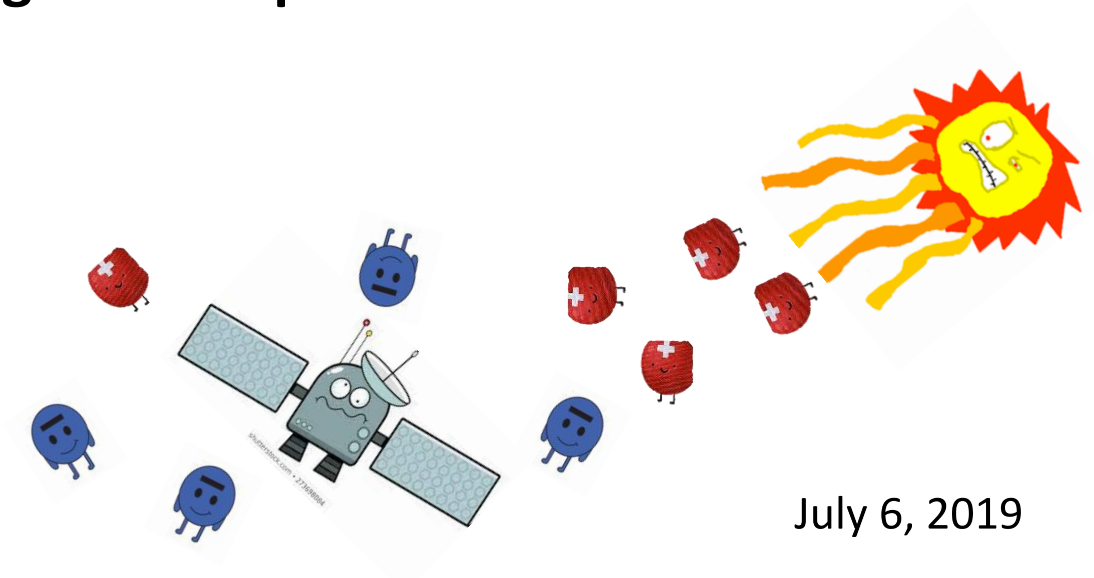
Space Weather Impacts on Space Assets

Francisco Iglesias

Yihua Zheng and **Joseph Minow**

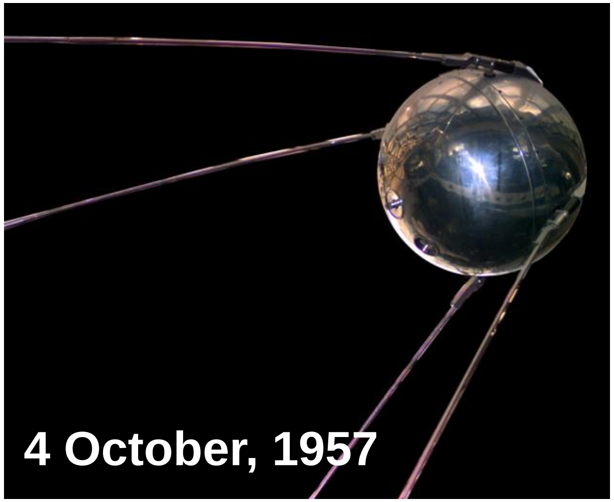


July 6, 2019

Outline:

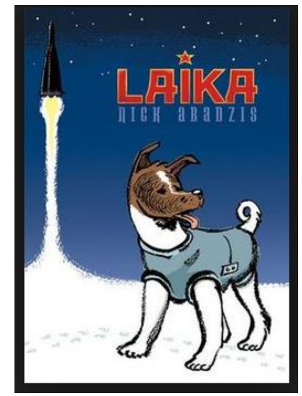
- Description of man-made satellites and orbits
- Space weather effects on spacecrafts
  - Mechanisms (focus on the 2 most important)
  - Sources
  - Impacts on space missions
  - Mitigation techniques
  - Examples

Artificial satellites



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

Laika (Sputnik 2)



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

1st U.S. Satellites:

- **Explorer 1** and 3 discovered the Van Allen inner radiation belt.
- **Explorer 4** and **Pioneer 3** discovered the outer belt (late 1958).

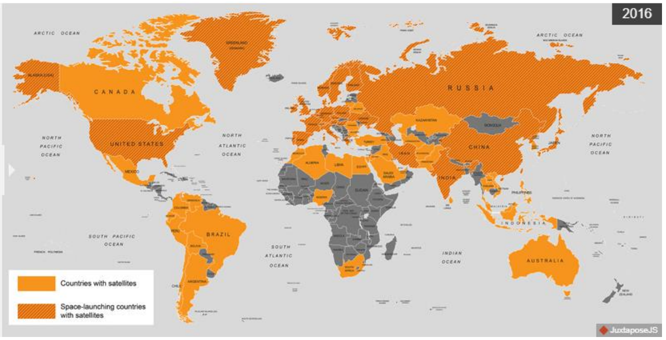
These events mark the start of the Space Age

Artificial satellites

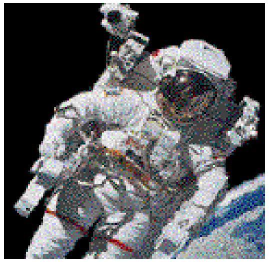
Since the 60's the importance & our reliance on space systems has dramatically increased.

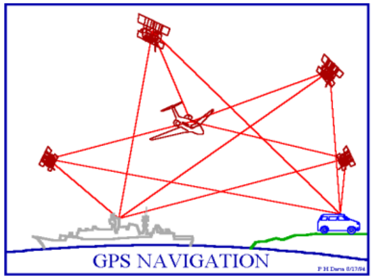
More than **8000 satellites** have been launched (2000 active right now) with diverse proposes:

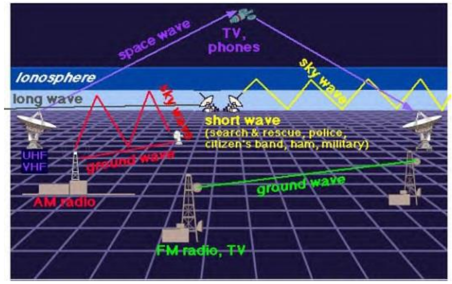
- Scientific Research
- Navigation
- Communications
- Defense
- Space environment monitoring
- Terrestrial weather monitoring

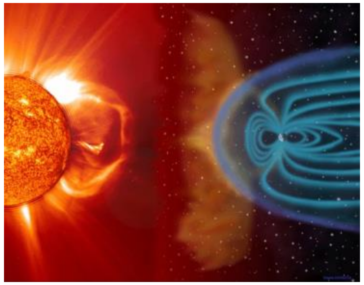


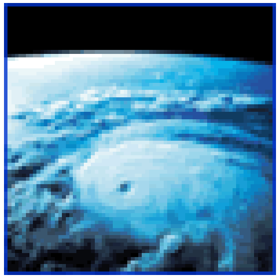
https://www.ucsusa.org/nuclear-weapons/space-weapons/satellite-database



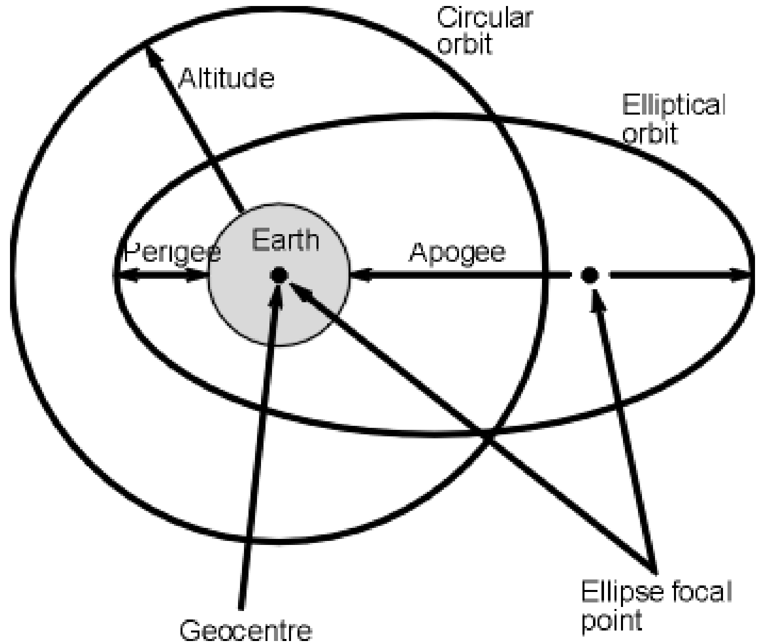








Orbits (shape)



