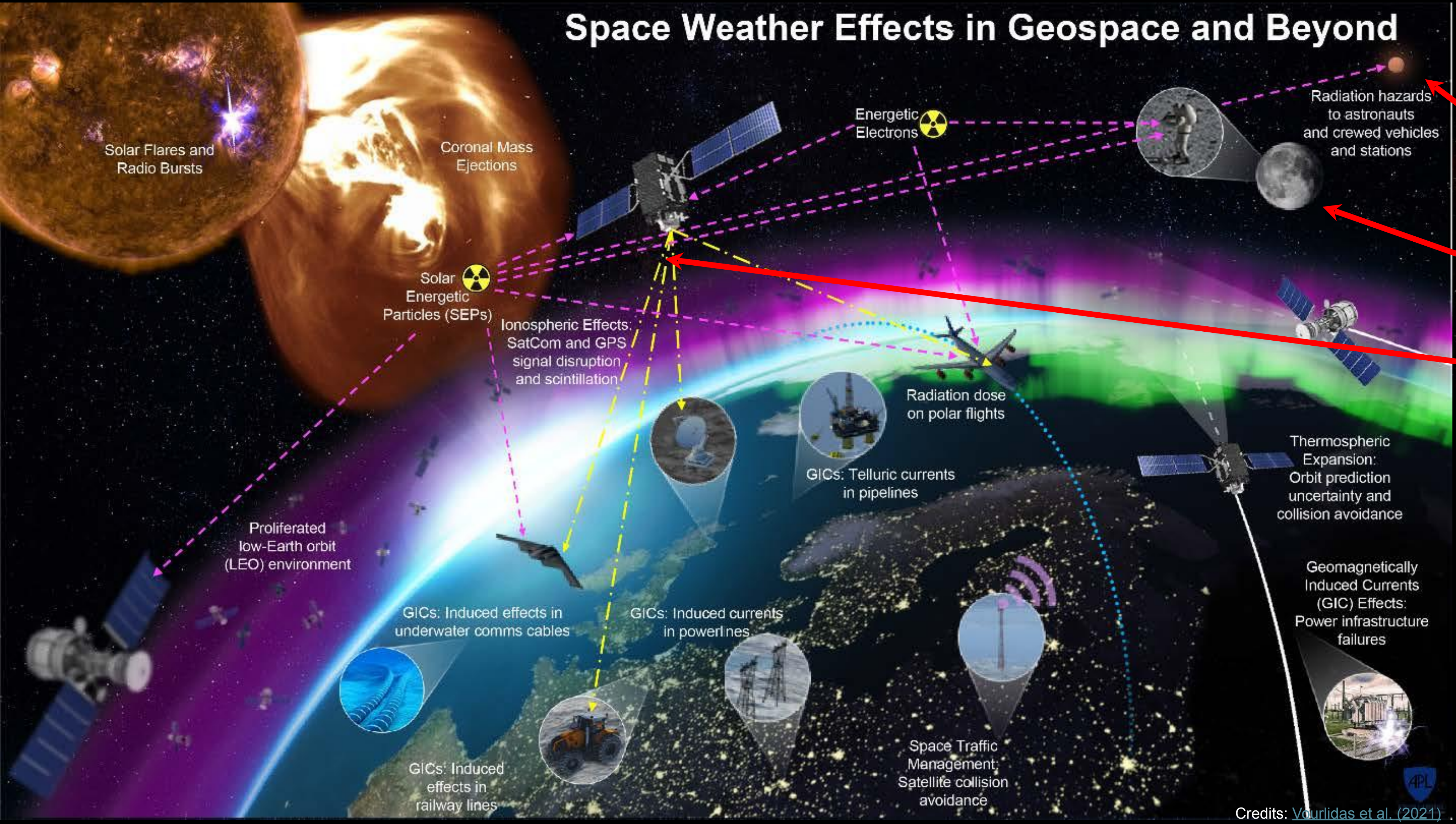
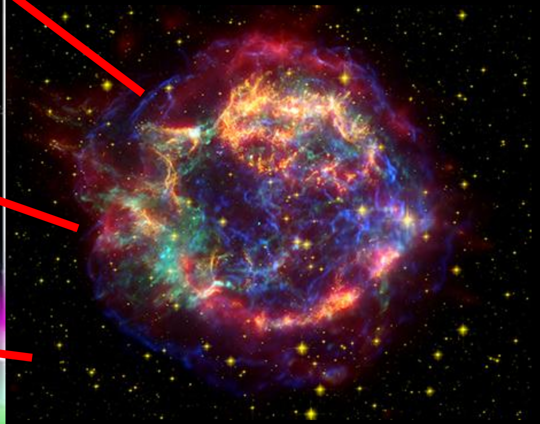
Satellite Impacts

