



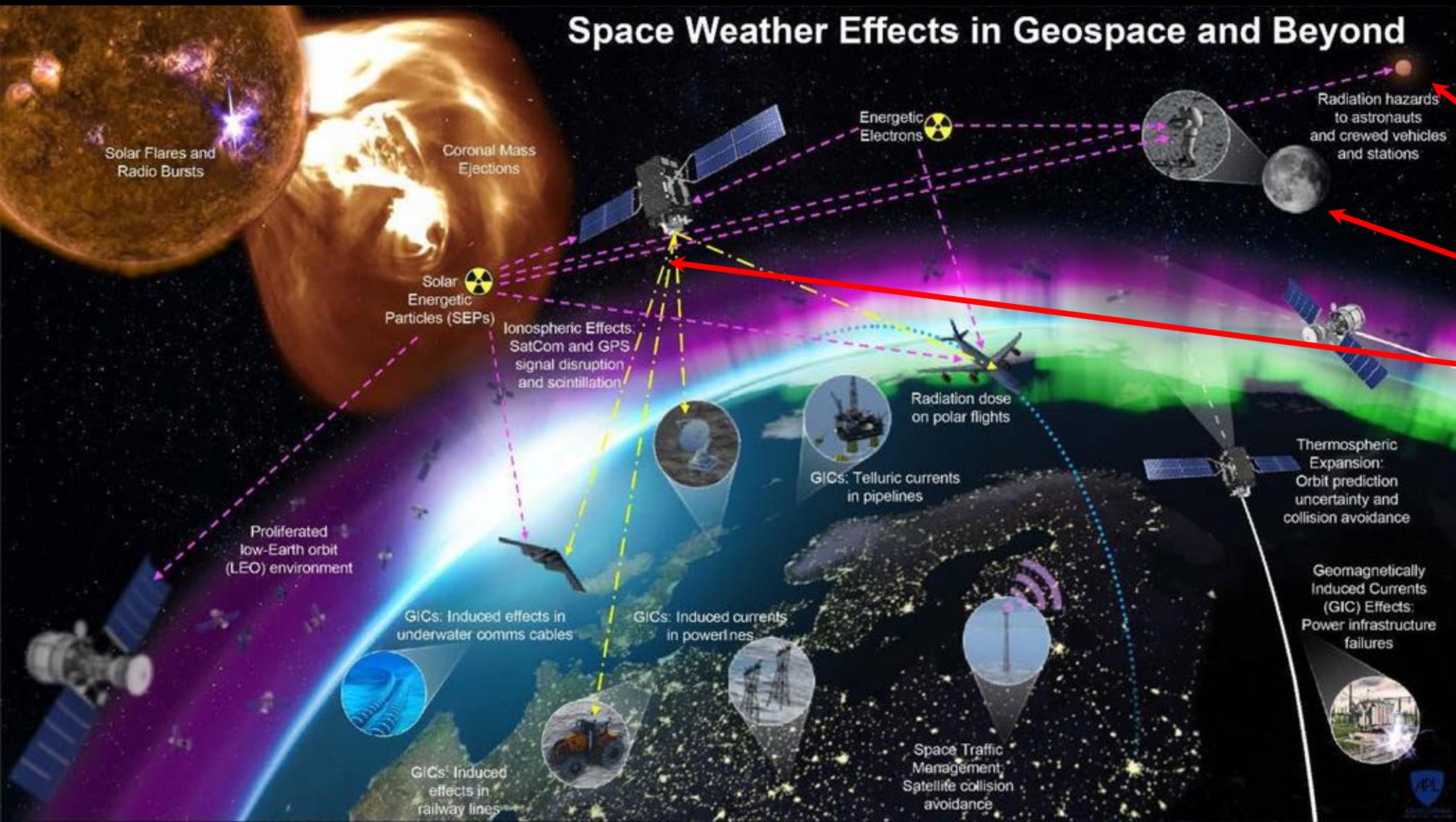
Space Weather Impacts on Satellites

location, location, location...

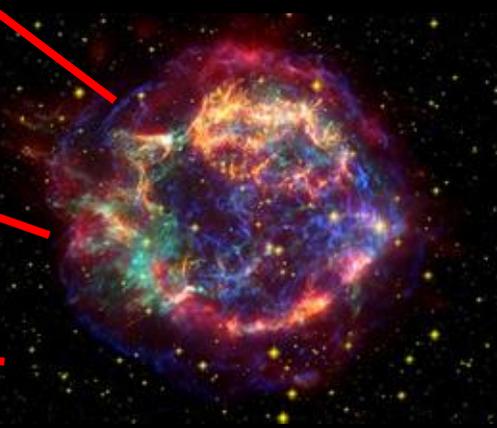
Yihua Zheng, Claudio Corti, Leila Mays, Elana Resnick (CCMC)

SWERV Training
24 February 2026





GCRs



Credits: [Vourlidis et al. \(2021\)](#)



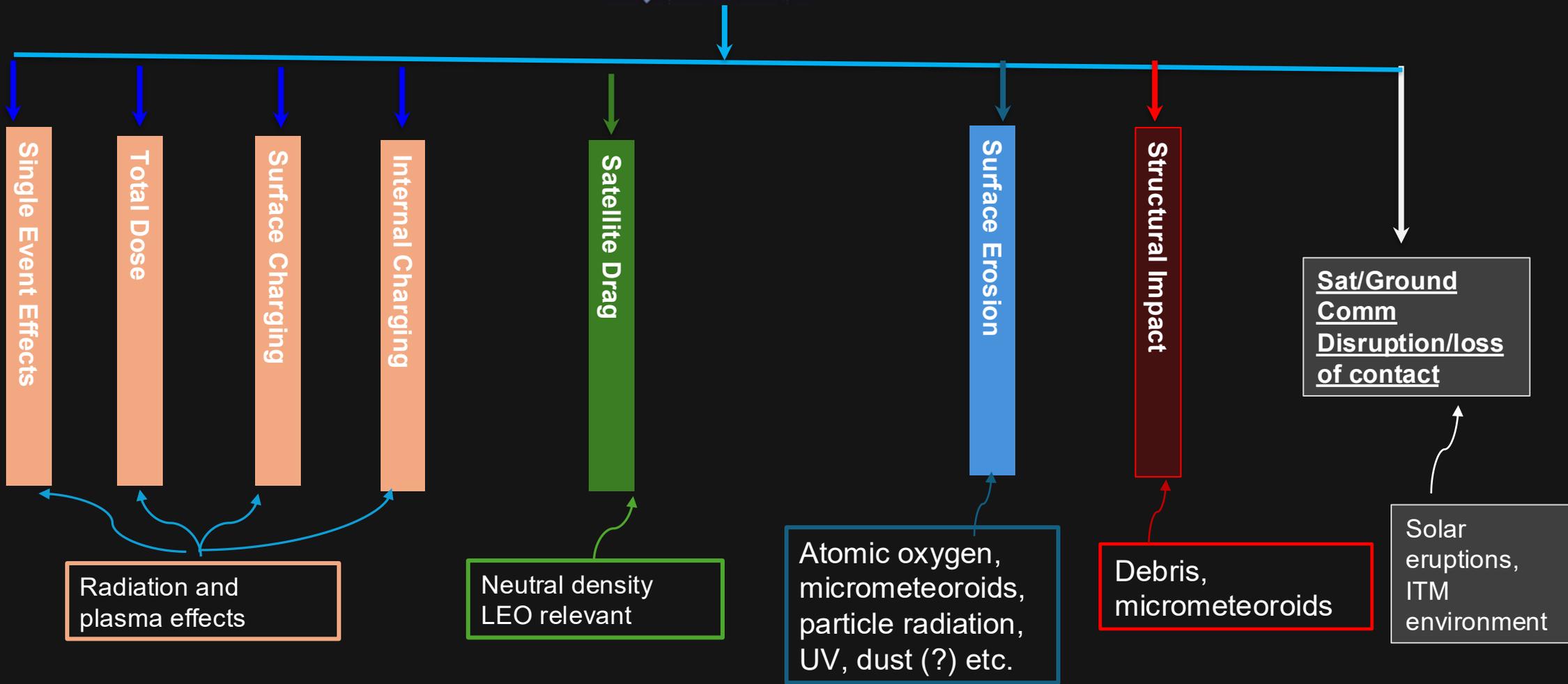
Space Climatology and Space Weather

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



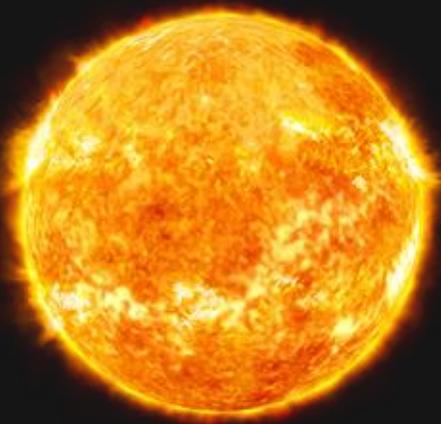
What is plasma?

4th State of Matter, 99% of the visible universe

When a neutral gas is heated such that some of the electrons are freed from the atoms or molecules, it changes state and becomes a plasma - consisting of a partially-ionized gas, containing ions, electrons, and neutral atoms.

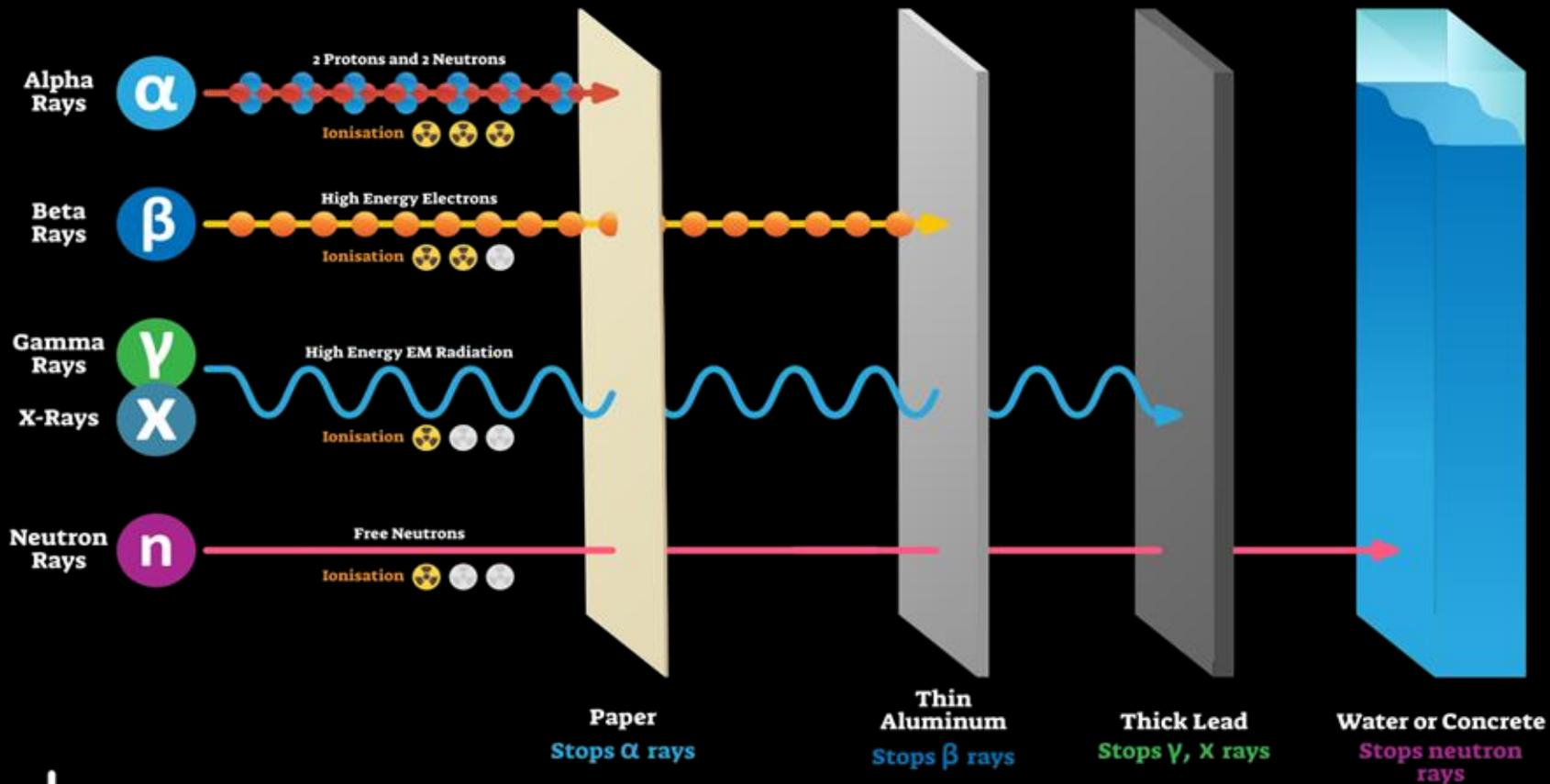


hello
beautiful



What is radiation?

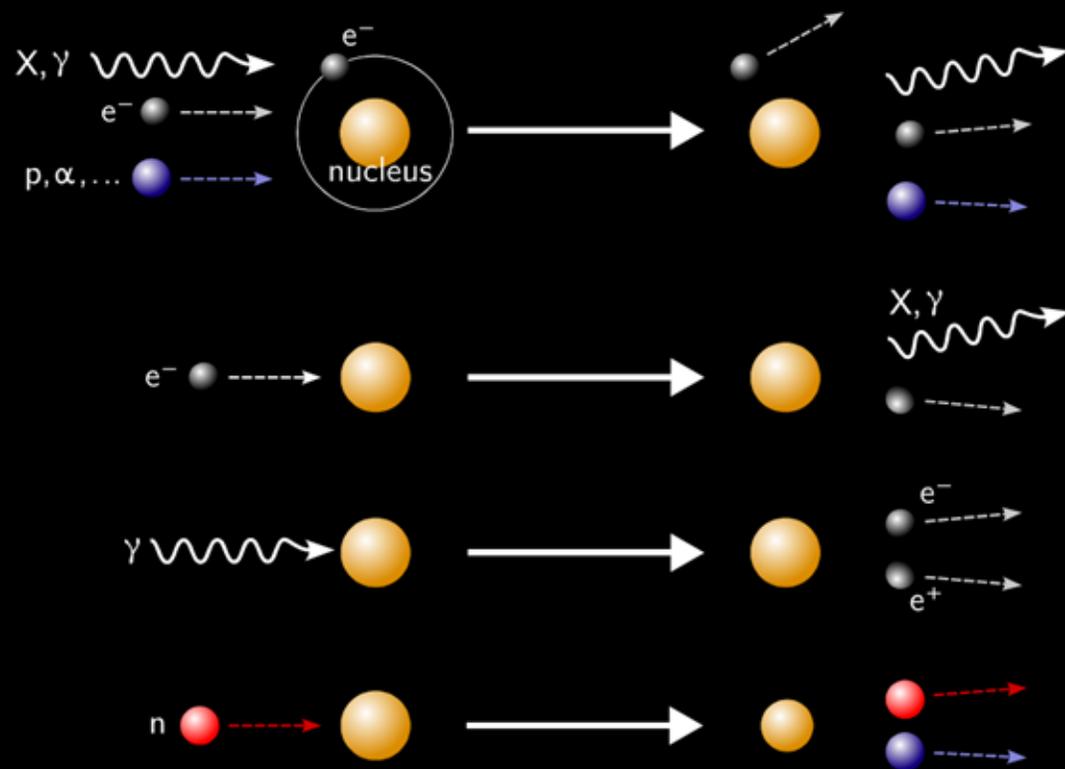
Transfer of energy to materials: objects, human body, etc



Adapted from American Nuclear Society

How does radiation affect materials?