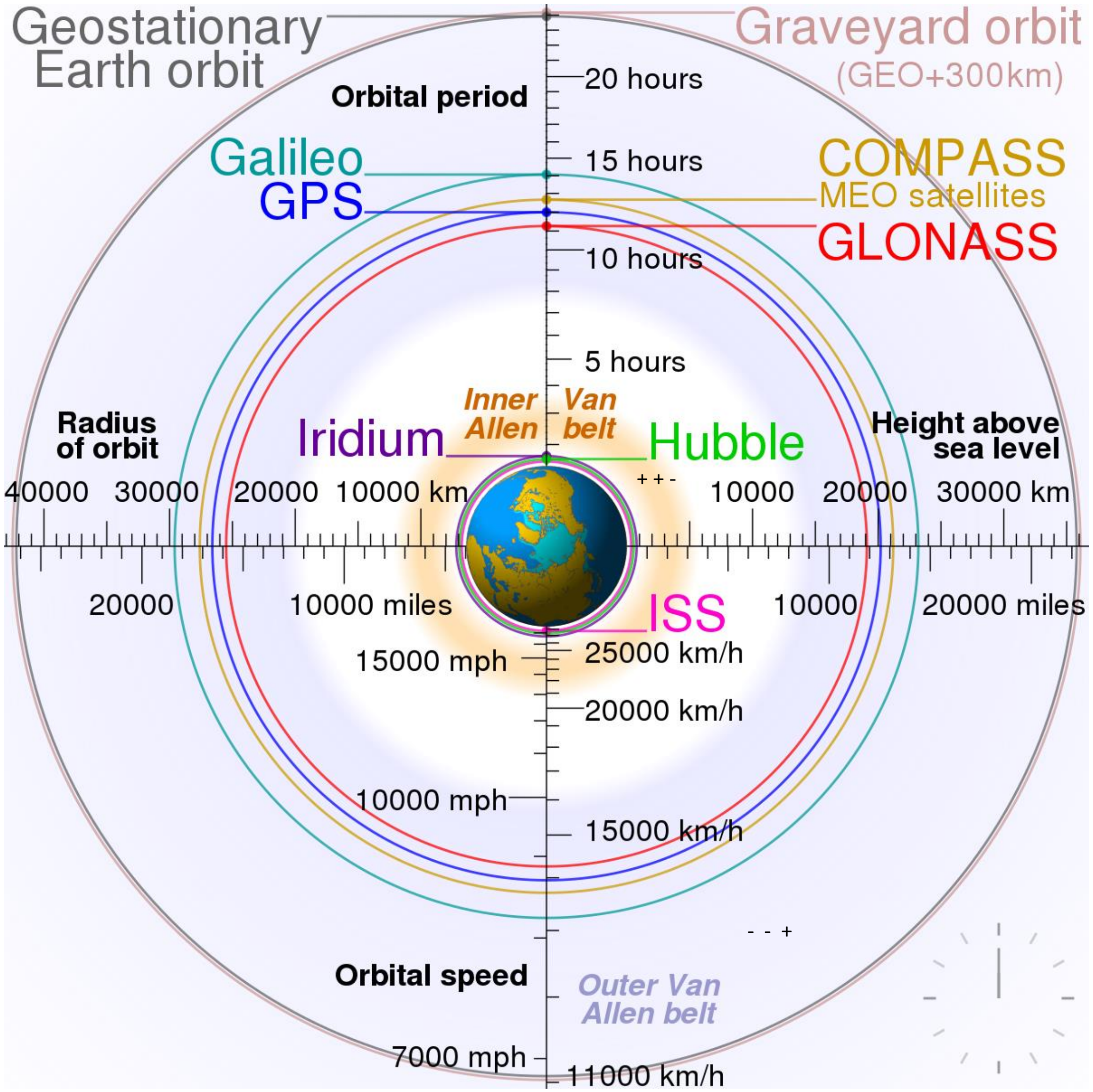
Orbits (inclination)

- **Equatorial orbit:** In the equatorial plane.
- **Inclined orbit**: An orbit whose inclination in reference to the equatorial plane is not zero degrees: **Polar orbit** with inclination ~90 deg.

Orbits (height)

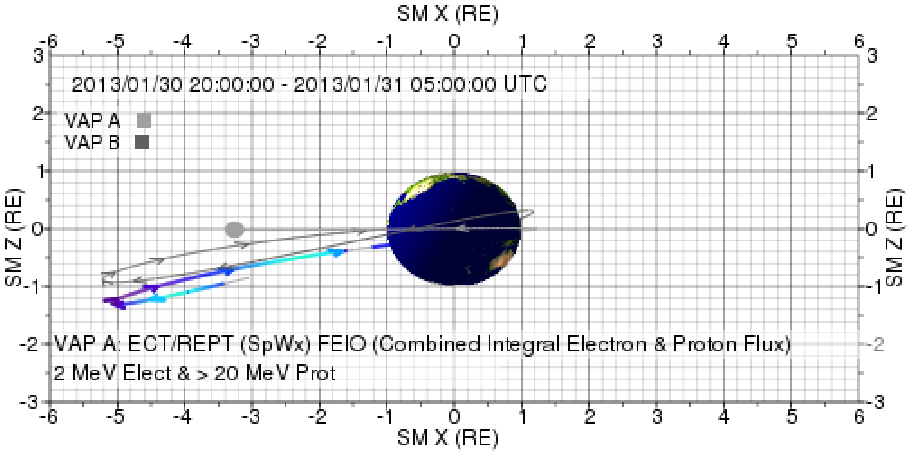
ORBIT NAME	ORBIT INITIALS	ORBIT ALTITUDE (KM ABOVE EARTH'S SURFACE)	DETAILS / COMMENTS
Low Earth Orbit	LEO	200 – 1200	
Medium Earth Orbit	MEO	1200 – 35790	
Geosynchronous Orbit	GSO	35790	Orbits once a day, but not necessarily in the same direction as the rotation of the Earth – not necessarily stationary
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	

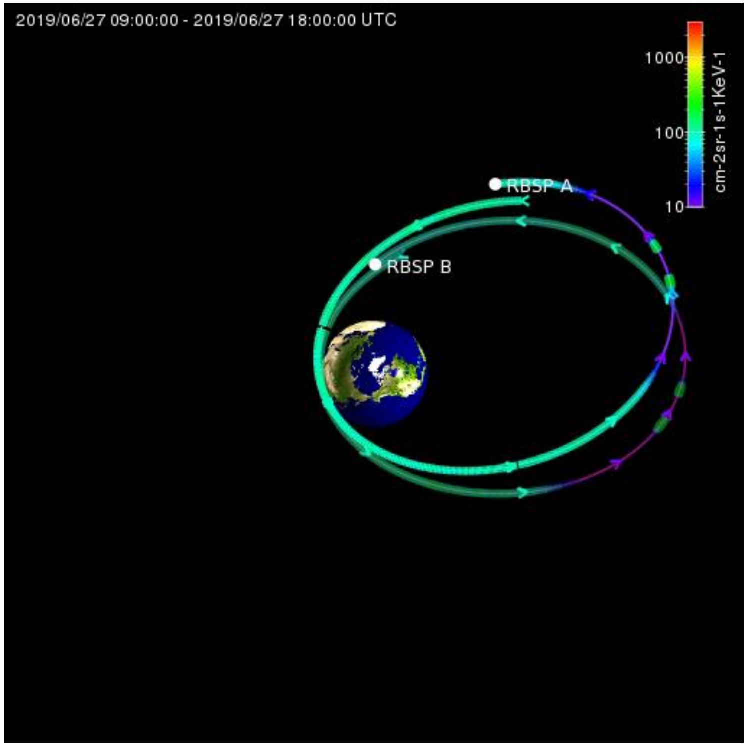
Orbits (parameters)

