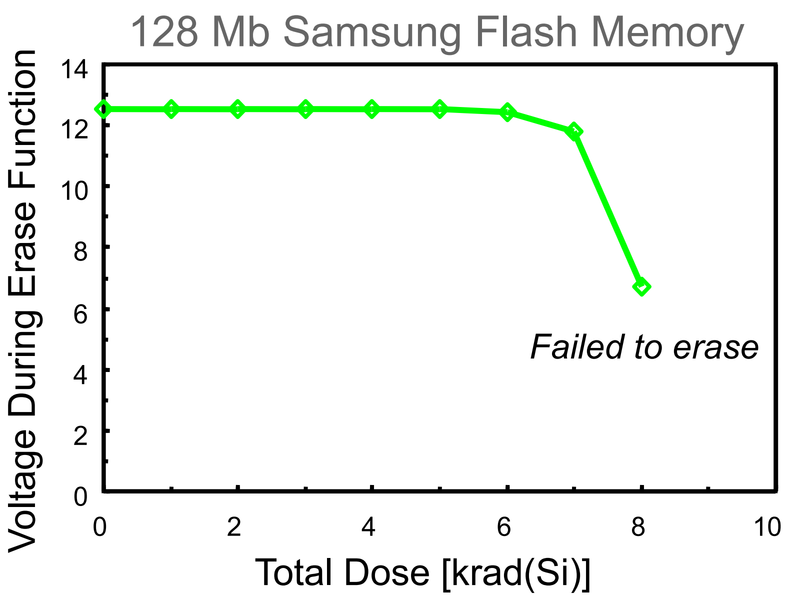
- **Surface ESD tends to occur when the spacecraft or surface potential is elevated: at 2000-0800 local time in the plasma sheet and in regions of intense field-aligned currents (auroral zone) (few eV – 50 keV) - plasma sheet, ring current, aurora zone, magnetosheath**

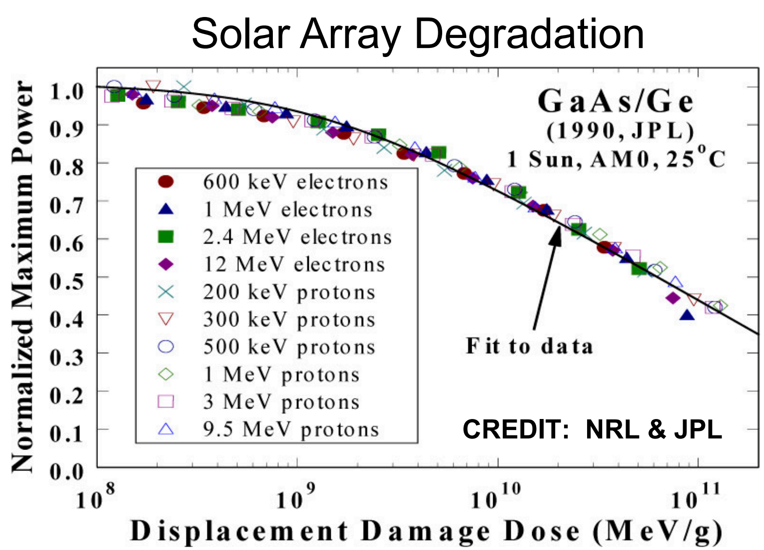
- **Event Total Dose occurs primarily in orbits that rarely see trapped protons in the 1-20 MeV range (e.g., GEO, GPS) because these are the orbits for which solar particle events and transient belts make up a majority of the proton dose (including displacement damage)**

Total Dose Effects

- Total Ionizing Dose (TID) – cumulative damage resulting from ionization (electron-hole pair formation) causing
  - Threshold voltage shifts
  - Timing skews
  - Leakage currents
- Displacement Damage Dose (DDD) – cumulative damage resulting from displacement of atoms in semiconductor lattice structure causing:
  - Carrier lifetime shortening
  - Mobility degradation

DDD can also be referred to in the context of Non-Ionizing Energy Loss (NIEL)





Messenger, S. R., Summers, G. P., Burke, E. A., Walters, R. J. and Xapsos, M. A. (2001), Modeling solar cell degradation in space: A comparison of the NRL displacement damage dose and the JPL equivalent fluence approaches. Prog. Photovolt: Res. Appl., 9: 103–121. doi: 10.1002/pip.357

Human Safety in Space

- GCR
- **SEP**

Johnson Space Center/Space Radiation Analysis Group (SRAG)

Limit: the > 100 MeV flux exceeding 1pfu

(1 pfu = 1 particle flux unit= 1/cm^2/sec/sr)

- All clear (EVA –extravehicular activity)