Mostly by ionizing the traversed matter: electrons are stripped out of atoms

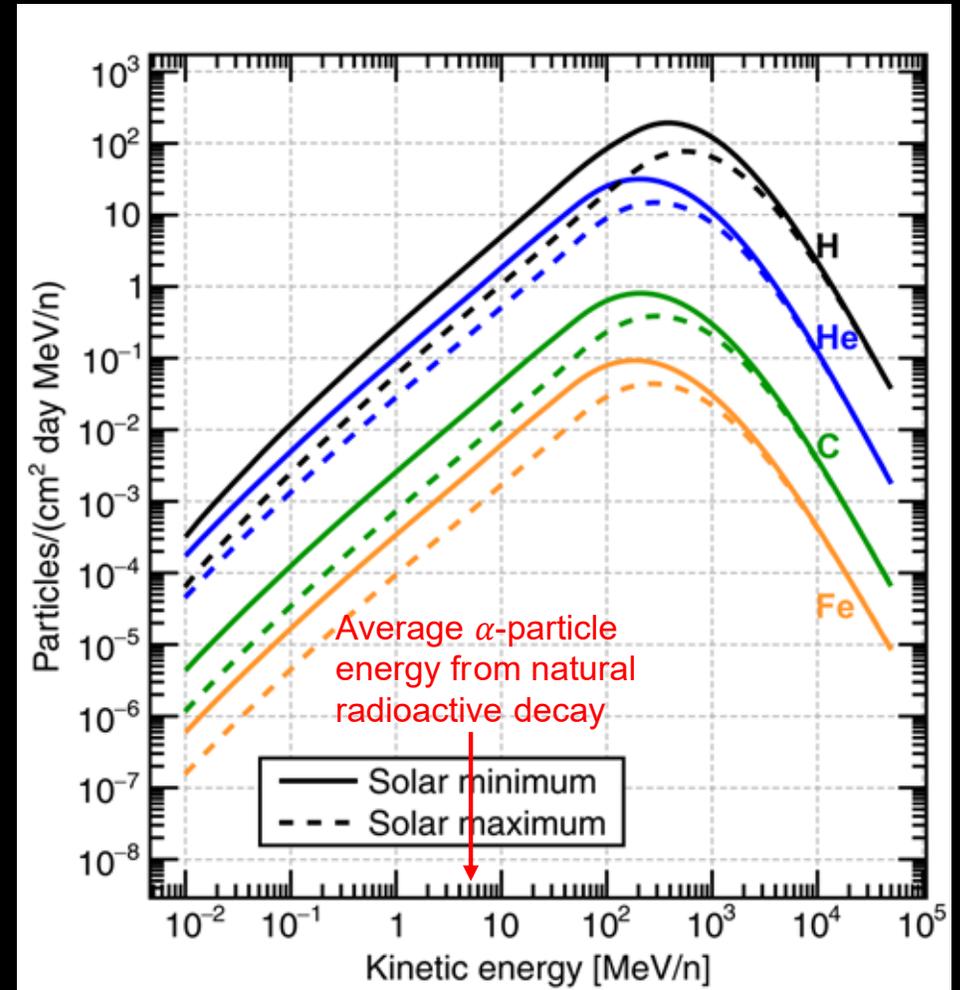
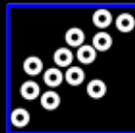


Radiation in space: galactic cosmic rays

Galactic cosmic rays (GCRs) are high-energy charged particles originating outside our solar system, usually in supernova explosions



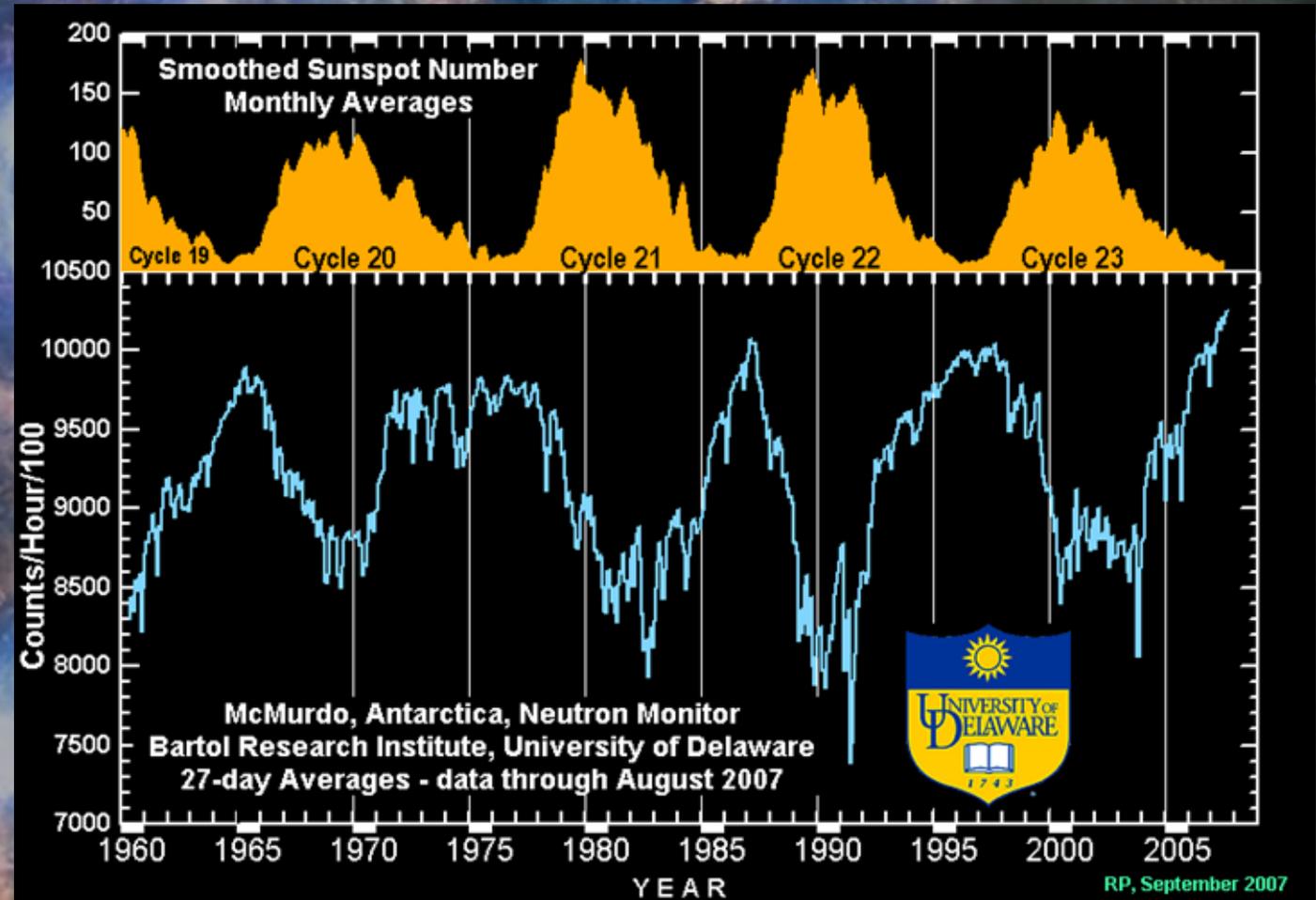
The Crab Nebula, as seen by the James Webb Space Telescope and Chandra X-ray Observatory (Image credit: X-ray, Chandra: NASA/CXC/SAO; Infrared, Webb: NASA/STScI; Image Processing: NASA/CXC/SAO/J. Major)



Radiation in space: galactic cosmic rays

GCR intensity is modulated by the solar activity:

- lower during solar maximum
- higher during solar minimum



Radiation in space: solar energetic particles

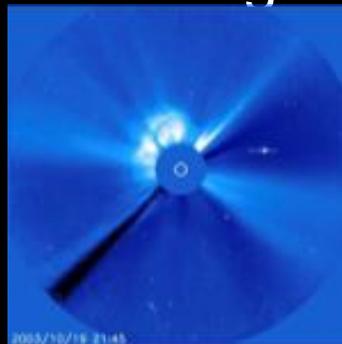
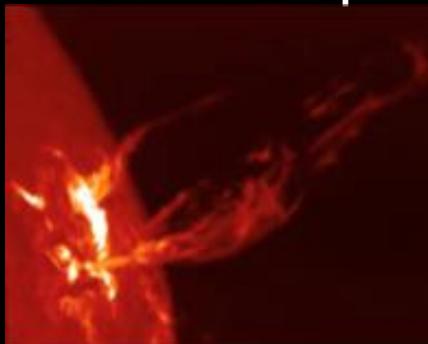
Solar energetic particles (SEPs) are accelerated in solar eruptions

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

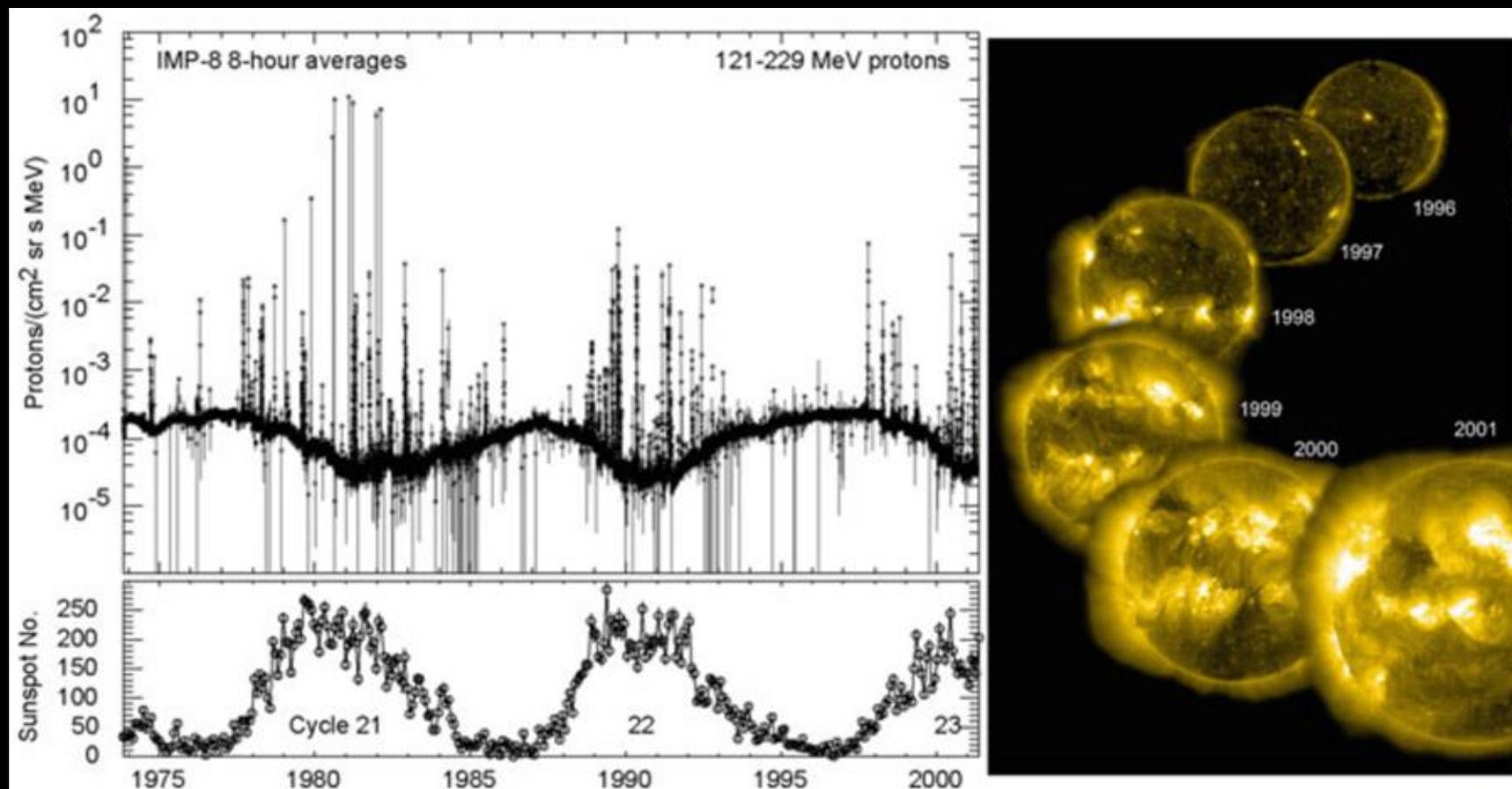
Event magnitude: can be up to 10^5 times higher than GCRs



Radiation in space: solar energetic particles

More likely to happen during solar maximum, but can still have large events during solar minimum

Hard to predict!

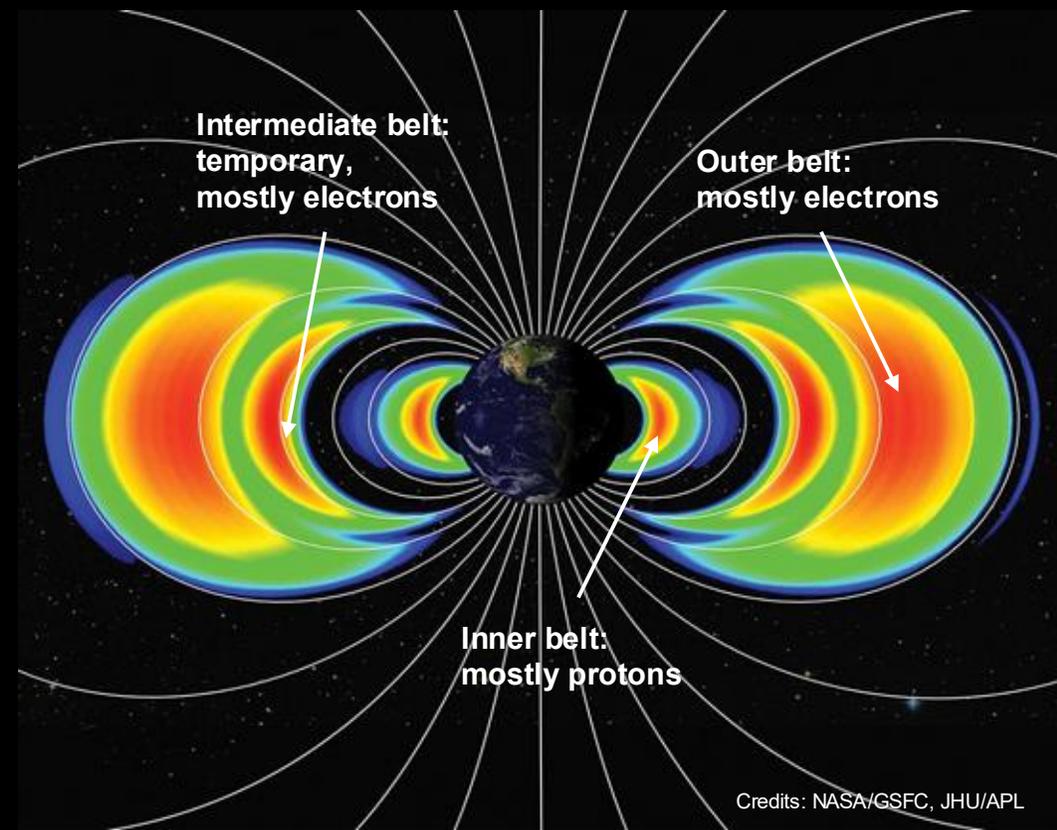
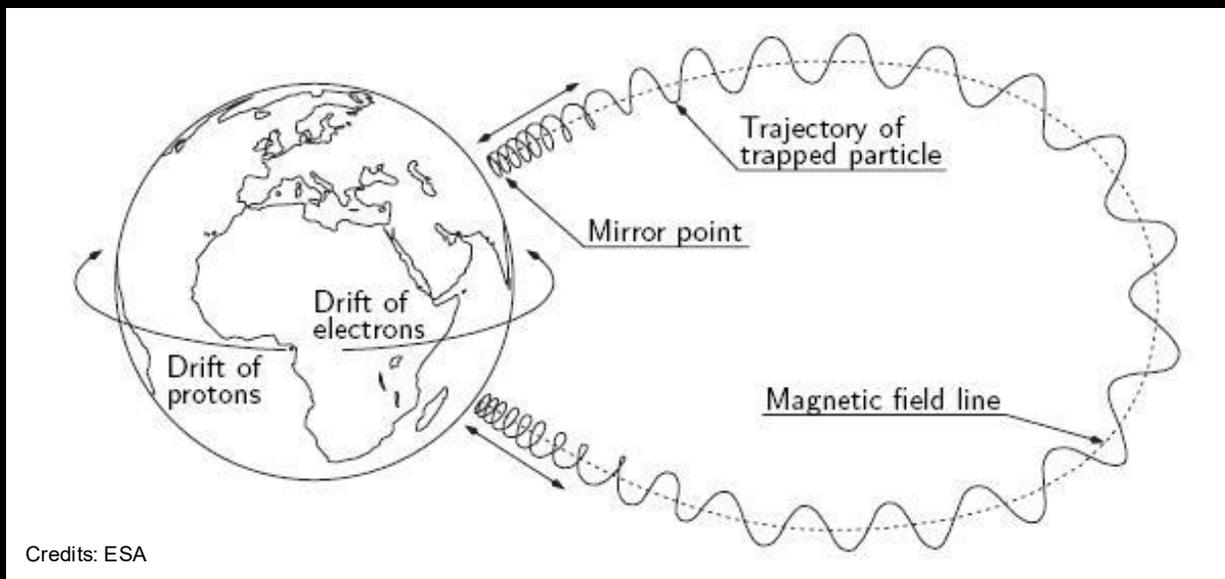


Credits: Reames (2021), DOI:[10.1007/978-3-030-66402-2](https://doi.org/10.1007/978-3-030-66402-2)