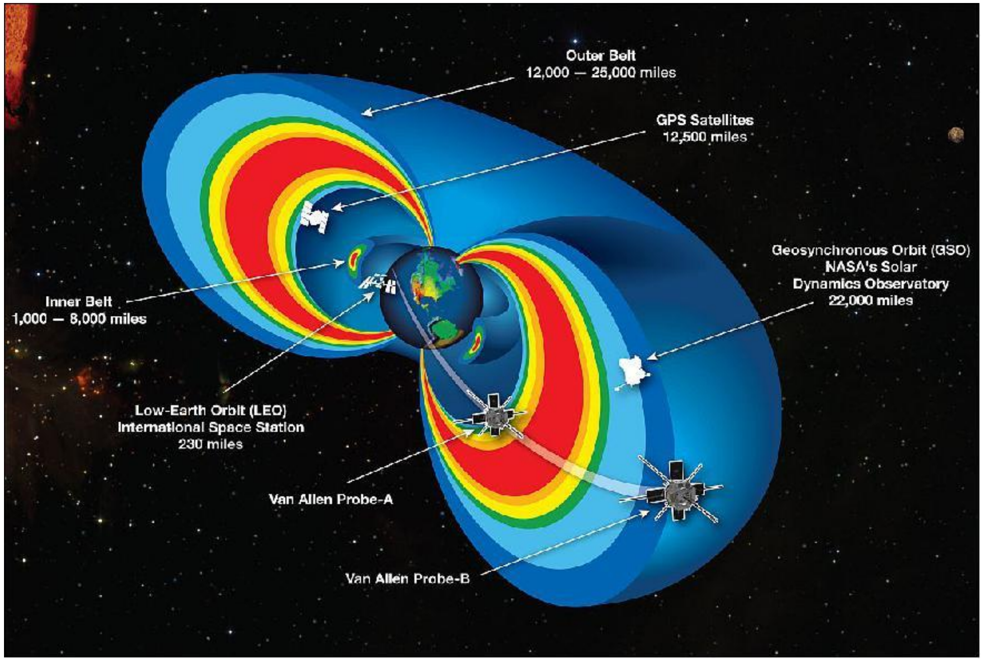


Orbits (examples)

Van Allen Probes (2012): Two spacecraft in an inclined elliptical Orbit (LEO to GEO)



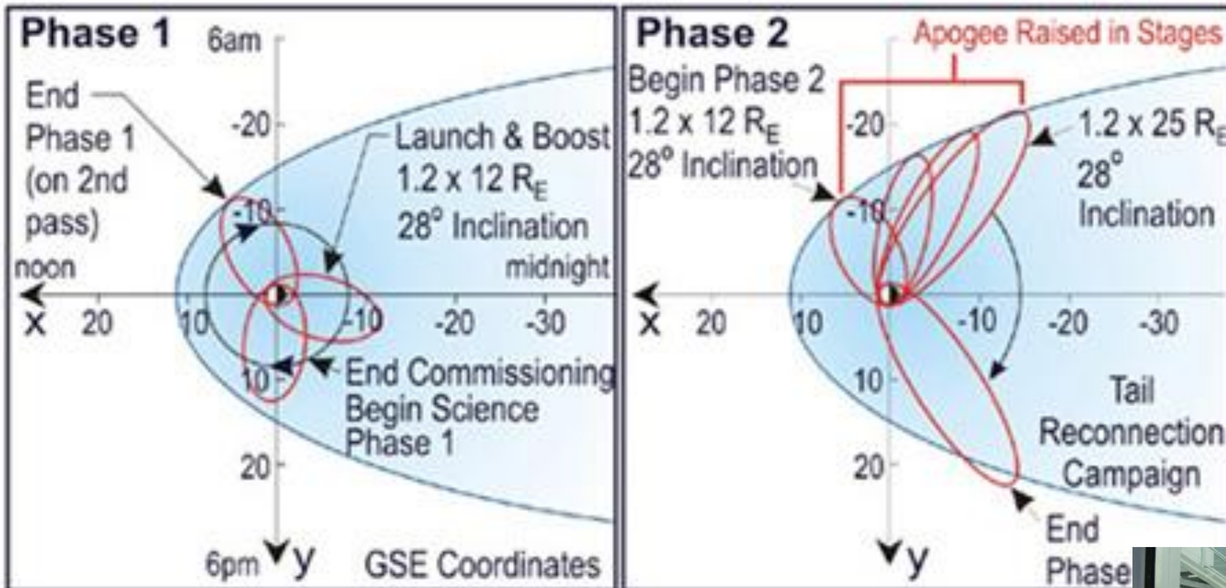


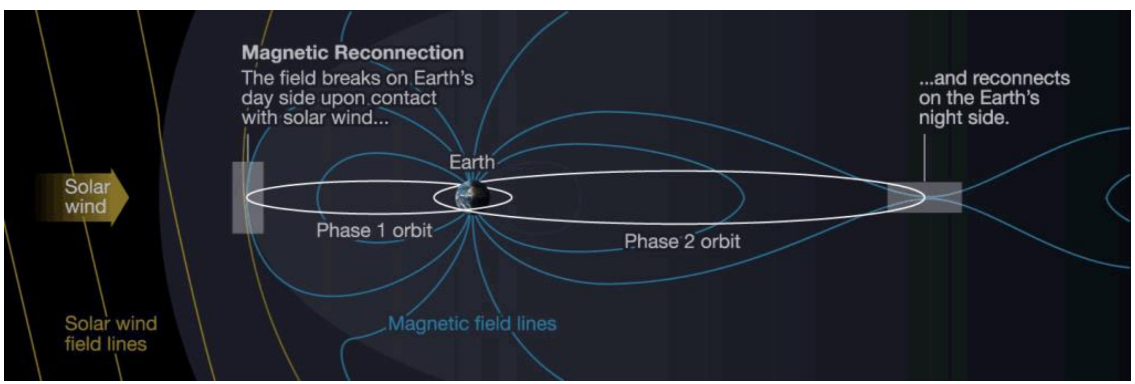


NASA

Orbits (examples)

MMS (Magnetospheric Multiscale Mission, 2015): Changing elliptical, inclined orbit.





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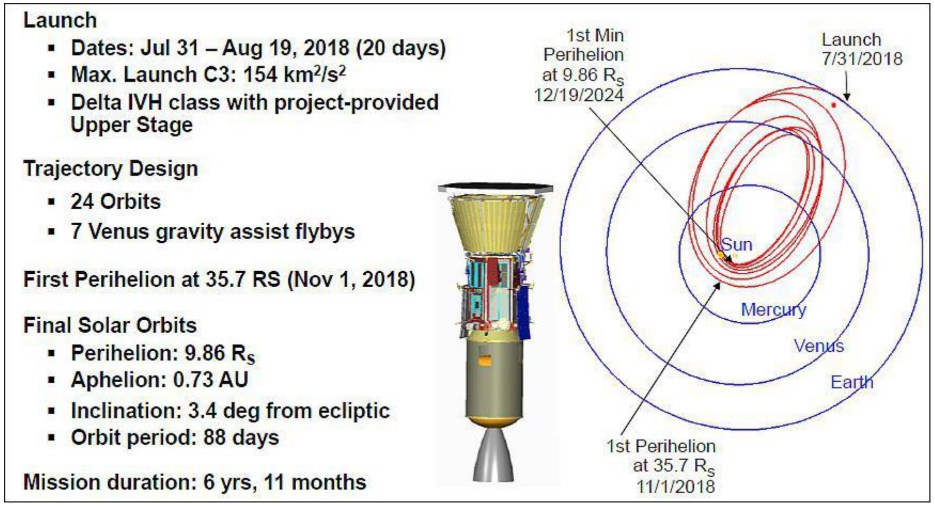
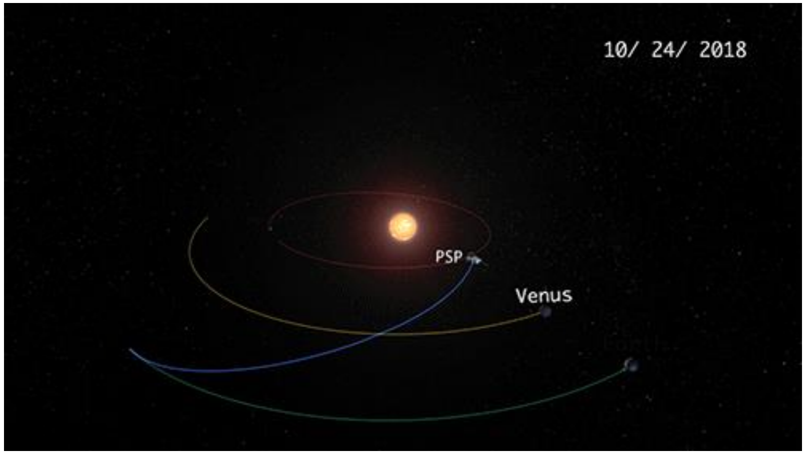
Orbits (other types)

- **Interplanetary Orbits:** At different planets (planetary magnetospheres)
- **Heliocentric Orbit**: An orbit around the Sun (out of the Earth magnetosphere!)

Parker Solar Probe (2018): Elliptical, low inclination and short perihelion





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Space environment

- Space Climatology:
  - Variability over months to years (slow)
  - Space environment effects on both satellites and launch vehicles are best mitigated by good design

- Space Weather
  - Variability over minutes to days (fast)
  - Design satellites to withstand mean and also extreme space weather events that may occur **during time on orbit**
  - But also mitigate effects by preventive **operational maneuvers**

✓ Specific details of space weather effects are often unique because spacecraft systems are unique, **there is no "standard" space weather support to mission operations (problem solving).**

Space Environment and Mission Life Cycle

Mission Concept

Mission Planning

Design

Space Climatology
Minimize Risk

Launch

Operations

Space Weather
Manage Residual Risk

NASA Space Weather services (e.g. CCMC)

Anomaly Resolution → **Both**

Space Environment Effects (Types and sources)

Mechanism	Effect	Source
Surface Charging	• Biasing of instrument readings • Power drains • Physical damage	• *Dense, cold plasma* • *Hot plasma*
Deep Dielectric Charging	• Biasing of instrument readings • Electrical discharges causing physical damage	• *High-energy electrons*
Structure Impacts	• Structural damage • Decompression	• *Micrometeoroids* • *Orbital debris*
Drag	• Torques • Orbital decay	• *Neutral thermosphere*
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 & 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*

Space Environment Effects/Anomalies

Spacecraft charging

SEE

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%

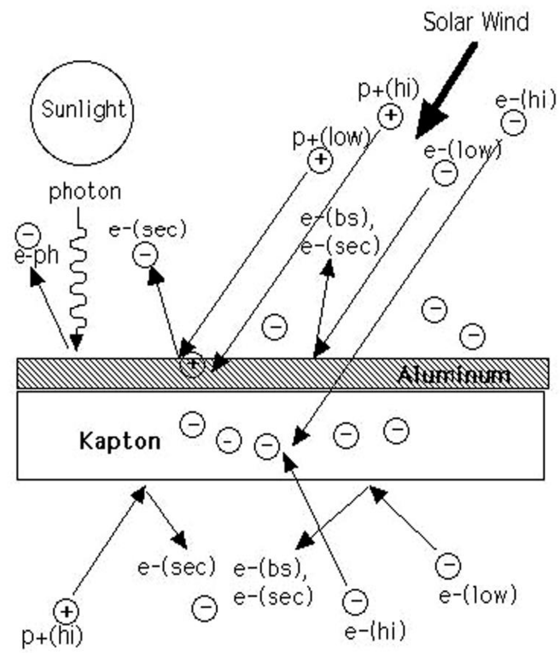
McKnight 2015

Surface Charging

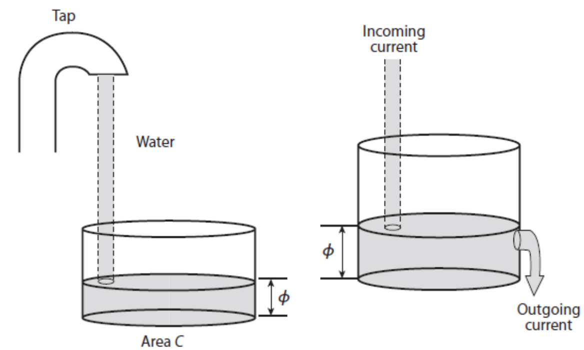
- Electric charging of spacecraft parts (conductors) that are exposed to space plasma.
- It is an current balance problem:

$$\frac{dQ}{dt} = \sum_k I_k =$$

$+I_i(V)$	incident ions
$-I_e(V)$	incident electrons
$+I_{bs,e}(V)$	backscattered electrons
$+I_c(V)$	conduction currents
$+I_{se}(V)$	secondary electrons due to I_e
$+I_{si}(V)$	secondary electrons due to I_i
$+I_{ph,e}(V)$	photoelectrons
$+I_b(V)$	active current sources (beams, thrusters)



(Garrett and Minow, 2004)



Surface Charging (sources)

- **Electrons and ions in the 1 eV to 100 keV are relevant** (surface ~3 mm of Aluminum)
- The EUV-created photoelectron emissions usually dominate in geosynchronous orbits and prevent the spacecraft potential from being very negative during sunlit portions of the mission.
- Other sources are Substorms (GEO charging), Auroral injection (at LEO), Radiation belts
- Useful doc: "*Mitigating In-Space Charging Effects-A Guideline*" (Rev A, 2016-03-03) by NASA

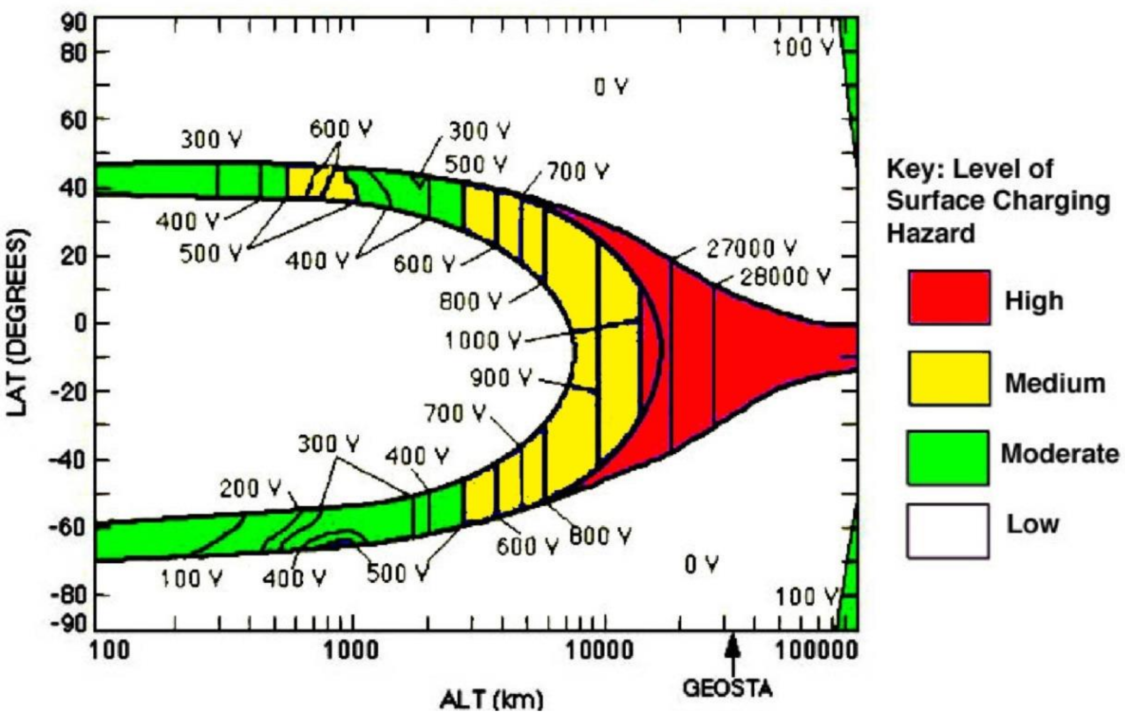
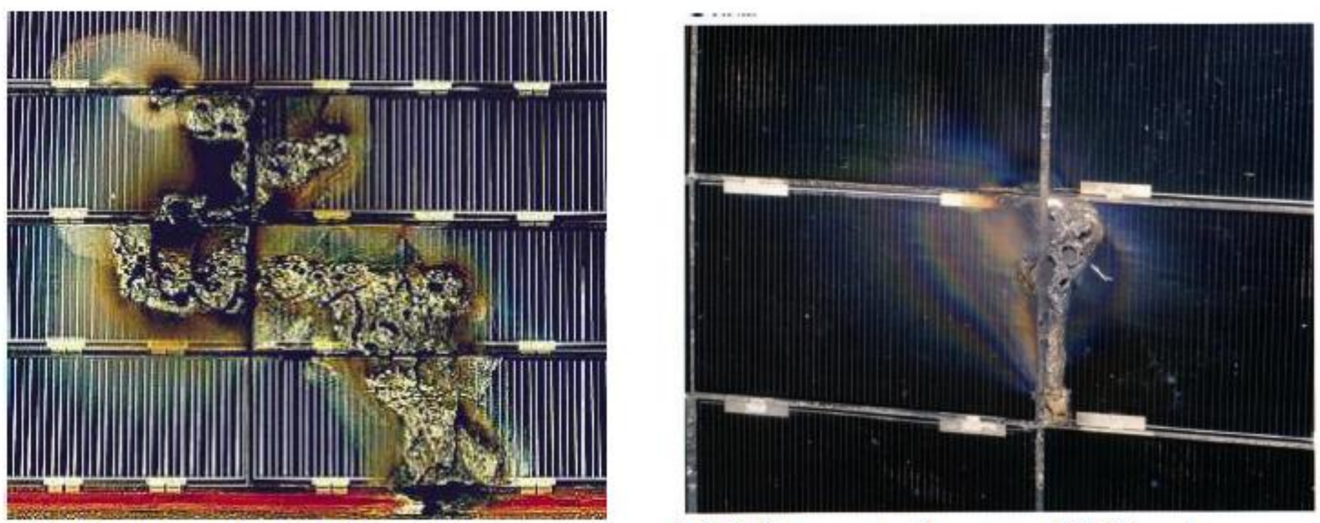