Radiation in space: Radiation belts



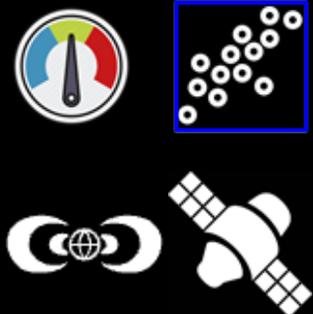
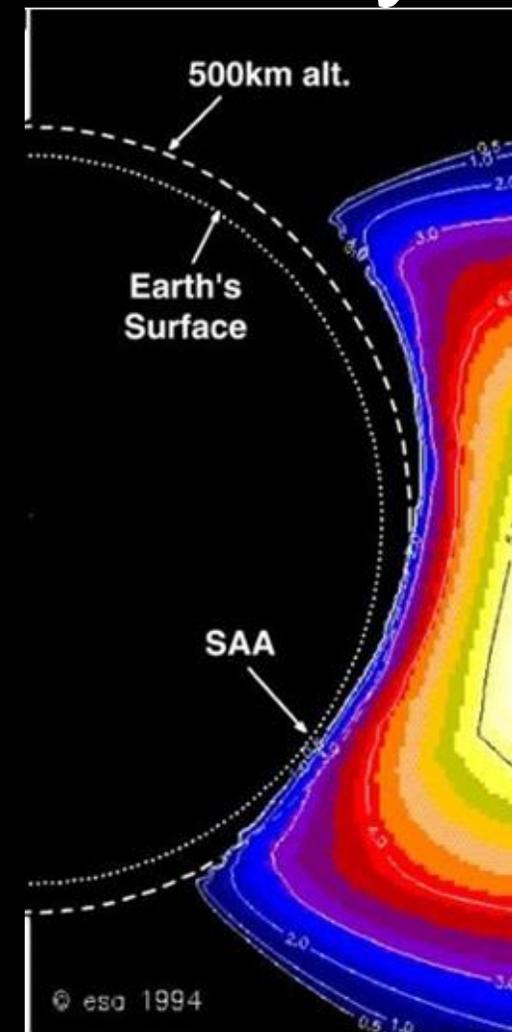
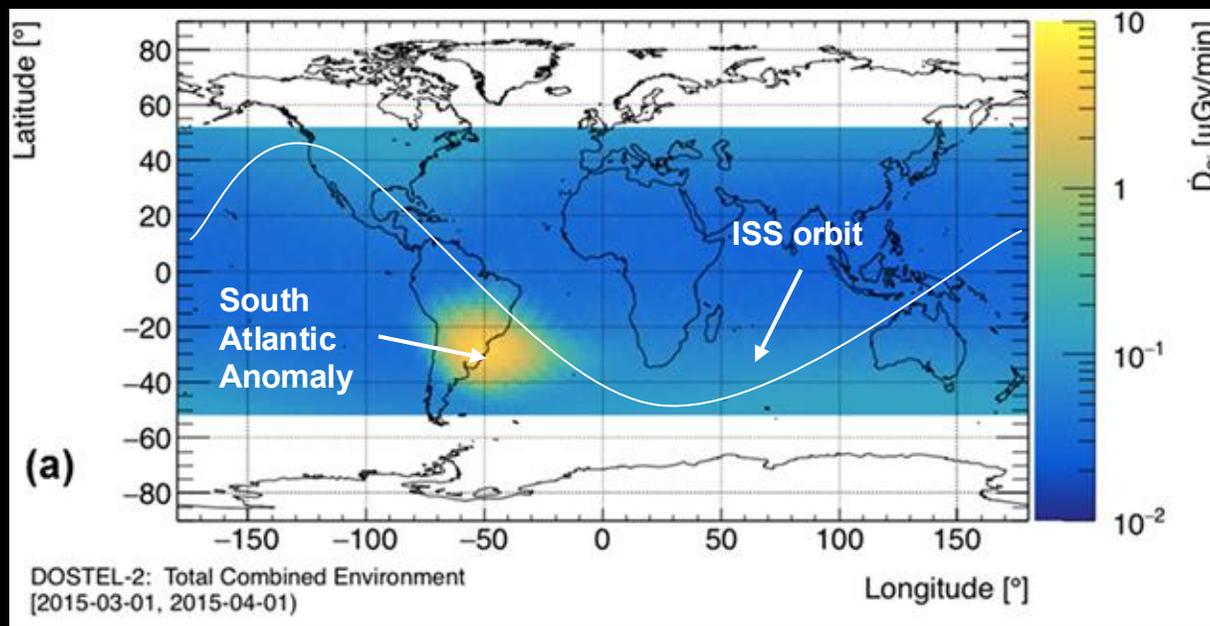
Protons (up to GeV) and electrons (300 keV – 10 MeV, internal charging) trapped in Earth's magnetic field



At the same time, Earth's magnetic field can deflect SEPs and GCRs

Radiation in space: South atlantic anomaly

- SAA dominates the radiation environment below 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



Adapted from Berger et al. (2020), DOI:10.1051/swsc/2020028

Quantifying radiation effects: particle spectrum

Effects of space radiation depend on:

- particle type (electrons, nuclei with different charge number)
- particle energy (how fast particles move)
- particle intensity (how many particles per unit area and time)

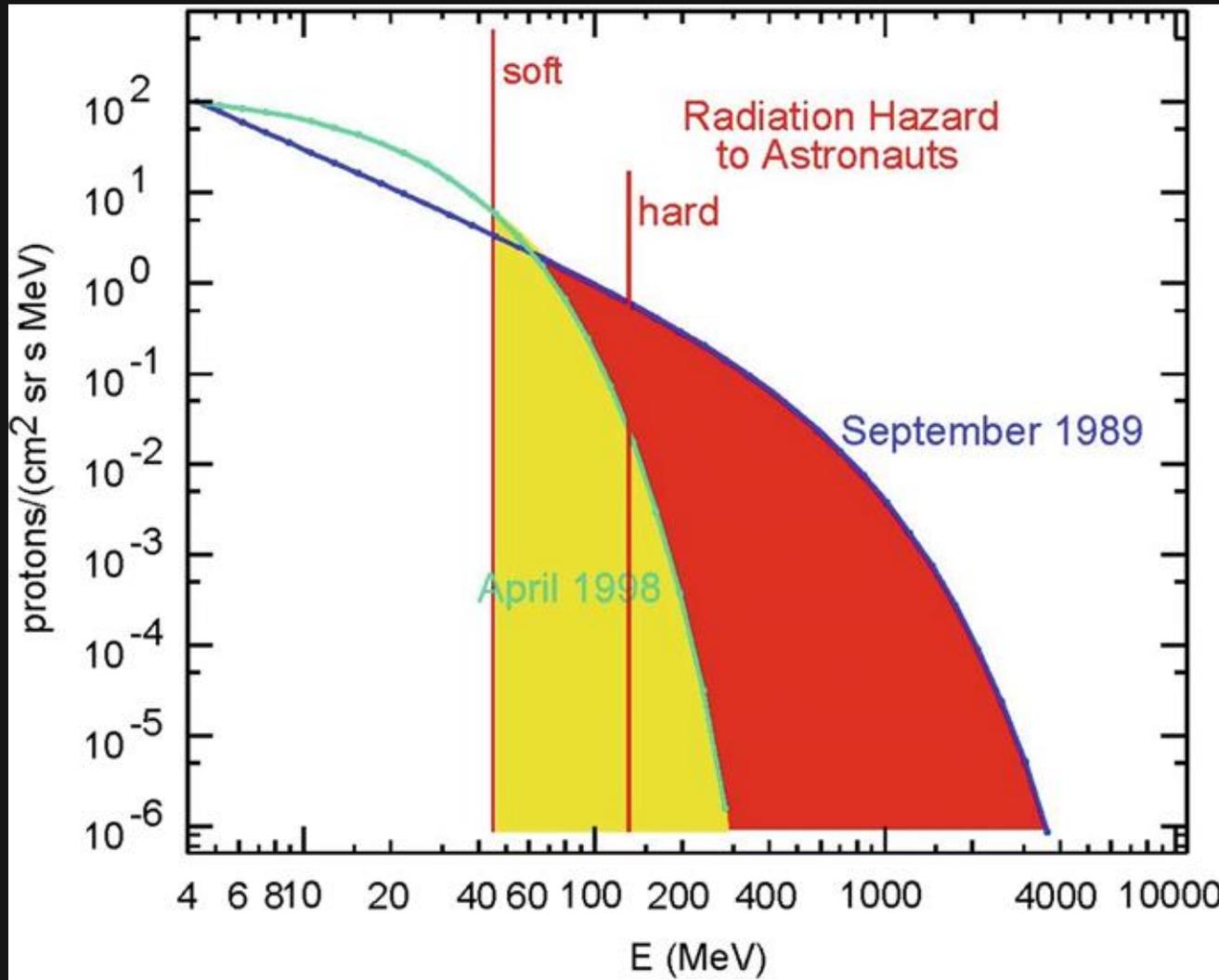
Particle spectrum (intensity vs energy) is a key factor in understanding space radiation effects:

- Soft spectrum: fast decrease of intensity with increasing energy
⇒ less particles at high energy
- Hard spectrum: slow decrease of intensity with increasing energy
⇒ more particles at high energy



Soft vs Hard Spectra

Increasing Intensity

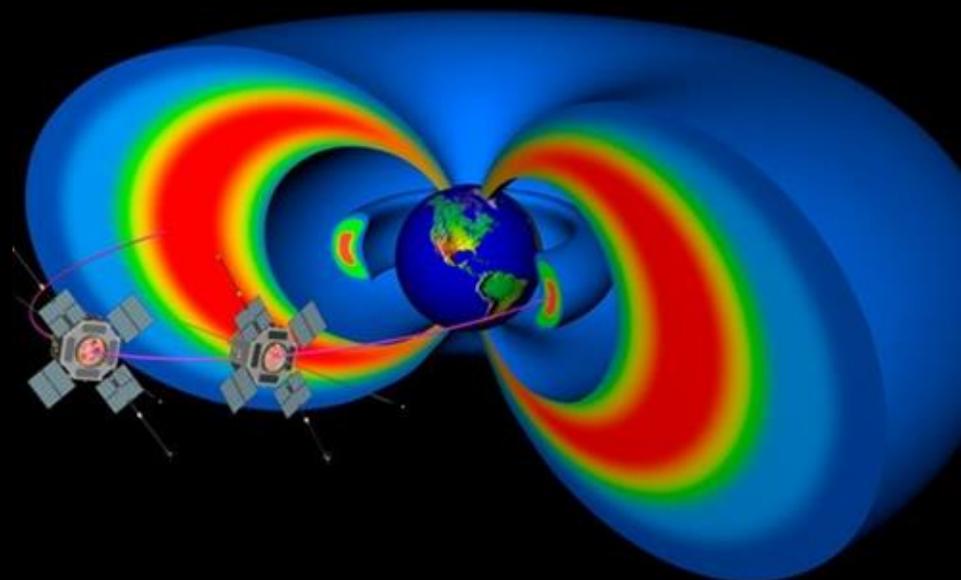
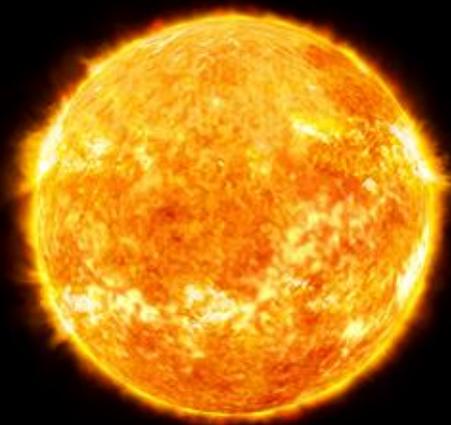


Reames, D.V. (2021)

Increasing Energy

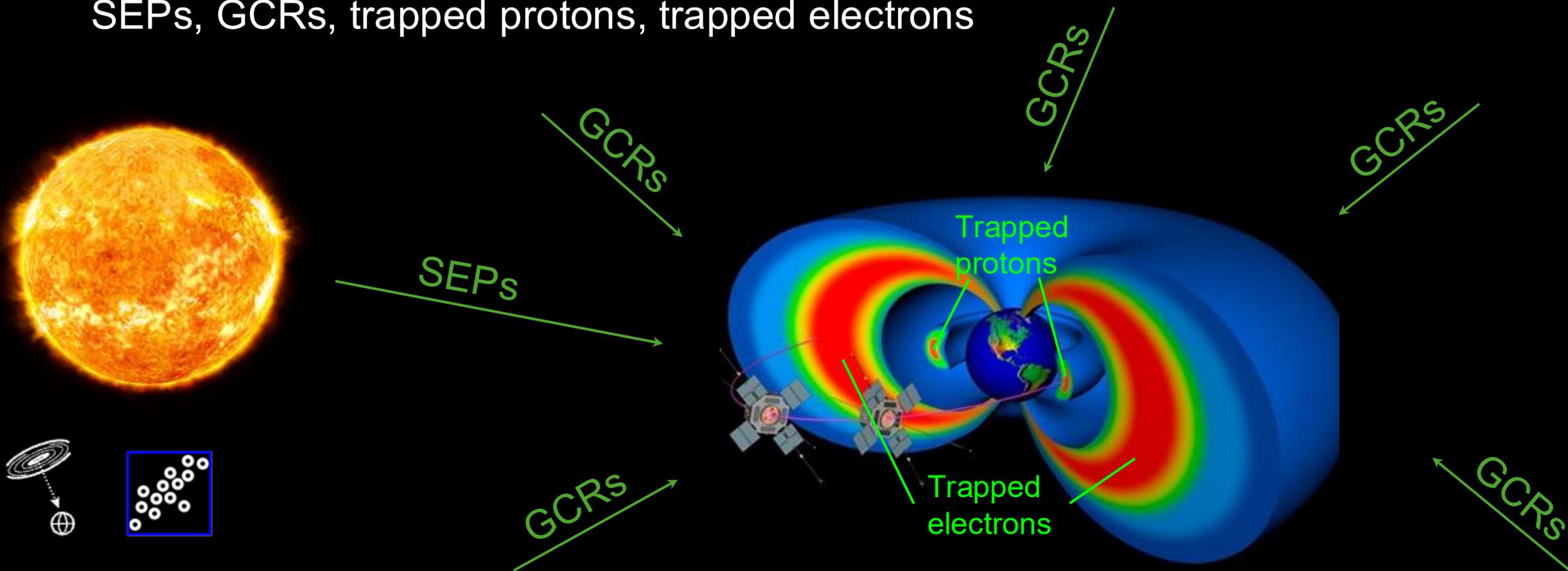
Quiz: which radiation is where?

Place the following radiation sources in the appropriate location in space:
SEPs, GCRs, trapped protons, trapped electrons



Quiz: which radiation is where?

Place the following radiation sources in the appropriate location in space:
SEPs, GCRs, trapped protons, trapped electrons



Satellite impacts

Radiation

Charging

Mechanism	Effect	Source
Total ionizing dose (TID)	<ul style="list-style-type: none"> Degradation of microelectronics 	<ul style="list-style-type: none"> Trapped protons Trapped electrons Solar protons
Displacement damage dose (DDD)	<ul style="list-style-type: none"> Degradation of optical components and some electronics Degradation of solar cells 	<ul style="list-style-type: none"> Trapped protons Trapped electrons Solar protons Neutrons
Single-event effects (SEE)	<ul style="list-style-type: none"> Data corruption Noise on images System shutdowns Electronic component damage 	<ul style="list-style-type: none"> GCR heavy ions Solar protons and heavy ions Trapped protons Neutrons
Surface charging	<ul style="list-style-type: none"> Biasing of instrument readings Power drains Physical damage 	<ul style="list-style-type: none"> Dense, cold plasma Hot plasma (ring current, aurora population, few eV to 10s keV)
Internal charging	<ul style="list-style-type: none"> Biasing of instrument readings Electrical discharges causing physical damage 	<ul style="list-style-type: none"> High-energy electrons (>300 keV)



Satellite impacts

Mechanism	Effect	Source
Surface erosion	<ul style="list-style-type: none"> • Degradation of thermal, electrical, optical properties • Degradation of structural integrity 	<ul style="list-style-type: none"> • Particle radiation • Ultraviolet • Atomic oxygen • Micrometeoroids • Contamination
Structure impacts	<ul style="list-style-type: none"> • Structural damage • Decompression 	<ul style="list-style-type: none"> • Micrometeoroids • Orbital debris
Satellite drag	<ul style="list-style-type: none"> • Torques • Orbital decay 	<ul style="list-style-type: none"> • Neutral thermosphere



Spacecraft anomaly attribution

- Most common anomalies are due to electrostatic discharges (ESDs) and single-event effects (SEEs)
- Spacecraft anomaly attribution is hard

Anomaly diagnosis	Koons et al, 2000	NGDC DB, 2006	Satellite Digest, 2014
ESD	54%	31 %	10%
SEE	28%	17%	5%
Radiation dose	5%	—	—
Meteoroids/Debris	3%	—	5%
Atomic oxygen	<1%	—	—
Atmospheric drag	<1%	—	—
Design	—	—	25%
Other/Unknown	8%	52%	55%



Credits: McKnight (2015)



Spacecraft charging

Buildup of charge, followed by a discharge, potentially disruptive for materials and electronic components

Surface vs. internal charging

Surface charging:

- affects surfaces directly exposed to space through interactions with space plasmas and sunlight
- absolute charging: potential difference between spacecraft and surrounding plasma
- differential charging: potential difference between adjacent surfaces

Internal charging:

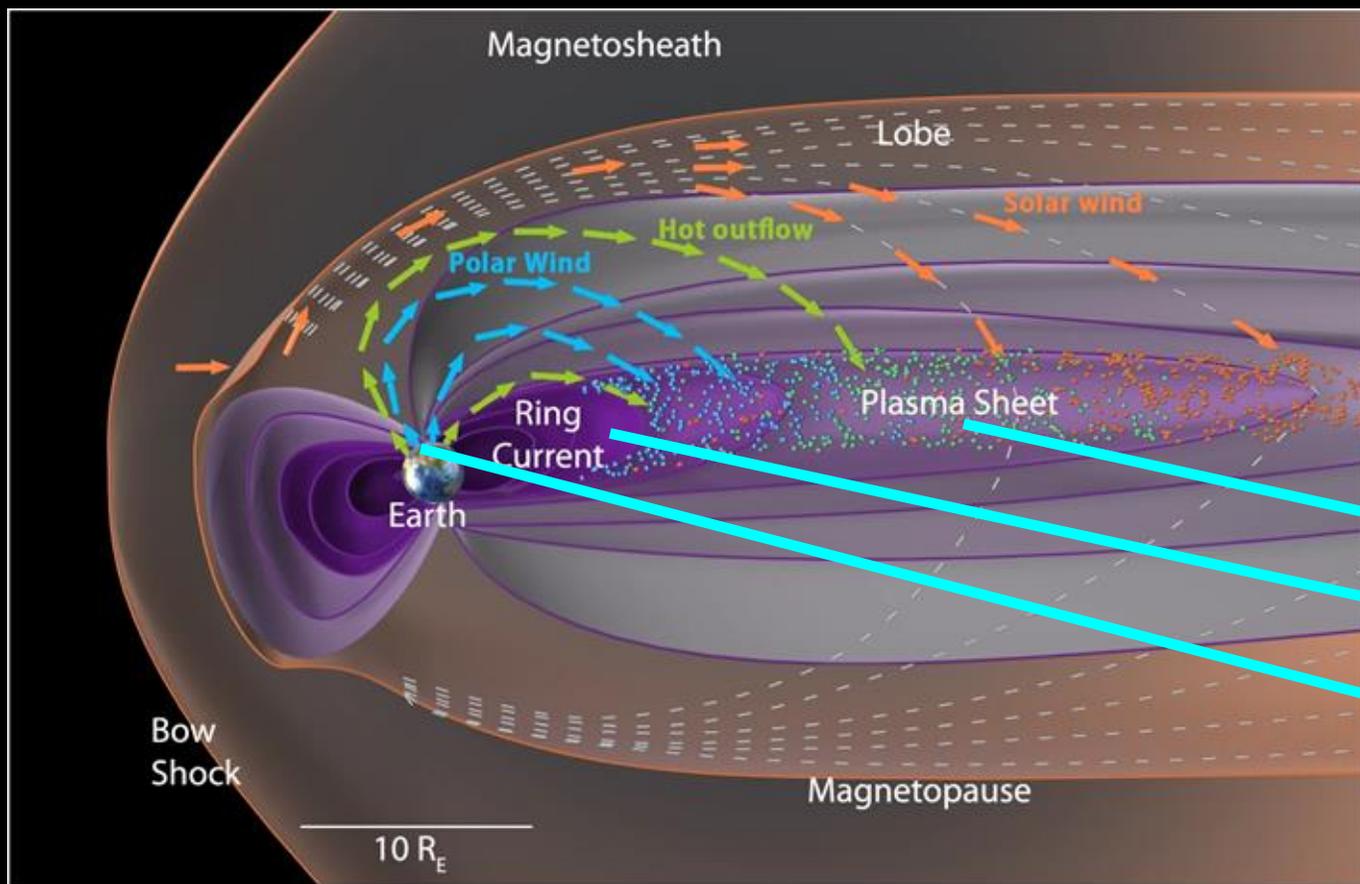
- affects volumes not directly exposed to space through interactions with more energetic (penetrating) electrons
- differential charging: potential difference between adjacent volumes and/or between internal volumes and spacecraft surfaces



Charging Mitigation

- Better engineering design
- Choose the right material for the space environment spacecraft and components are subject to
- Testing, testing... both through lab testing and computer simulation

Surface charging: sources in space



Several eV – 10s keV electrons are generally considered the main source for surface charging

Spacecraft in aurora (polar) regions, ring current, plasma sheet (magnetotail) may be subject to surface charging

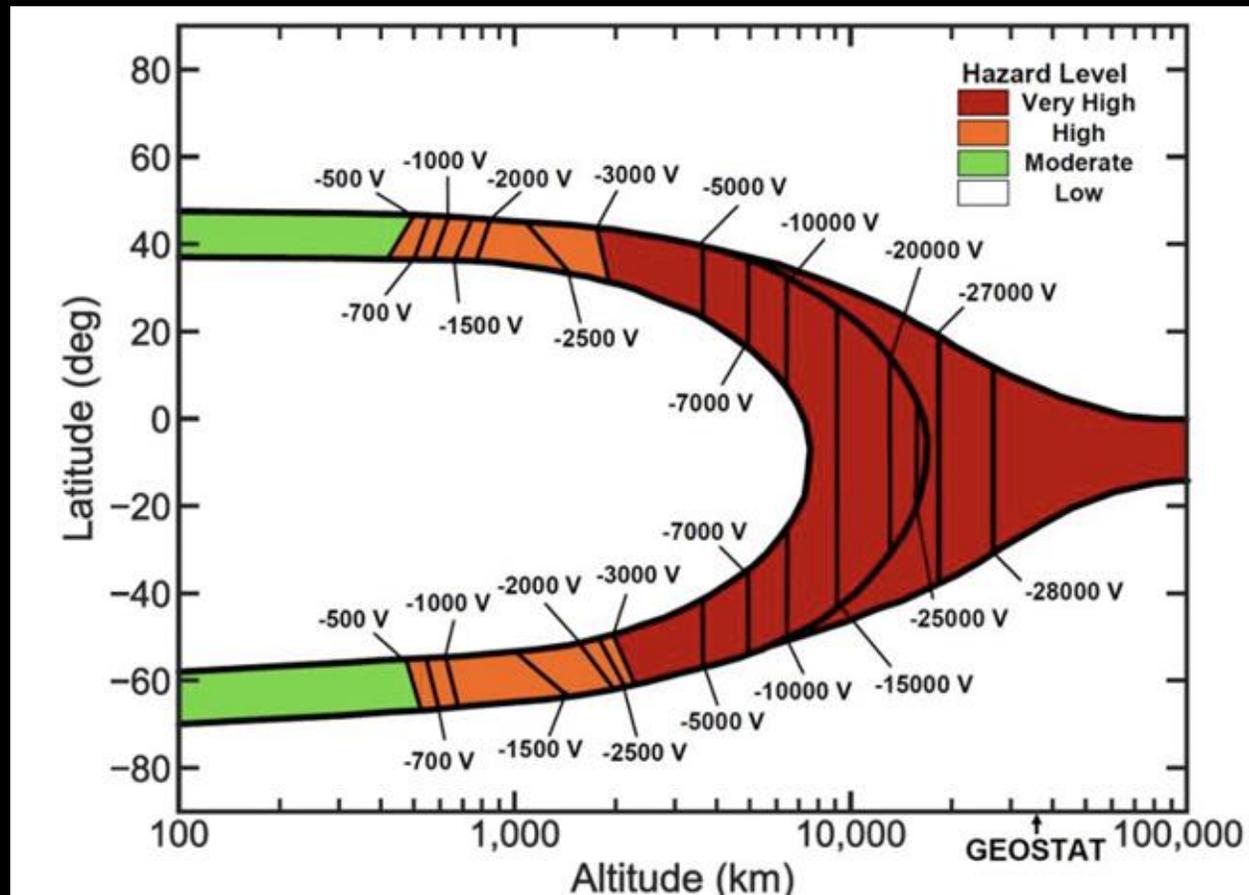
Sunlight (UV) charges surfaces via photoelectric effects



Surface charging: hazard distribution

Probability and magnitude of charging depend on spacecraft orbit

Sunlight-to-shadow transition enhance differential charging



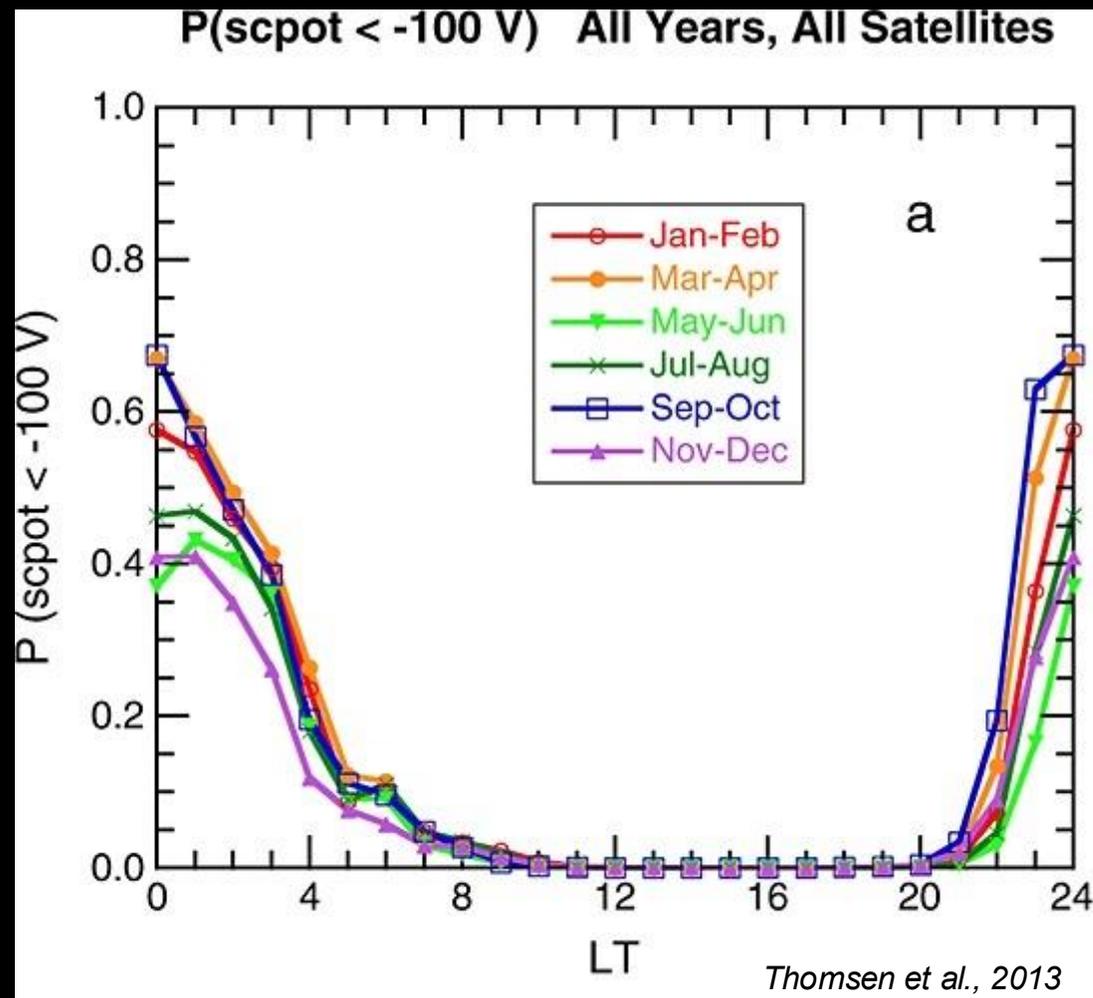
Credits: NASA-HDBK-4002B



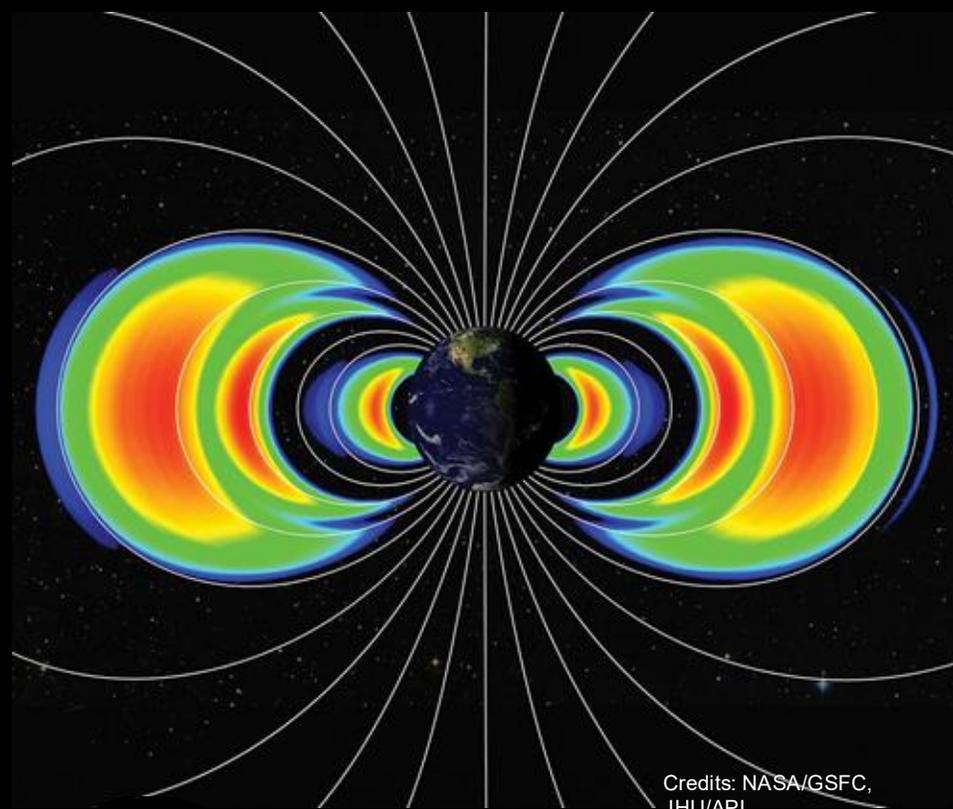
Surface charging: local time dependence

More common for the midnight-morning sector (22 MLT - 04 MLT) at GEO (Thomsen et al., 2013, using 13 years of charging data from LANL satellites)

Similar statistical dependencies as found by Choi et al. (2011) in the satellite anomaly database



Internal charging: sources in space



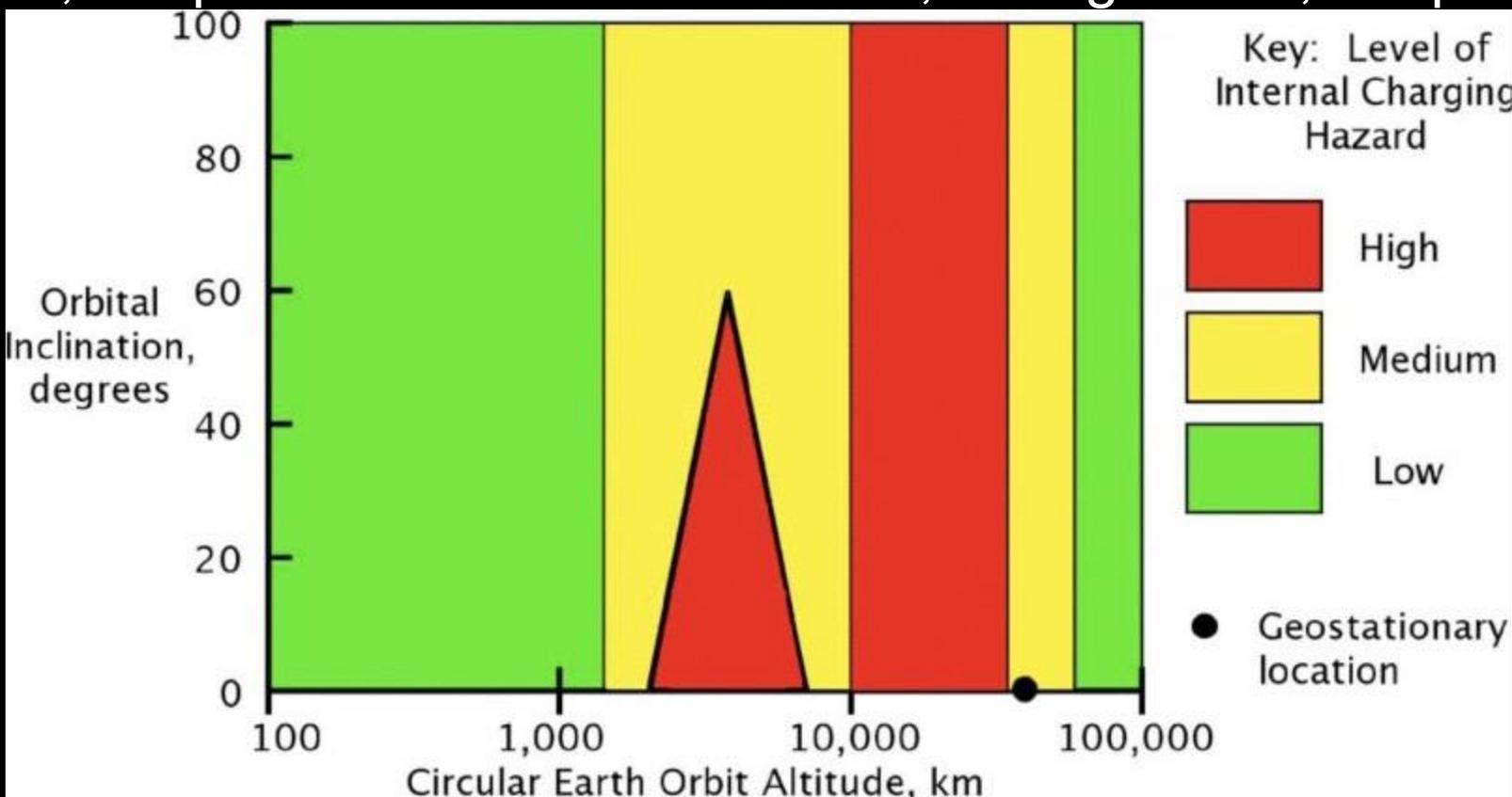
>300 keV electrons (radiation belt) in the near-Earth region are generally considered as the source for internal charging

SWPC: threshold for warning is >2 MeV electron flux above 1000 particle flux units [pfu = $1/(\text{cm}^2 \text{ s sr})$]



Internal charging: hazard distribution

Highest risk: outer radiation belt, changing during geomagnetic storms
 During HSS, the peak is close to GEO orbits; during CMEs, the peak moves inward





Quiz: Spacecraft charging

What are the differences (source, hazard distribution, etc) between surface and internal charging?