Figure 1—Earth Regimes of Concern for On-Orbit Surface Charging Hazards for Spacecraft Passing Through Indicated Latitude and Altitude (Evans and others (1989))

Surface Charging (effects)

- Bias particles sensors (affect spacecraft interaction with charged particles)
- Produce Electrostatic Discharge (**ESD,** arc with **high current** and strong **EM emission**):
  - Corrupt data (communication noise)
  - Destroy electronic or electro-optical components
  - Damage solar panels
  - etc…



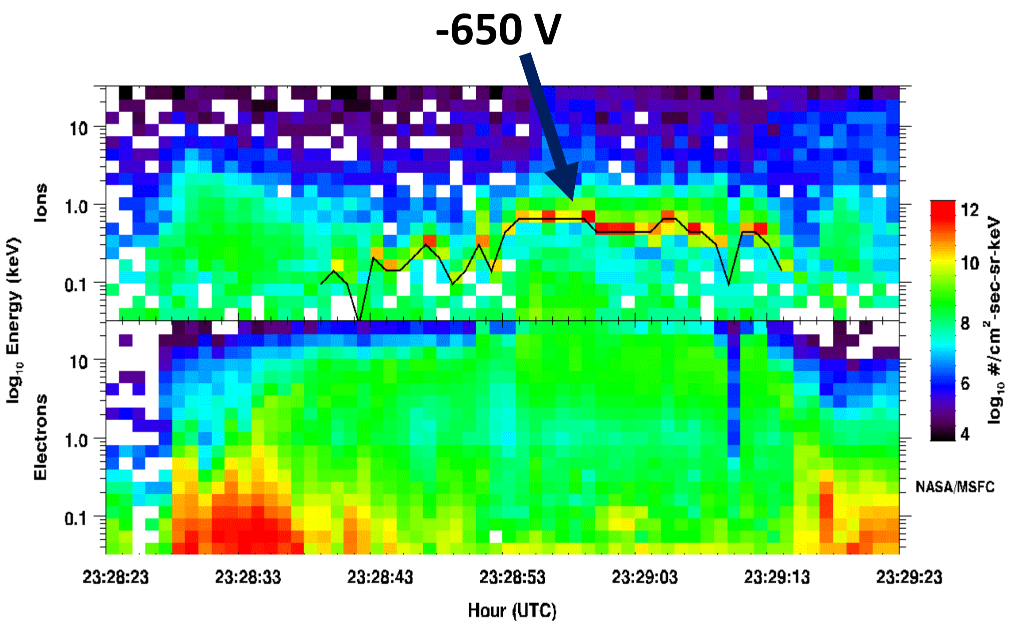
(a) Failure caused by in-flight ESD arcing (b) Failure caused by ground ESD arcing

Figure 10—Examples of Solar Array Failure

Surface Charging (monitor and mitigation)

To monitor:

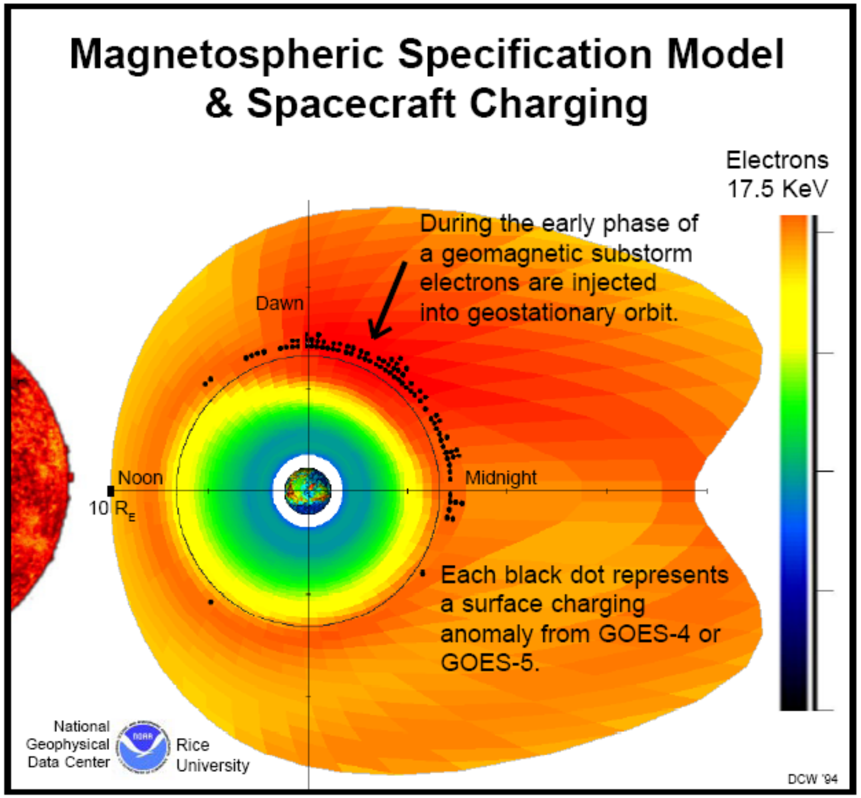
- Use the “Ion Line” in any onboard particle detector
- Langmuir probe (small)
- Include an “Environmental and event monitor” (1 kg and 2 W)

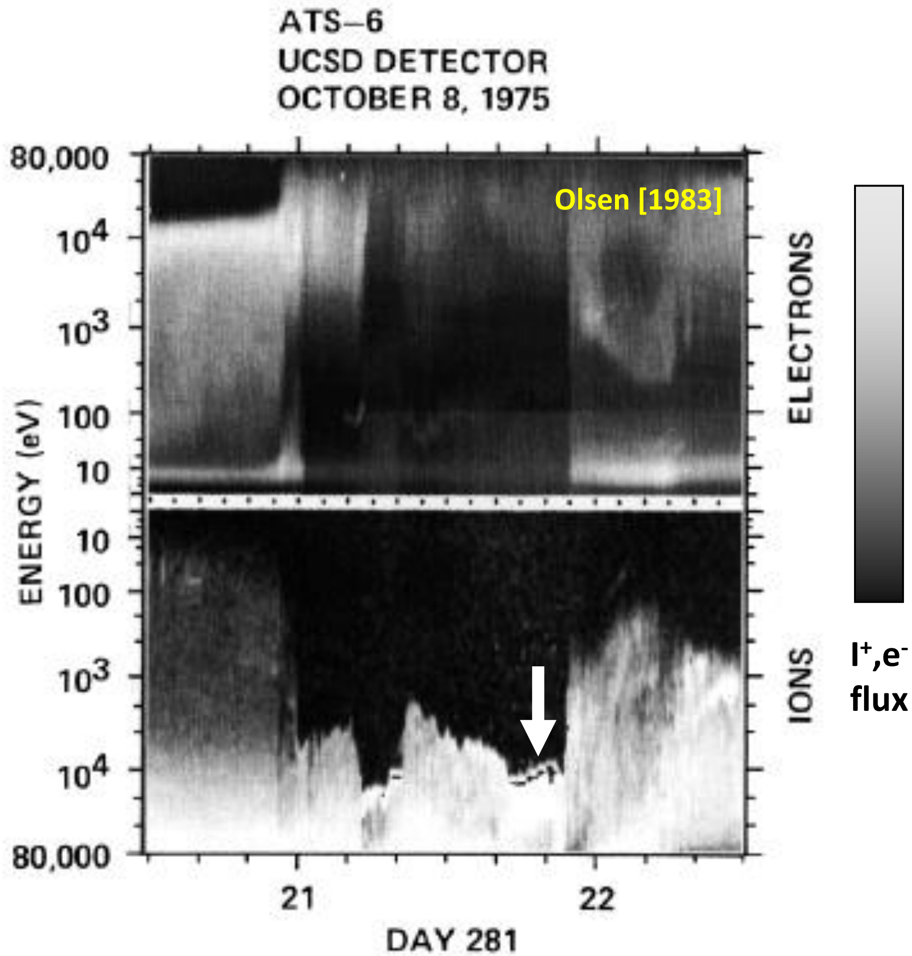


Fight by spacecrafts design:

- Avoid charge accumulation (grounding circuit design)
- Prevent arc formation (specs. of insulating materials)
- Testing, testing and more testing…**on realistic conditions**
- Active spacecraft charge control devices (to control current balance)

Surface Charging (example at GEO)





Surface charging anomalies typically occur in midnight to dawn local time sector where hot electrons are injected during geomagnetic substorms

Record ATS-6 charging event
Φ ~ -19 kV

Internal Charging

- **High energy electrons (100 keV - 3 MeV)** penetrate spacecraft walls and accumulate in dielectrics or isolated conductors
- **Sources:** energetic e- in outer belt and geomagnetic storms (CMEs).
- **Effect is ESD:** which produce material damage, discharge currents inside or near critical circuitry, and RF noise.
- Mitigated by spacecraft design (shield thickness, grounding , PCB design, etc.).

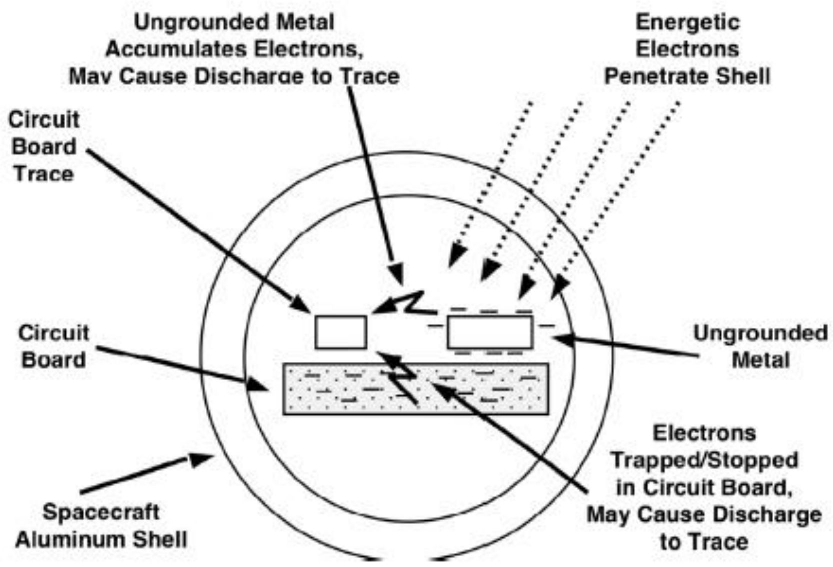
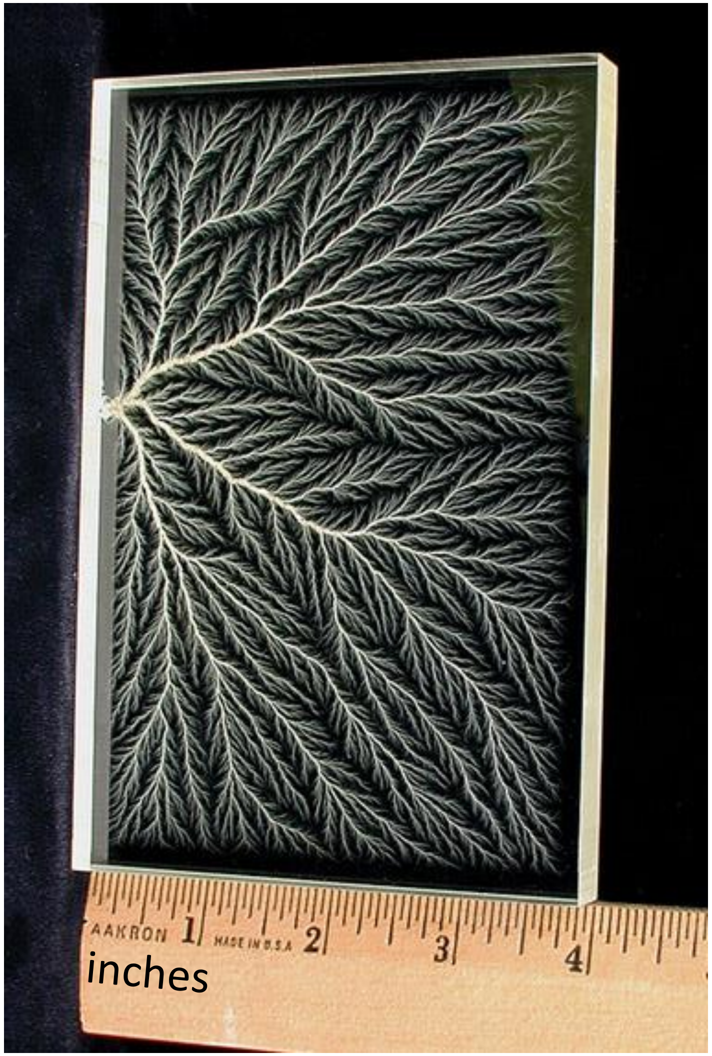