Radiation Effects on Satellites

- Single Event Effects (SEE): Damage from individual particle strikes
 - Total Ionizing Dose (TID): Cumulative radiation damage
 - Displacement damage: Atomic lattice disruption
- } Total Dose

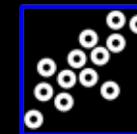
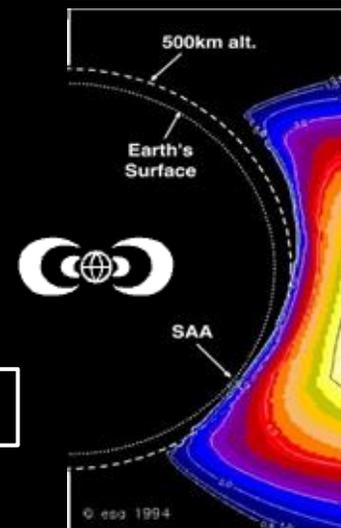
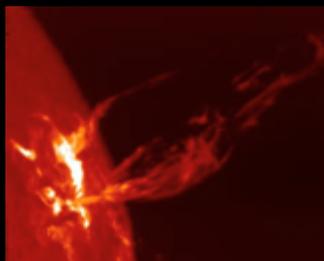
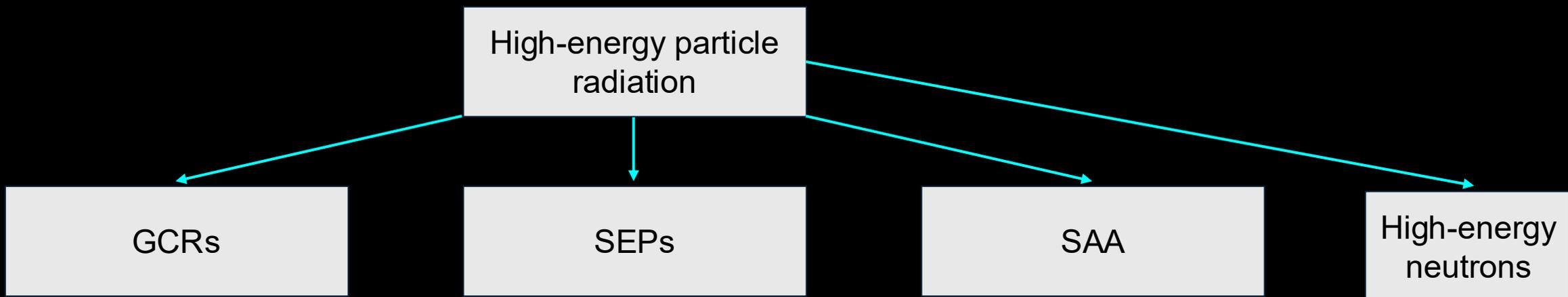




Single-Event Effects (SEEs)

Any measurable effect in a circuit caused by a single incident ion

SEEs: sources in space



protons/ions from GCR, SEP, and SAA with energy > 30 MeV

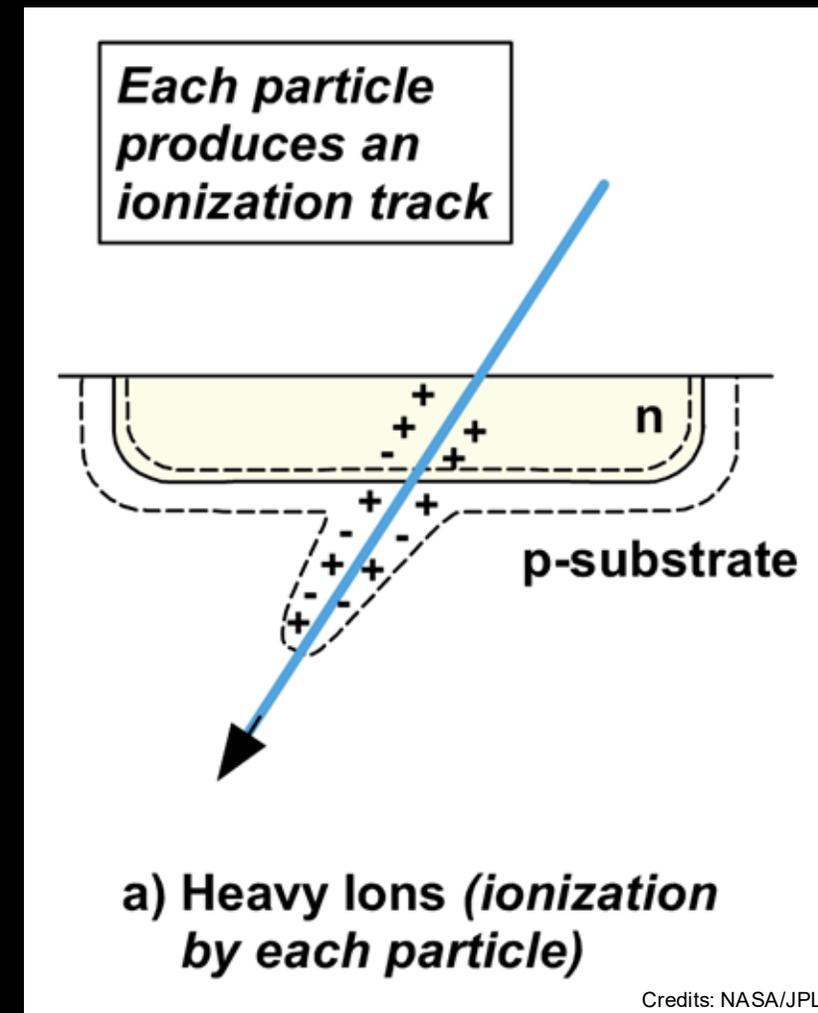


SEEs: what are the causes?

SEEs are due to the current generated by particles passing through the sensitive volume of a biased electronic device: it changes the device operating state

Direct ionization (heavy ions, $Z=2-92$)

Dense ionization track over a short range produces sufficient charge in sensitive volume to cause SEE



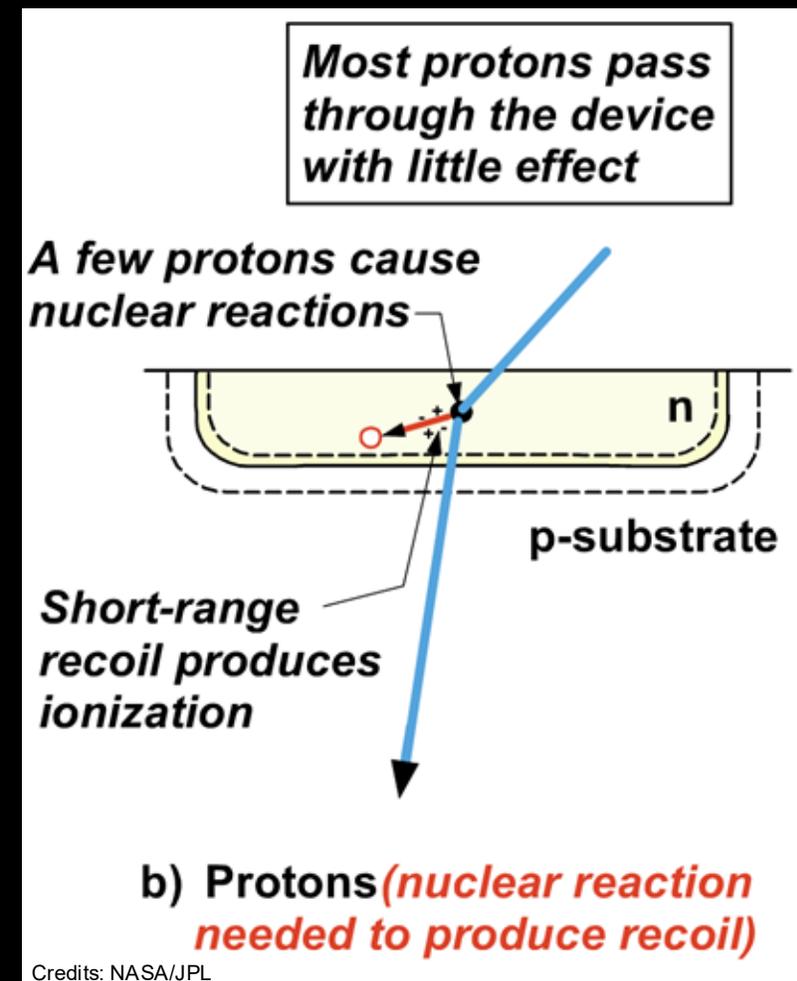
Credits: NASA/JPL



SEEs: what are the causes?

Indirect ionization (protons, $Z=1$)

- Proton ionization too low to generate SEEs
- Secondary heavy ions produced in nuclear reactions with nuclei of atoms (usually silicon) generate SEEs
- Only a small fraction of protons are converted to such secondary particles (1 in 10^4 to 10^5).



Quiz: who did what?

Match each radiation source with the corresponding impact

Radiation
GCR Carbon, 100 MeV/n
Trapped proton, 1 MeV
SEP proton, 1 GeV/n
SEP electron, 30 MeV/n

Impact
None
Direct ionization SEE
None
Indirect ionization SEE

Quiz: who did what?

Radiation	Impact
GCR Carbon, 100 MeV/n	Direct ionization SEE
Trapped proton, 1 MeV	None
SEP proton, 1 GeV/n	Indirect ionization SEE
SEP electron, 30 MeV/n	None

SEEs: what problems do they cause?



Non-destructive

- Affect component functionality, but are reversible errors, usually fixed by themselves or by power cycling the affected component/system



Destructive

- Permanent damage to component

Mitigation

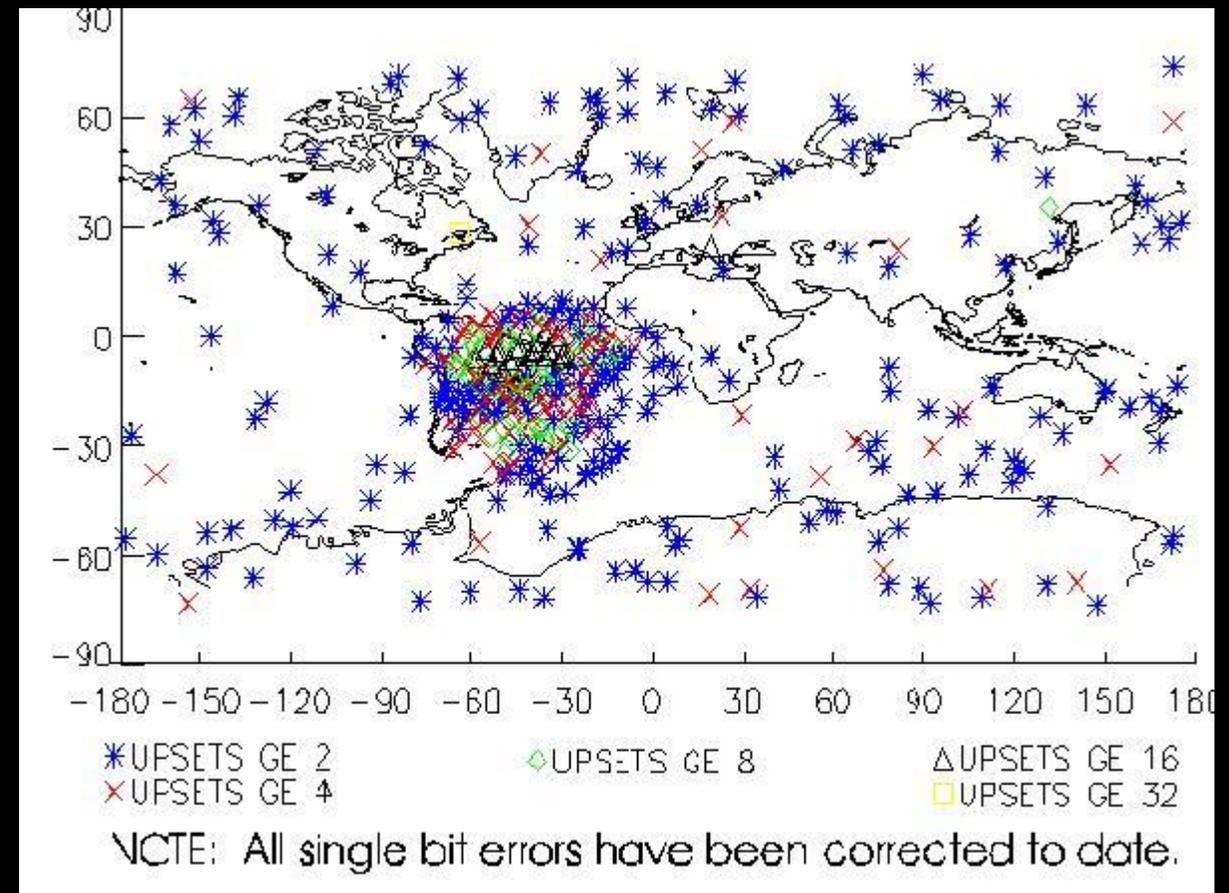
- Radiation hardening (insulating substrates, “simpler” components, ...)
- Shielding
- Error correcting code memory, redundancy

Non-destructive SEEs

 Soft errors, normally appear as transient pulses in logic or supporting circuitry, or as bitflips in memory cells or registers

- SEU: Single-event upset
- SET: Single-event transients
- MBU: Multiple-bit upsets
- Hot pixels

Non-destructive SEEs can still lead to destructive effects for upstream systems!



Credits: [Seidleck et al. \(2003\)](#)

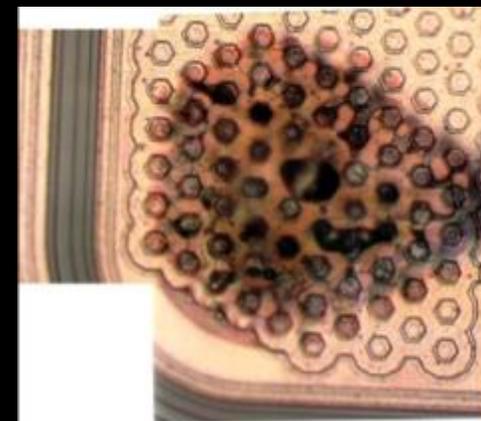
Destructive SEEs



Hard errors, usually some kind of short-circuit:

- SEL: Single-event latchup (might be recoverable with power cycle)
- SEGR: Single-event gate rupture
- SEB: Single-event burnout
- Stuck bits (hard SEU)
- Dead pixels

Different technologies (BJT, FET, MOSFET, CMOS, etc) are affected in different ways



*Destructive event in a COTS 120V
DC-DC Converter*

Quiz: Destructive and non-destructive SEEs

The sentences below have multiple options in the brackets: please, choose the best answer to complete each sentence.

- Destructive SEEs [**are/are not**] permanent damages to electronics components
- Bit flips are an instance of [**SEU/SEL**]
- SEUs are more frequent [**in the SAA/at high latitudes**]
- Dead pixels [**can/can not**] restored with a power cycle
- Error correction code memory [**is/is not**] a mitigation strategy against SEB

Quiz: Destructive and non-destructive SEEs

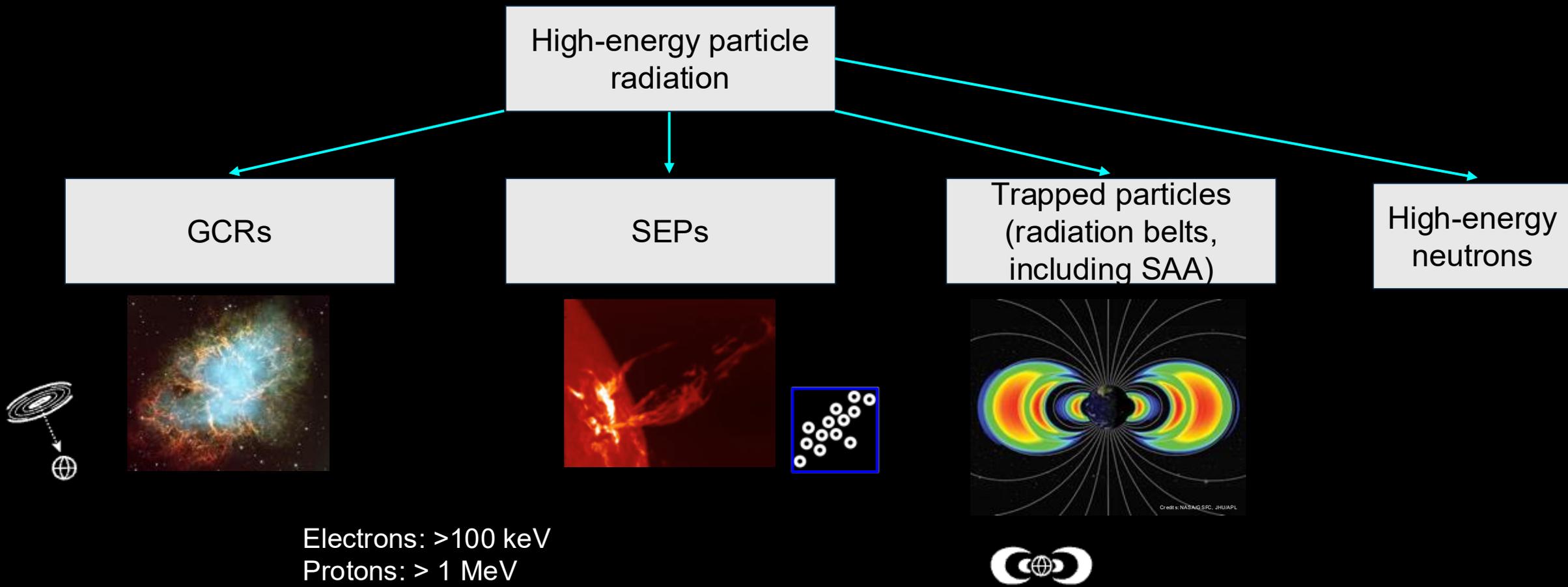
The sentences below have multiple options in the brackets: please, choose the best answer to complete each sentence.