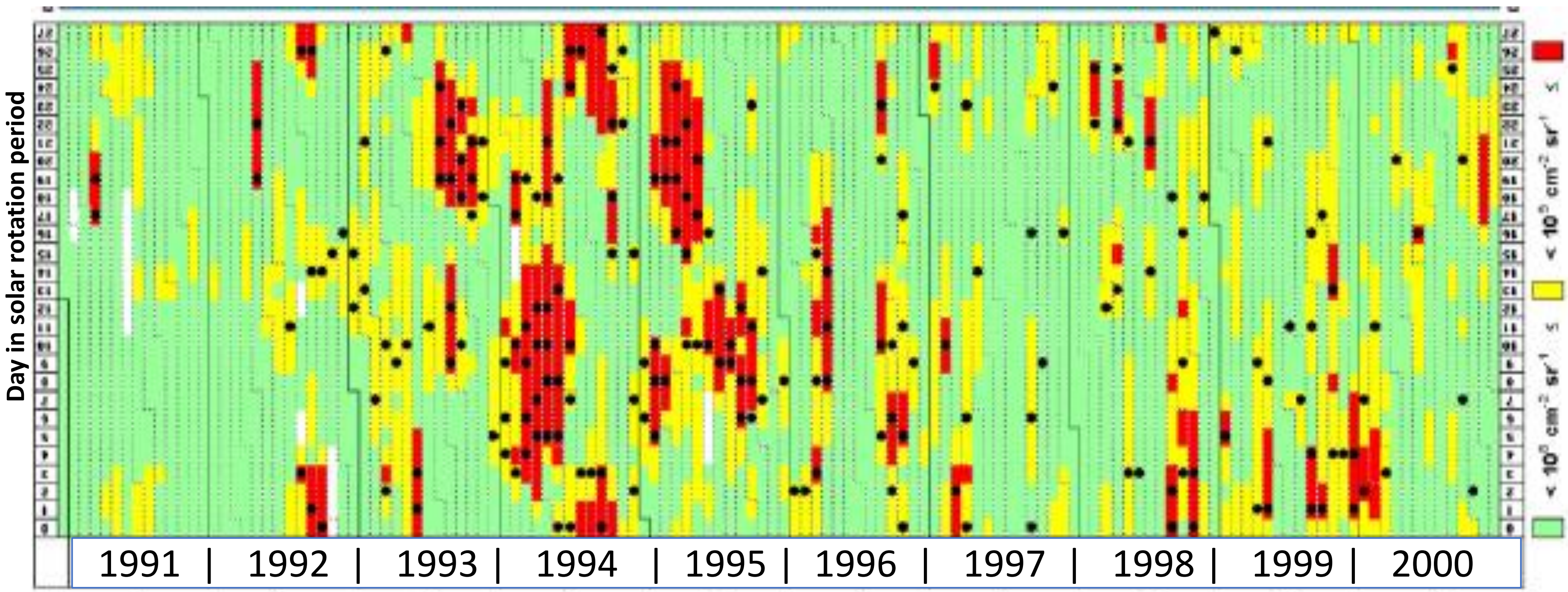
Figure 6—Internal Charging, Illustrated



PMMA (acrylic) charged by ~2 to 5 MeV electrons

Internal Charging (example)

GOES Internal Charging Anomalies during Solar Cycle 21 (at GEO)



[adapted from *Wrenn et al.* 2002]

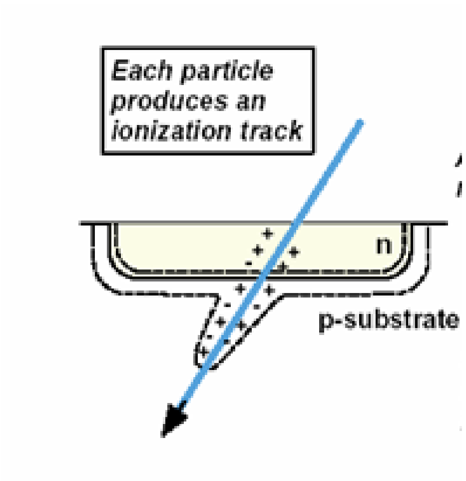
Black dots: GOES phantom (not sent but executed) commands

Colors: > 2 MeV electrons flux (red highest)

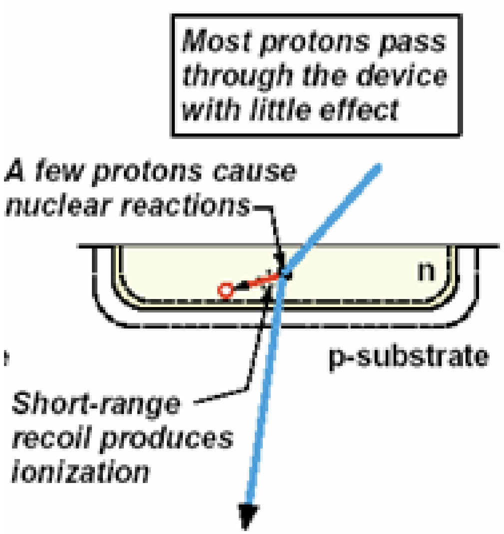
Single Event Effect (types)

- **Single Event Effect** (SEE) – any measureable effect 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)

Heavy Ions (Z=2-92)



Protons (Z=1)

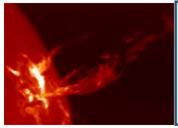


Single Event Effects (sources)

High Energy Particles

Galactic Cosmic Rays

- High-energy charged particles that originate outside our solar system.
- Anticorrelates with solar cycle

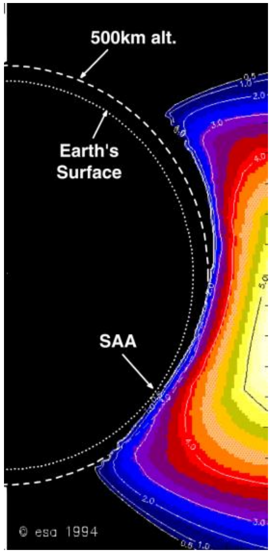


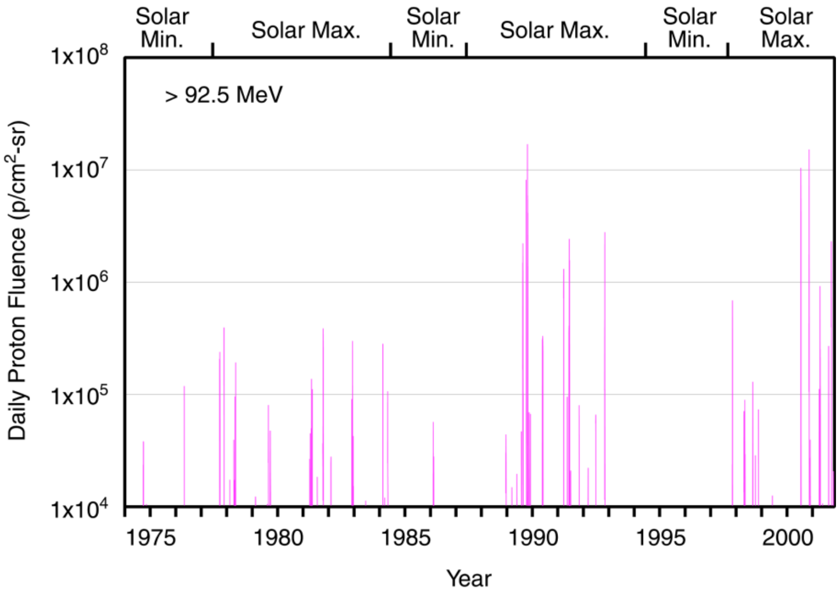
Solar Particle Events (flare/CME)

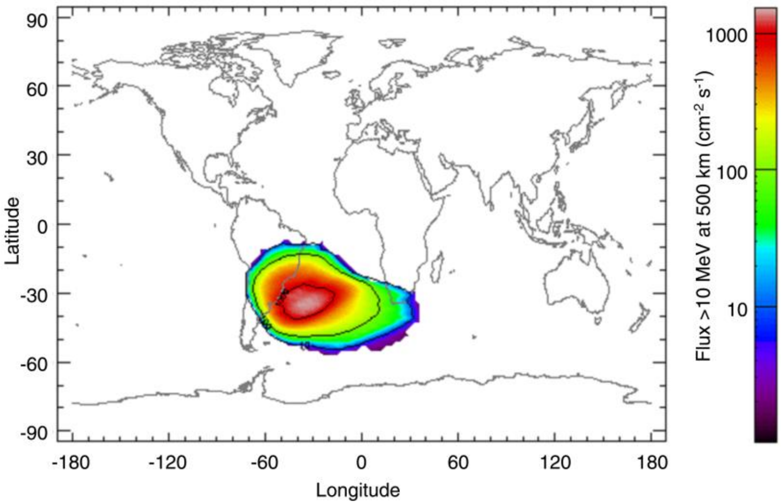
- Composition is **96.4% protons** ; 3.5% alpha particles and 0.1% heavier ions (not to be neglected!)
- Energies up to ~ GeV/nucleon

Trapped Particles (SAA)

- Dominates at LEO (<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.