- Destructive SEEs **are** permanent damages to electronics components
- Bit flips are an instance of **SEU**
- SEUs are more frequent **in the SAA**
- Dead pixels **can not** restored with a power cycle
- Error correction code memory **is not** a mitigation strategy against SEB



Total dose

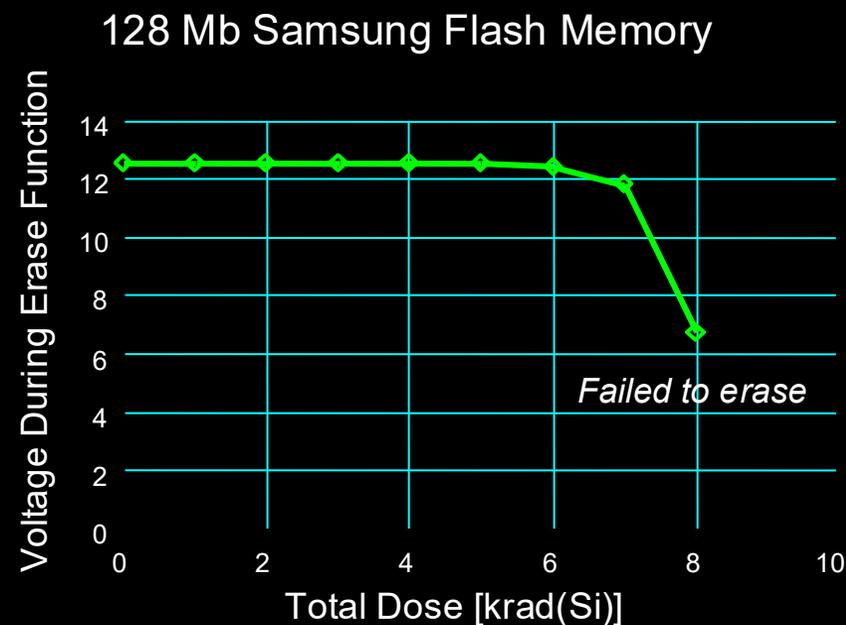
Total dose: sources in space



Total dose effects: TID

Total Ionizing Dose (TID): cumulative damage resulting from ionization (electron-hole pair formation) causing

- Threshold voltage shifts
- Timing skews
- Leakage currents

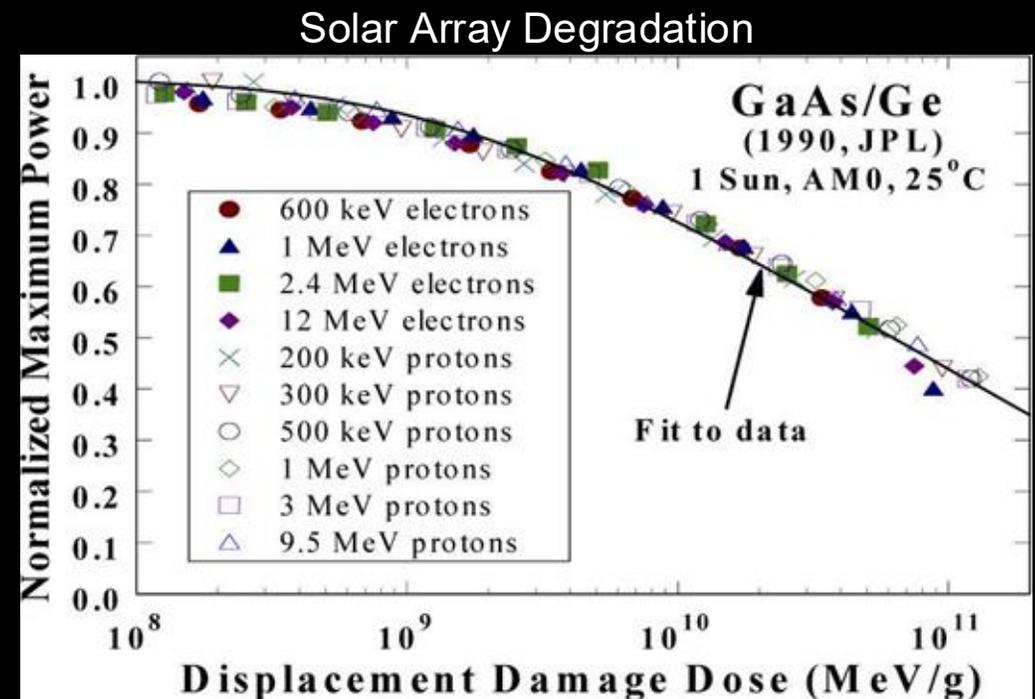


Total dose effects: DDD

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 et al. (2001), DOI:[10.1002/PIP.357](https://doi.org/10.1002/PIP.357)

SEE vs TID



TID: lightly ionizing particles are important if abundant enough to **collectively** produce an effect

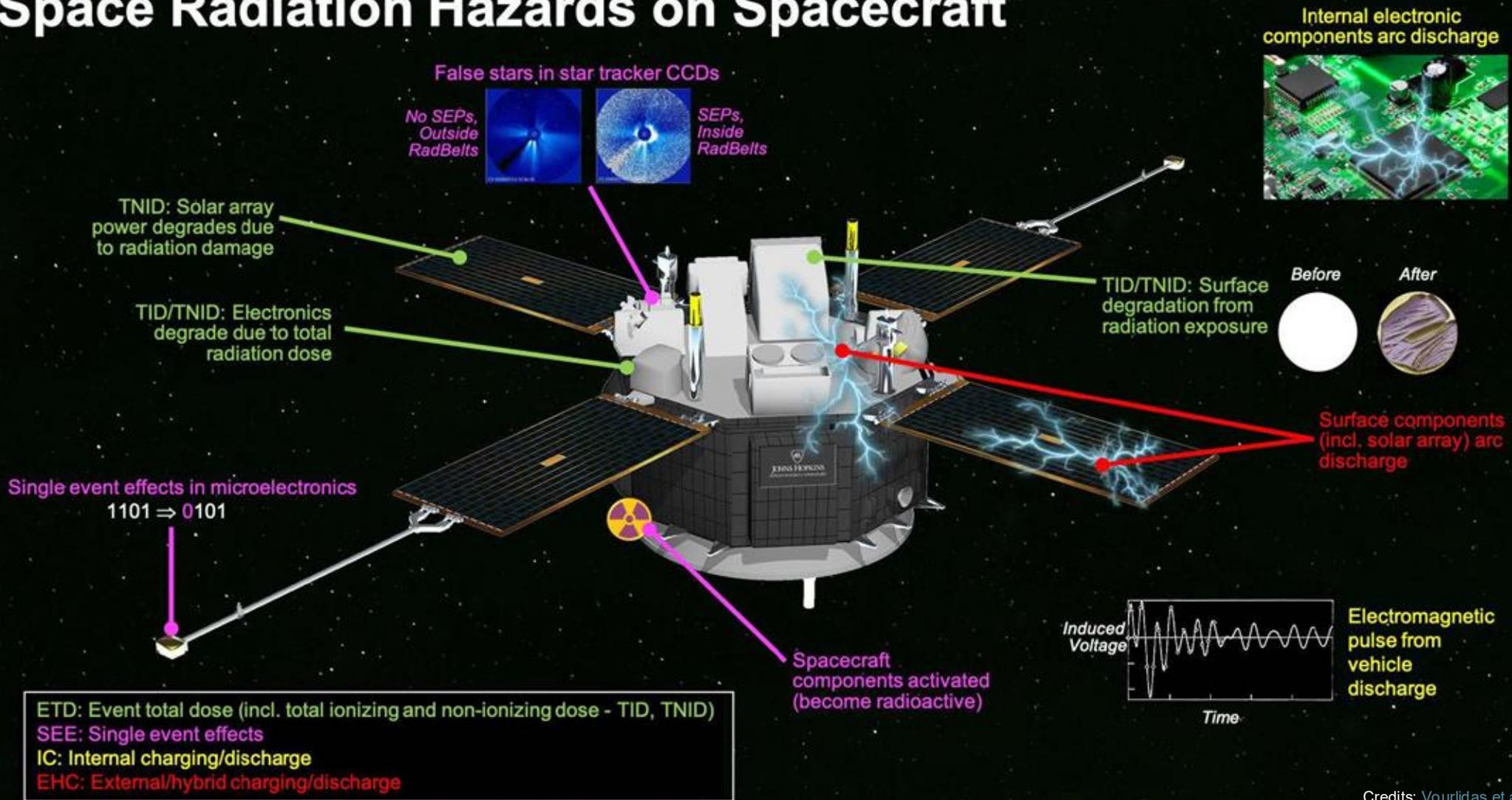
SEE: only the particles **individually** able to produce an event are relevant



Quiz: Total dose

- What are the two categories of total dose?
- What is the difference between SEE and TID?

Space Radiation Hazards on Spacecraft



Credits: [Vourlidis et al. \(2021\)](#)



SEAES-FC tool at CCMC

Spacecraft Environmental Anomalies Expert System - Flow Chart

SEAESFC
Spacecraft Environmental Anomalies Expert System - Flow Charts
Hosted by the Community Coordinated Modeling Center (CCMC)

Anomaly Entry

UNCLASSIFIED DATA ENTRY ONLY!!!

Anomaly Description:
Aqua

Date and Time of Anomaly (yyyy-mm-dd HH:MM:SS, UTC):
2024-06-20 08:00:00

History of GCR SEE on vehicle or in constellation:
NO

Internal charging anomaly on vehicle or in constellation during 5 days (120 hours) prior to anomaly: NO

Automatically store anomalies in browser database

Orbit

Specify Type & Location | ECP Sensor Host | Catalog Lookup | Enter TLEs

On-Line Ephemeris Source:
NASA SSCWeb

Aqua

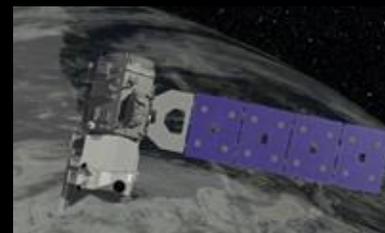
Results

Hazard	Conclusion	Explanation
Surface Charging	SC Unlikely	Does not fit SAMPEX or DMSP pattern
Internal Charging	Investigate IC	Enhanced slot
Event Total Dose	ETD Unlikely	LEO sees SAA/Inner Belt every day
Single Event Effects	SEE Unlikely	Ruled out SEP, SAA/inner belt, slot belt, GCR

Tap or click diagrams to expand once generated.

Surface Charging Flow Chart

- Used by Moon-to-Mars Space Weather Analysis Office (M2M SWAO) to support spacecraft anomaly resolution for NASA missions and joint missions
- Used by some of the mission teams (including joint missions with USGS, NOAA) directly for their anomaly analyses



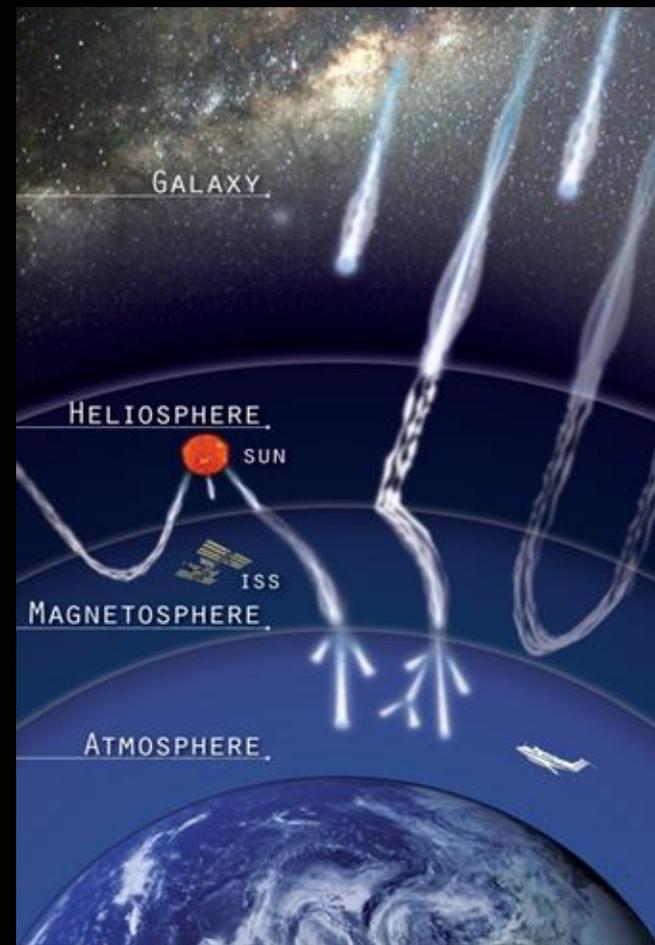
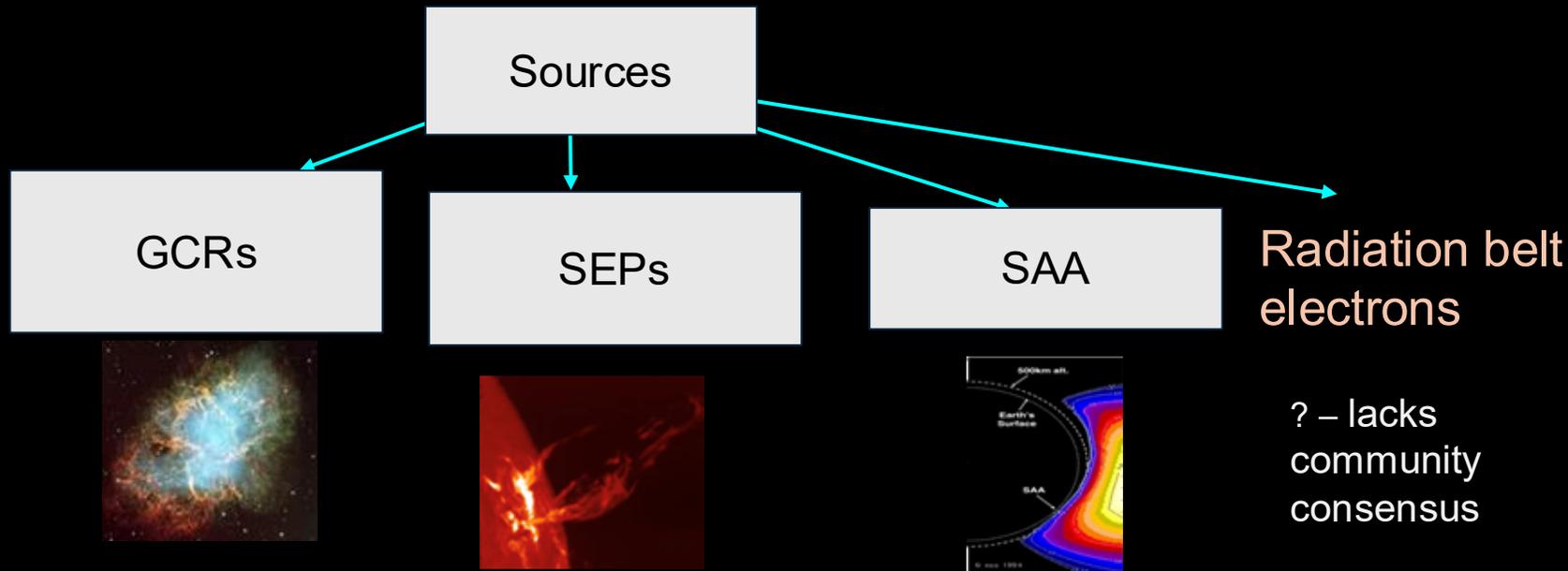
On June 20, Aqua and Aura came within minutes of having to go into safe mode.



Aviation impacts



Radiation effects at aviation altitudes



- Main impact: increase of cancer risk on crew and passengers
- SEEs on avionics
- More risks for polar flights during SEPs and to higher altitude flights



NAIRAS model at CCMC

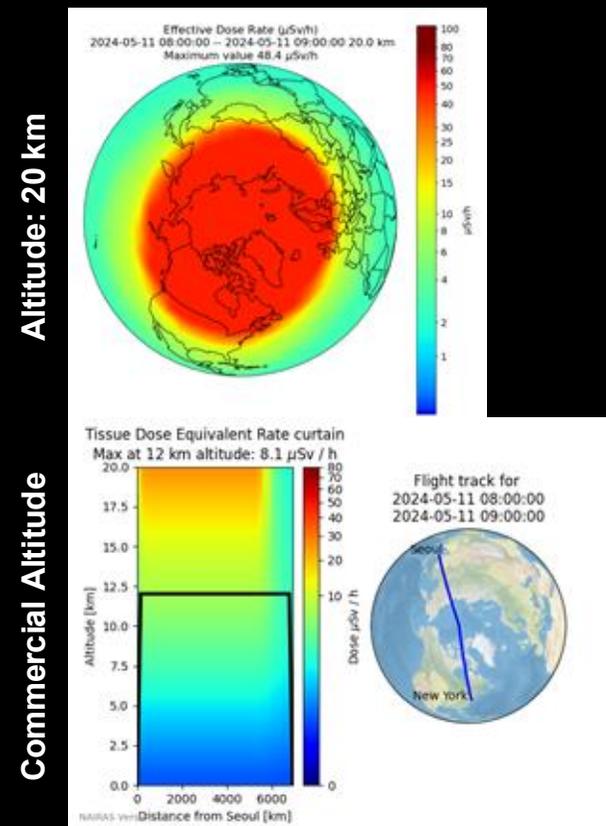
Nowcast of Aerospace Ionizing RAdiation System (NAIRAS)

- **Output products:** dose quantities for assessing human radiation exposure and radiation flux quantities for characterizing single event effects (SEE) in flight electronic systems
- **Model Domain:** Earth's surface to cislunar (at Mars too)
- **Output availability:** (1) real-time atmospheric radiation environment, and (2) run-on-request (RoR) service (all products over all model domain)

Recent News:

- U.S. Space Force (USSF) using NAIRAS predictions at 20 km in operations to support U2 pilot exposure.
- USSF used NAIRAS predictions to recall operational U2 flight during the May 10-12, 2024 SEP and Nov 2025 events
- **Forecasting:** 3-7 hours SEP forecast of peak dose after event onset by coupling NAIRAS with UMASEP.

May 10-12, 2024 SEP Event



<https://ccmc.gsfc.nasa.gov/models/NAIRAS~3.0>

Essential Space Environment Quantities and Impacts

Table 11. Essential Space Environment Quantities (ESEQs): their corresponding impacts and temporal scales.

Impacts	Impact Quantity	ESEQ	Time Scales
Surface Charging	>10keV e- flux	>10keV e- flux; Te; Ne	seconds
Internal Charging	>100 fA/cm ² (100 mils)	1 MeV and >2MeV e- flux	24-hour, 72hr averaged
Single Event Effects	SEE rate (100 mils)	>30MeV p+flux	5-min, daily, weekly (worst)
Total Dose in orbit and in the atmosphere	Dose in Silicon (100 mils; 4 mils)	30–50MeV p+flux; >1.5MeV e- flux 1–10MeV p+	5-min, Hourly, Daily, weekly, yearly
Aviation	Dose rate in aircraft (D-index) and single event rates in avionics	>300MeV p+flux; spectral parameter (power law with rigidity)	5-min, Hourly

- ESEQs: a bridge between space environment and effects
- Can serve as a ‘proxy’ for effects



Zheng et al., 2024



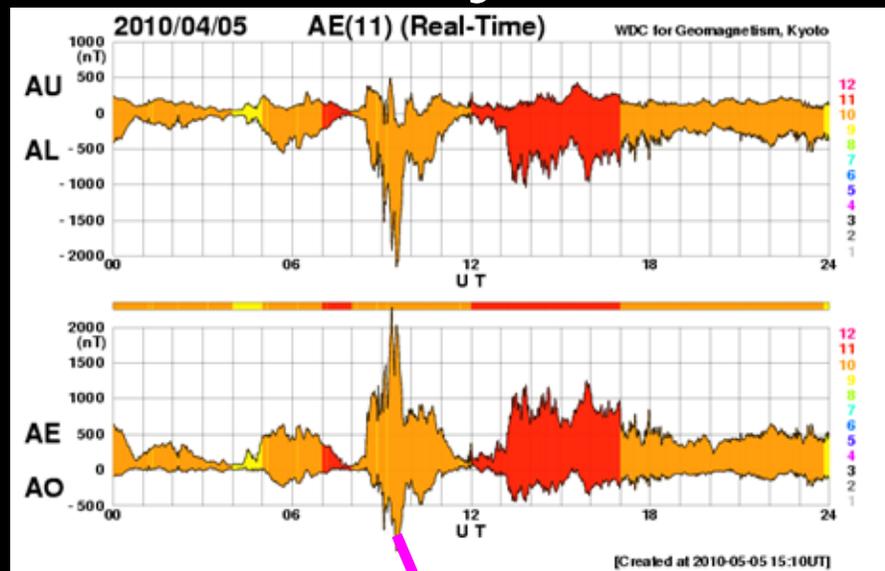
Exercises

Exercise 1: Galaxy 15 failure on April 5, 2010

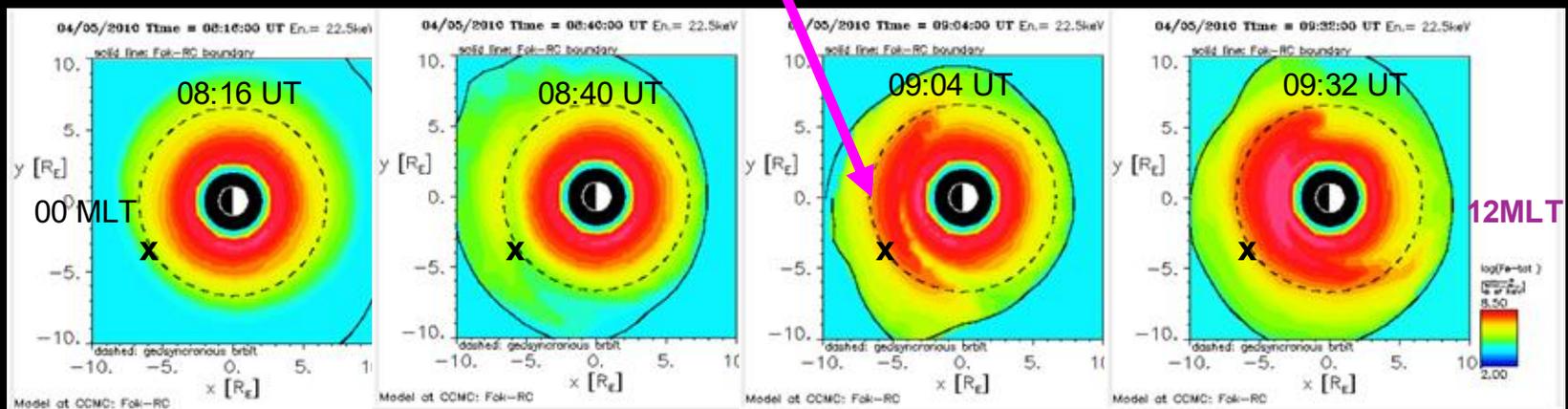
AU/AL/AE: indices for substorm activity

super substorm (AL: -2200 nT)!

nominal AL intensity (-200 nT)



Galaxy 15 failed approx 9:48 UT, located around 01 MLT



Simulations show a new population of **~22 keV electrons** (with high intensity) due to substorm injections overwhelms the satellite at 09:04 UT

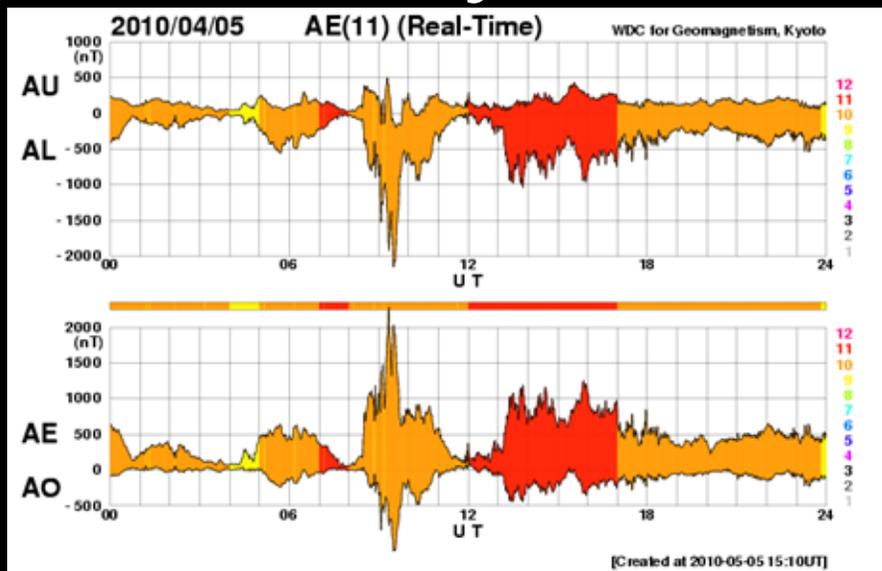
The color-bar is flux in logarithmic values

Exercise 1: Galaxy 15 failure on April 5, 2010

AU/AL/AE: indices for substorm activity

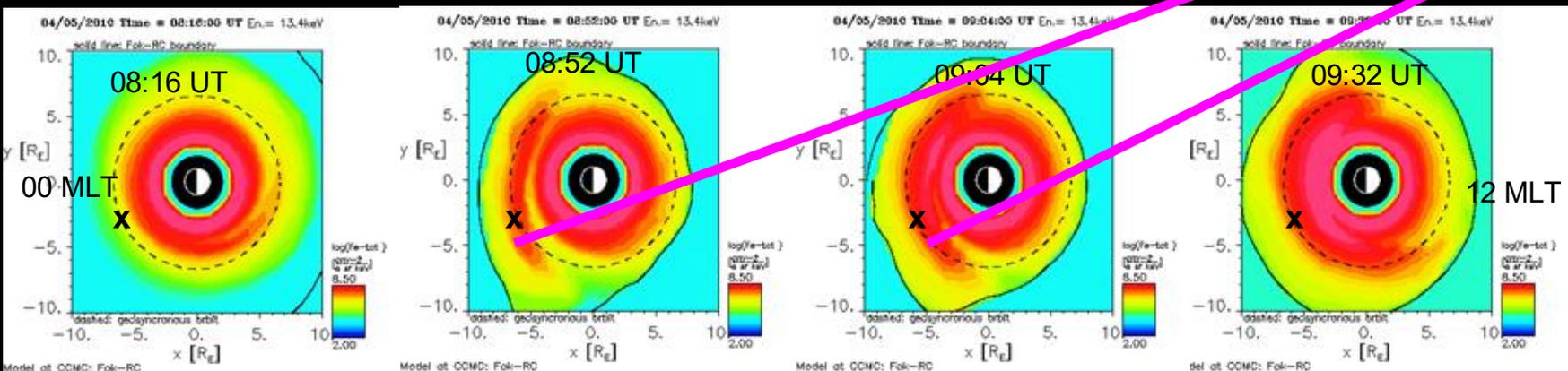
super substorm (AL: -2200 nT)!

nominal AL intensity (-200 nT)



Galaxy 15 failed approx 9:48 UT, located around 01 MLT

Simulations show a new population of 13 keV electrons (with high flux intensity) due to substorm injections overwhelms the satellite starting at 08:52-09:04 UT



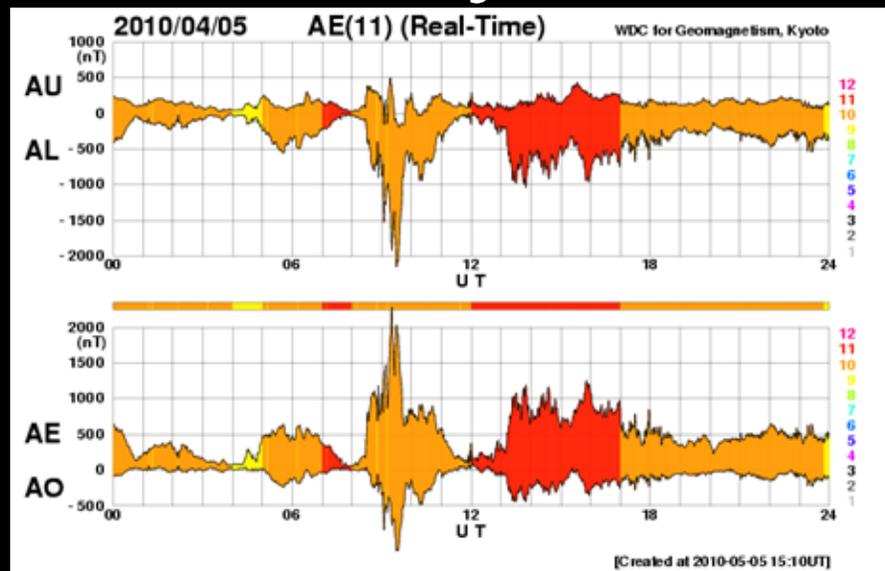
The color-bar is flux in logarithmic values

Exercise 1: Galaxy 15 failure on April 5, 2010

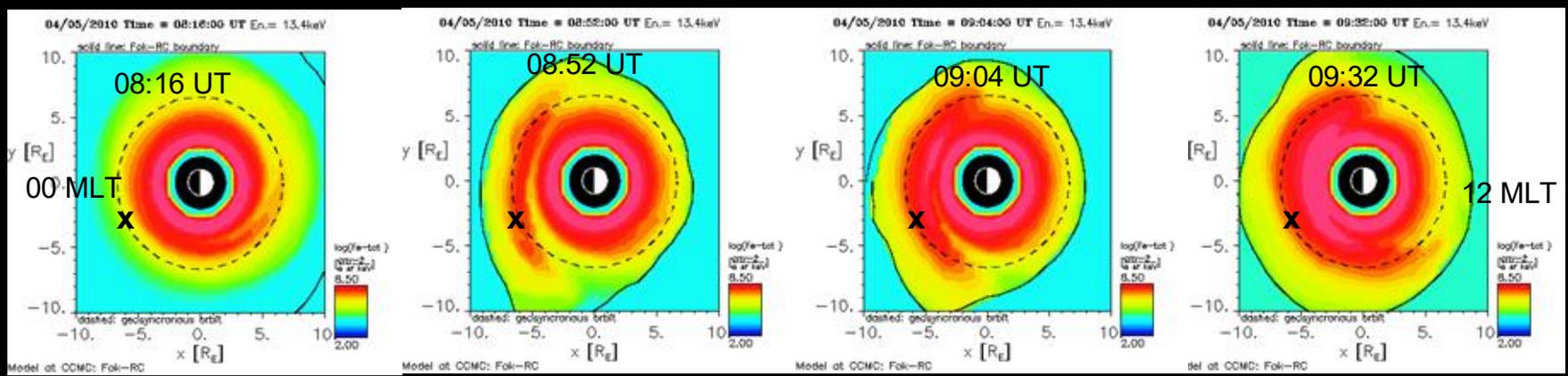
AU/AL/AE: indices for substorm activity

super substorm (AL: -2200 nT)!

nominal AL intensity (-200 nT)



Q: What kind of spacecraft impact may have contributed to this anomaly?