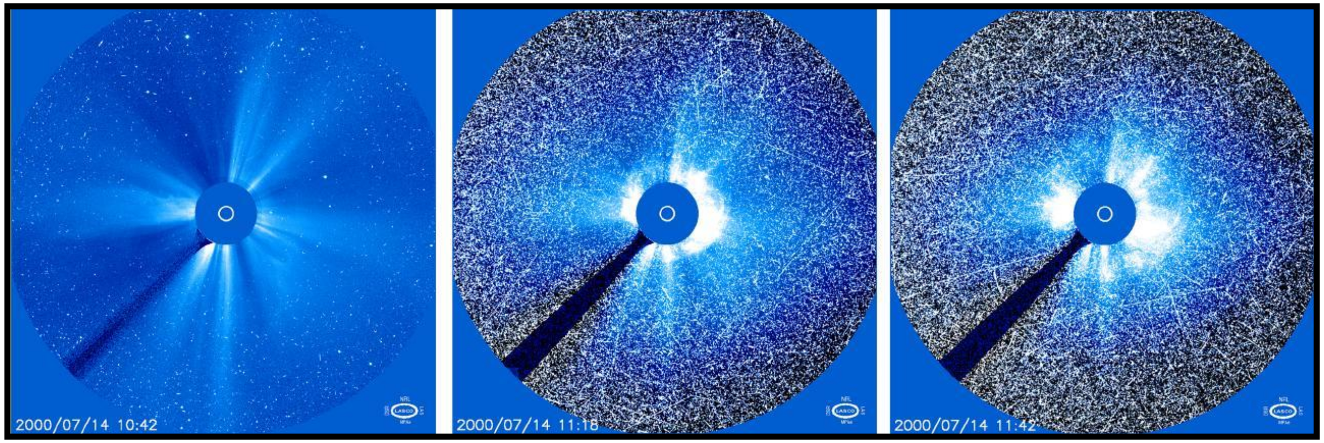




Single Event Effect (non-destructive)

- They are transient and reversible:
  - Transient pulses in logic or support circuitry
  - Bitflips in memory cells or registers.
  - Hot pixels in CCDs

SOHO (L1) 14 July 2000 "Bastille Day Event"



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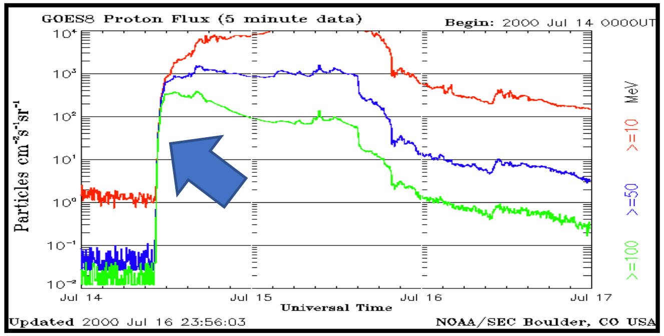
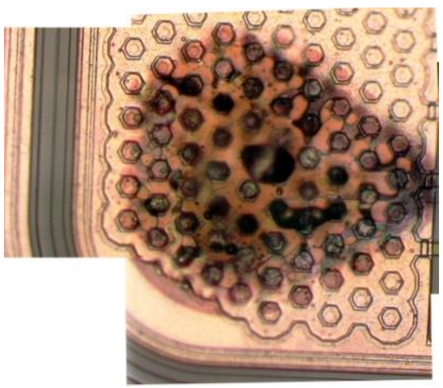


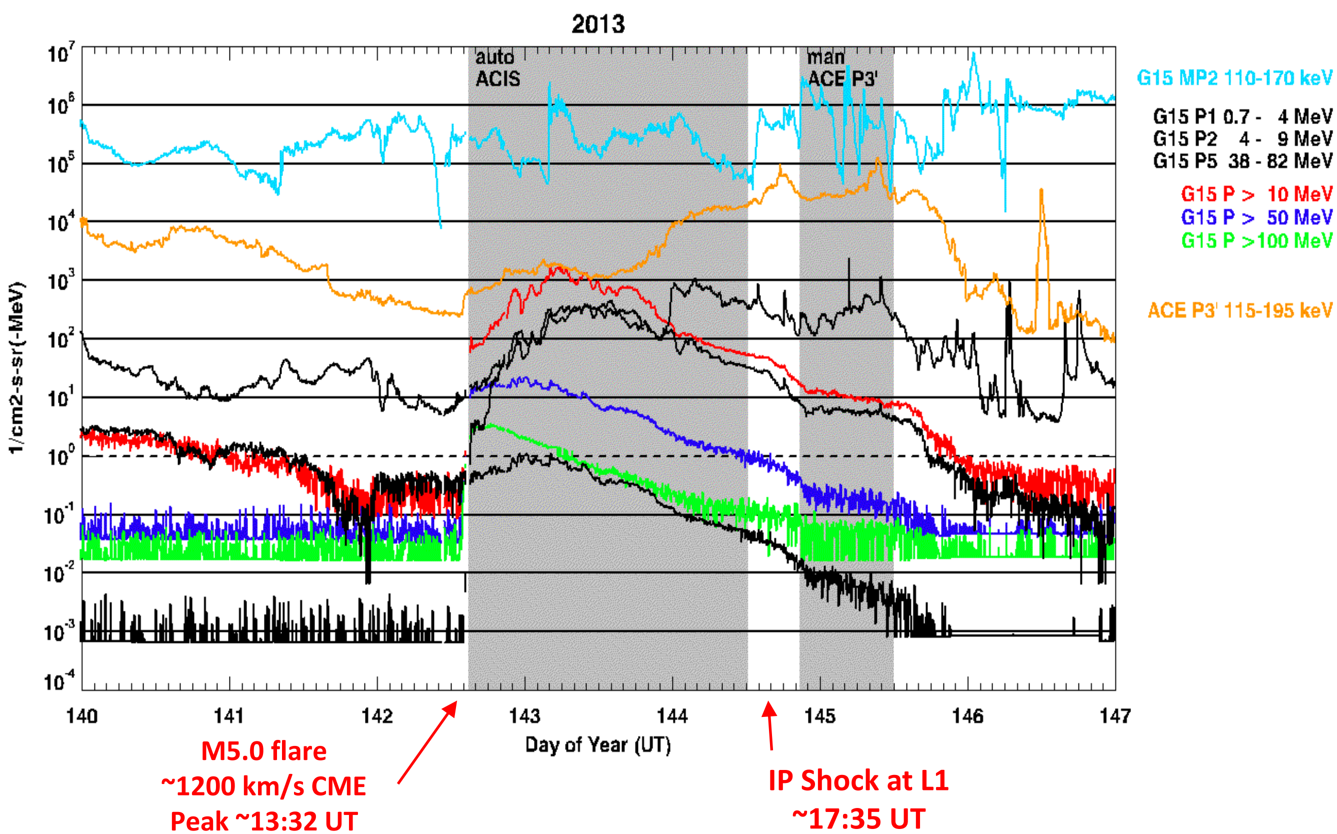
Single Event Effect (destructive)

- SEL results in a high operating current, above device specifications, and must be cleared by a power reset.
- Burnout of power MOSFETS, Gate Rupture, frozen bits and increase noise in CCDs.



Destructive event in a COTS 120V DC-DC Converter

Mitigated by **Spacecraft design** and
Operational interventions (CHANDRA example)



Summary:

- Space assets (spacecrafts) are **crucial to modern society** (research, communications, defense, etc.)
- **Space Weather is important during the full mission life-cycle** (concept, engineering, launch and operation).
- The **mission orbit determines the Space Environment** the spacecraft will have to endure (magnetosphere, radiation belts, light conditions, SAA, etc.)
- The most common **mitigation is done by proper design** (better for space climate). **Mission operation** is typically affected by space weather conditions.
- **There is not a standard procedure, is mission dependent.**
- The main effects are:
  - **Spacecraft charging** (50% cases) -> **ESD**
    - Surface (electrons in the 1 eV to 100 keV range)
    - Internal (electrons in the 100 keV to 3 MeV range)
  - **Single Event Effects** (30%)
    - Non-destructive (heavy, z>1, energetic ions) -> Data upsets, etc.
    - Destructive (even more energetic ions, GeV) -> Electronic components
  - Long term effects (5%)
    - Total Ionization Dose -> Device Malfunctioning
    - Total Displacement Dose -> Device degradation (Solar Panels)
  - Others: Atmospheric Drag, Impacts, Surface Erosion -> Break stuff