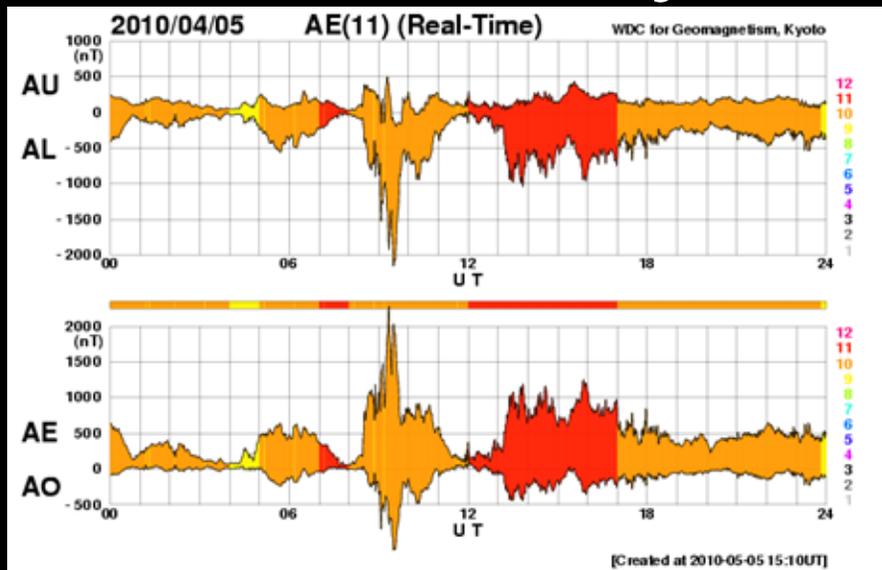
Galaxy 15 failed approx 9:48 UT, located around 01 MLT

Exercise 1 answer: Galaxy 15 failure on April 5, 2010

AU/AL/AE: indices for substorm activity

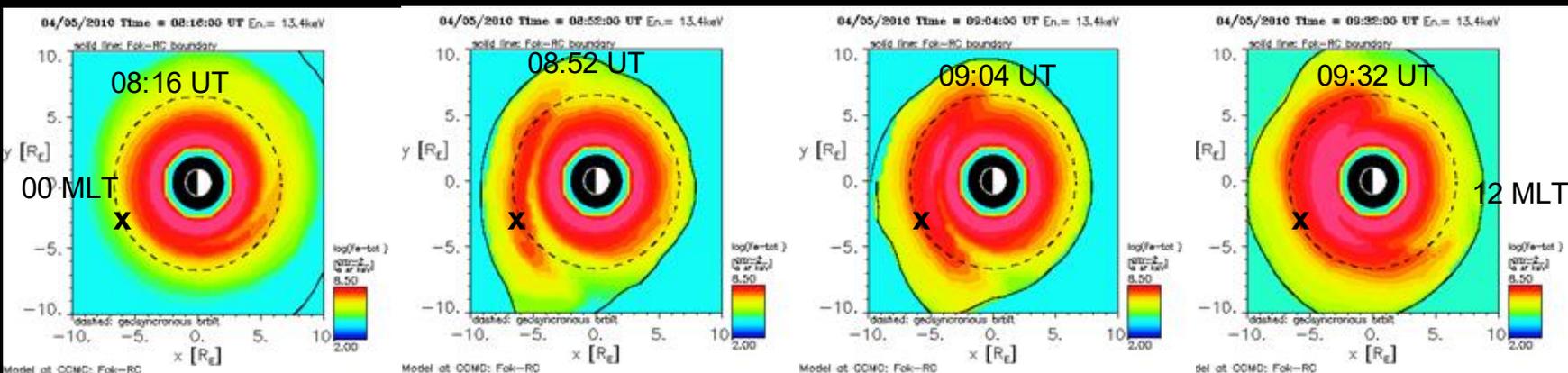
super substorm (AL: -2200 nT)!

nominal AL intensity (-200 nT)



Q: What kind of spacecraft impact may have contributed to this anomaly?

Answer: Just before failure, there were strong intensity substorm injections of 13-22 keV electrons and the satellite location was 01 MLT (early morning). The particle energy range, intensity and location puts the spacecraft at risk for **surface charging**.



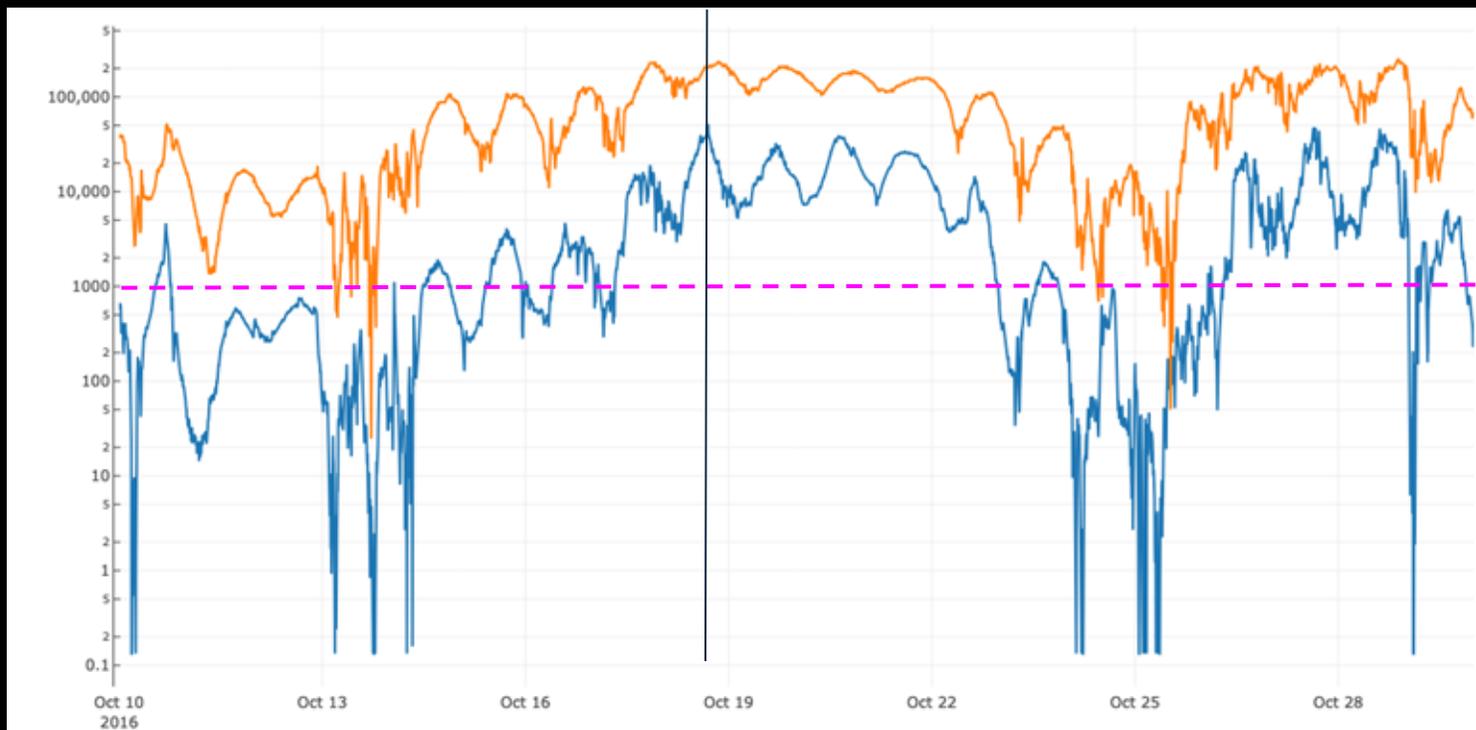
Galaxy 15 failed approx 9:48 UT, located around 01 MLT

Exercise 2: The >2 MeV electron flux

GOES 15
electron flux
measurements
(pfu)

Orange: >0.8
MeV electrons
integral flux

Blue: >2 MeV
electrons
integral flux



SWPC threshold: 1000 pfu

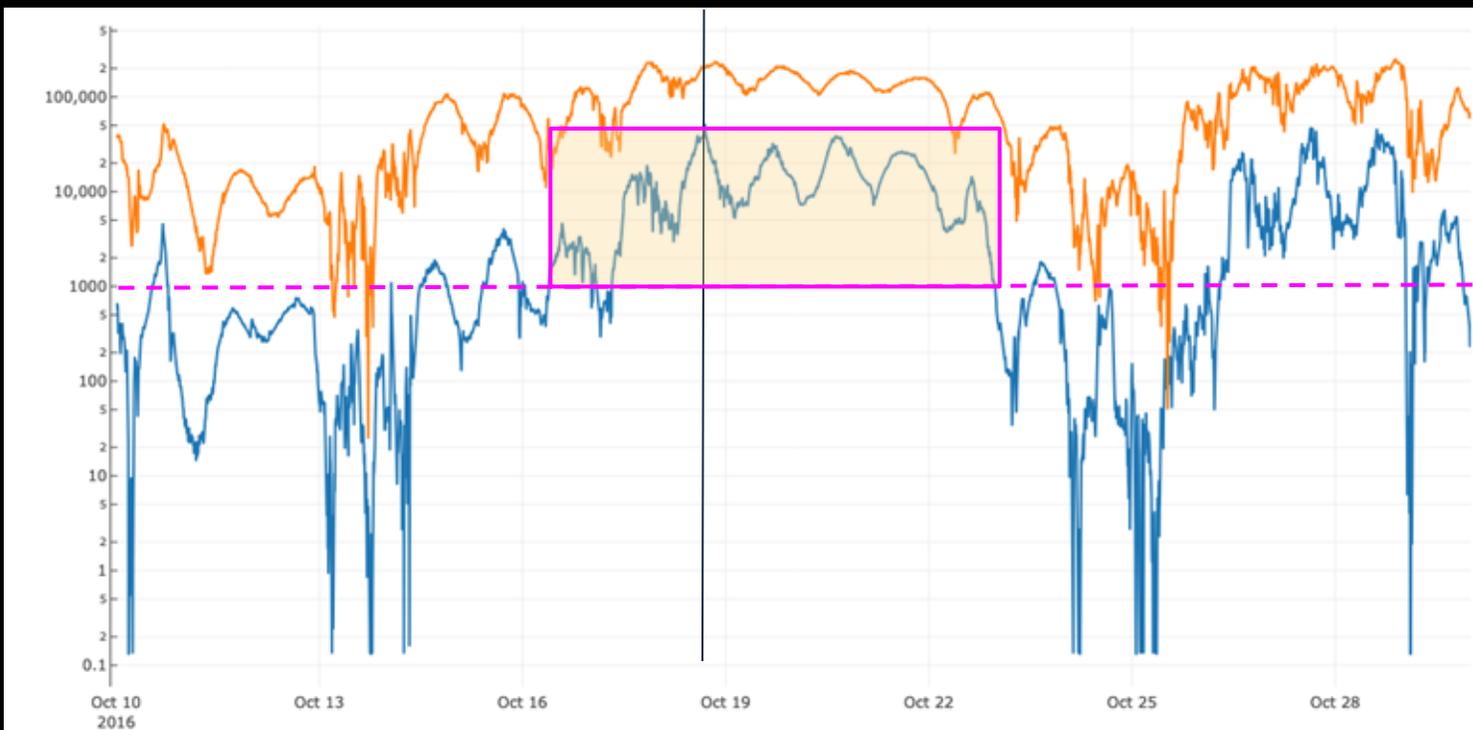
Q: A spacecraft experiencing these conditions on 2016-10-18T16:00Z might experience anomalies due to what spacecraft impact?

Exercise 2 answer: The >2 MeV electron flux

GOES 15
electron flux
measurements
(pfu)

Orange: >0.8
MeV electrons
integral flux

Blue: >2 MeV
electrons
integral flux



SWPC threshold: 1000 pfu

Q: A spacecraft experiencing these conditions on 2016-10-18T16:00Z might experience anomalies due to what spacecraft impact?

Answer: Starting on 2016-10-18T16:00Z the >2 MeV electron flux well exceeds the threshold of 1000 pfu over a period of one week. This puts this spacecraft at risk for internal charging.

Exercise 2 answer: The >2 MeV electron flux

UNCLASSIFIED - For Demonstration Purposes Only

SEAESFC
 Spacecraft Environmental Anomalies Expert System - Flow Charts
 Hosted by the Community Coordinated Modeling Center (CCMC)

Anomaly Entry

UNCLASSIFIED DATA ENTRY ONLY!!!

Anomaly Description:

Date and Time of Anomaly (yyyy-mm-dd HH:MM:SS, UTC):
 History of GCR SEE on vehicle or in constellation:
 Internal charging anomaly on vehicle or in constellation during 5 days (120 hours) prior to anomaly:
 Automatically store anomalies in browser database

Orbit

Specify Type & Location	ECP Sensor Host	Catalog Lookup	Enter TLEs
On-Line Ephemeris Source:			

Results

Hazard	Conclusion	Explanation
Surface Charging	SC Unlikely	Does not fit SAMPEX or DMSP pattern
Internal Charging	Investigate IC	Enhanced electrons near GEO
Event Total Dose	ETD Unlikely	No big SEP in progress (high perigee only)
Single Event Effects	SEE Unlikely	Ruled out SEP, SAA/inner belt, slot belt, GCR

Tap or click diagrams to expand once generated.

Input for the tool SEAES-FC:

Time: 2016-10-18 16:00:00 UT

satellite: GOES 15

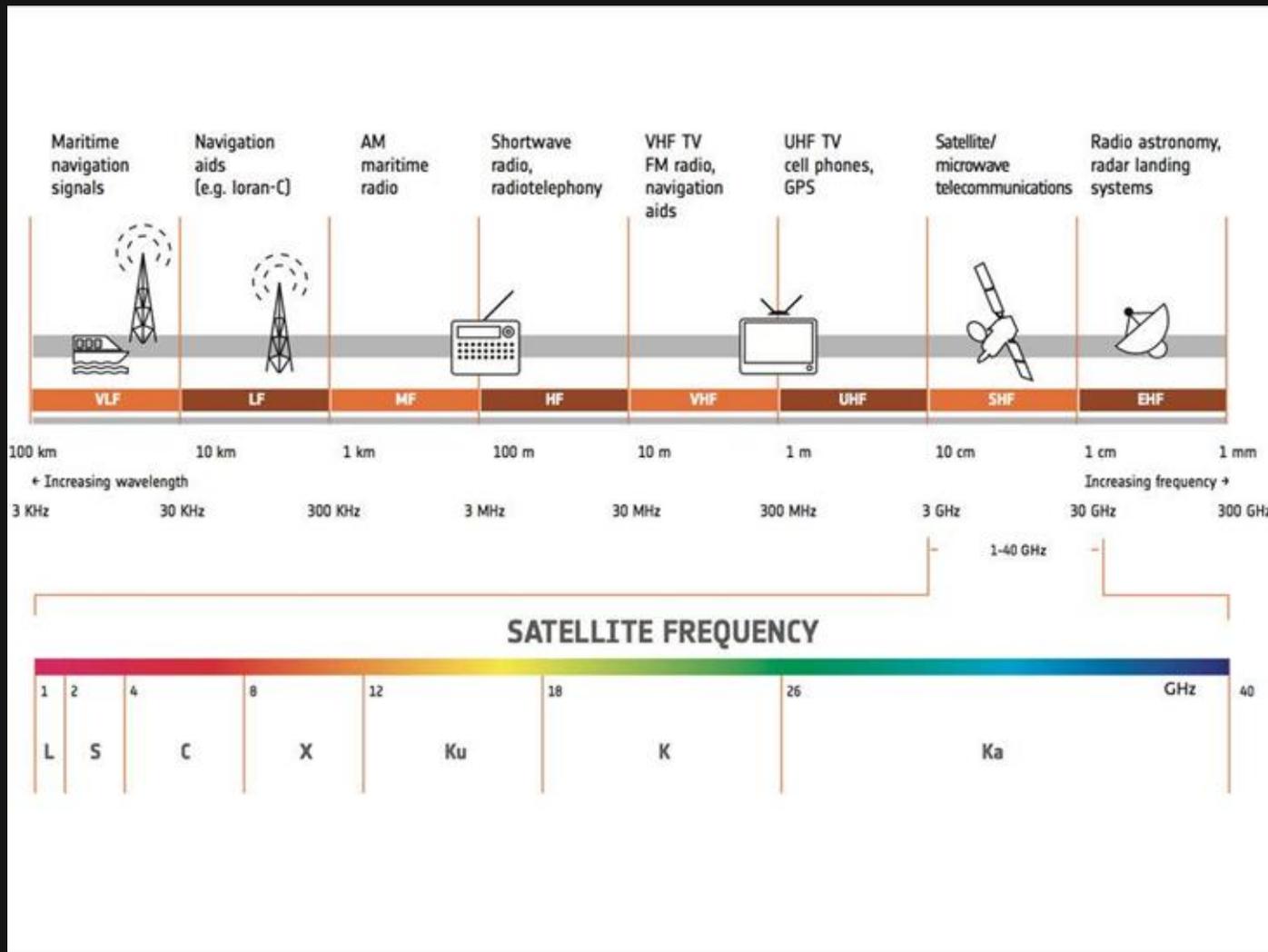
IC: Internal Charging

<https://ccmc.gsfc.nasa.gov/seaesfc/>

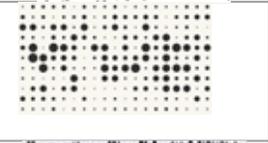
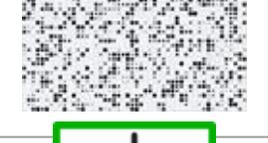
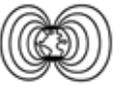


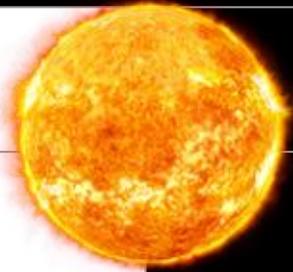
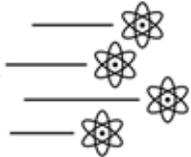
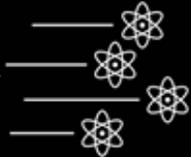
Backup slides

Satellite Frequency Bands in the Context of the Commonly Used Frequencies



		Altitude			dipole
		Antenna			disturbed magnetic field auroral oval
		atmosphere polar cap			disturbed magnetosphere
		atmosphere			earth continents
		blue earth			Earth day/night
		cloud with wind no frame			earth latitude
		cloud with wind			EGSOL

		electrons scintillation		planet
		electrons scintillation		IO
		electrons scintillation		scintillation
		EM radiation		velekken copy
		energetic particles		earth
		folder archive icon		magnetosphere polar caps
		FP Satellite Icon		magnetosphere

		mass		sun!
		plane		
		polar caps		transmit time
		position earth		
		radiation		
		satellite		
		scale		