location, location, location

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


Space Weather Effects in Geospace and Beyond
Solar Flares and Radio Bursts
Coronal Mass Ejections
Energetic Electrons
Radiation hazards to astronauts and crewed vehicles and stations
Solar Energetic Particles (SEPs)
Ionospheric Effects: SatCom and GPS signal disruption and scintillation
Radiation dose on polar flights
GICs: Telluric currents in pipelines
Thermospheric Expansion: Orbit prediction uncertainty and collision avoidance
Proliferated low-Earth orbit (LEO) environment
Geomagnetically Induced Currents (GIC) Effects: Power infrastructure failures
GICs: Induced effects in underwater comms cables
GICs: Induced currents in powerlines
GICs: Induced effects in railway lines
Space Traffic Management: Satellite collision avoidance
Credits: Vourlidas et al. (2021)


GCRs

Space climatology and space weather

Space climatology:

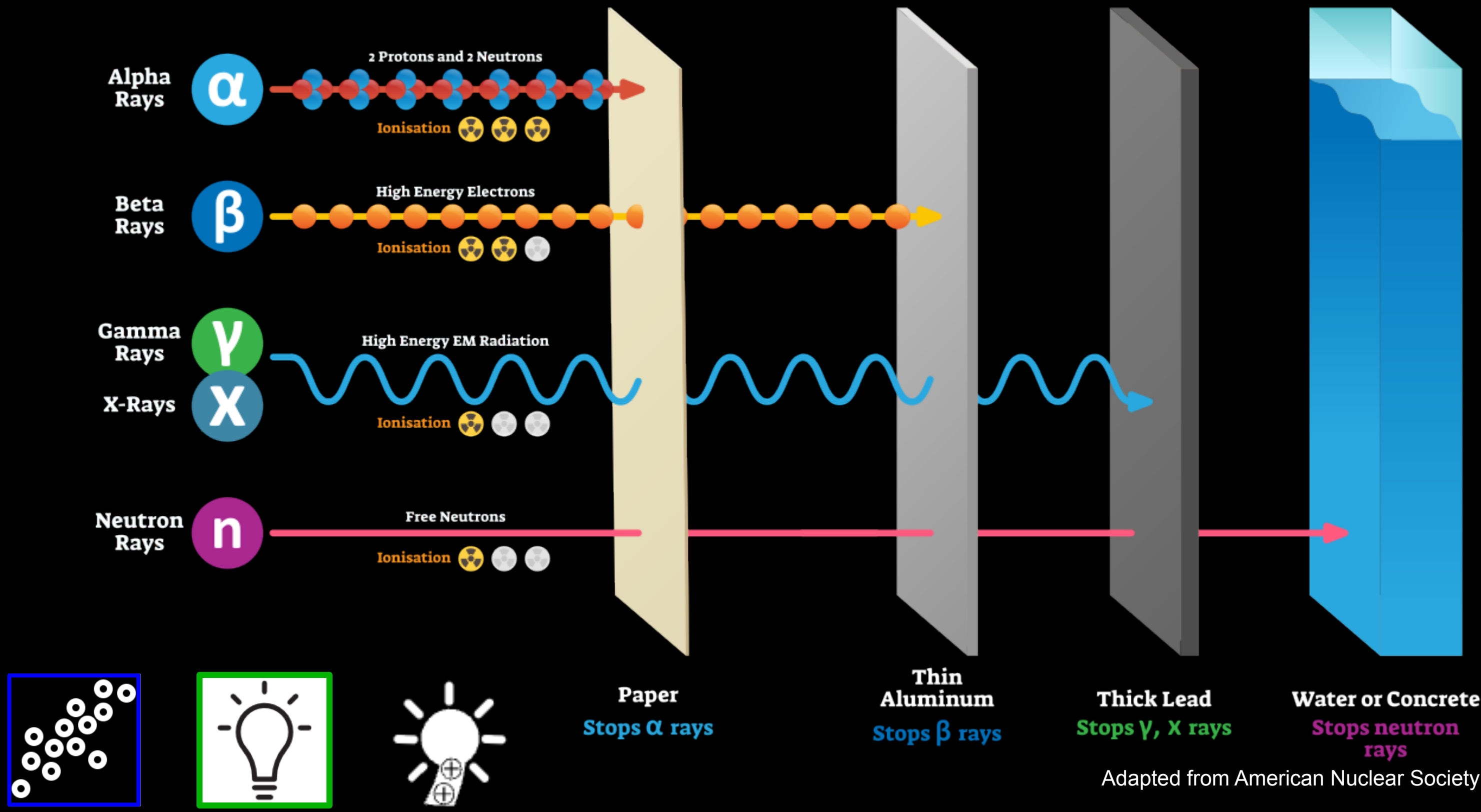
- Variability over months to years
- Space environment effects on both satellites and launch vehicles are best mitigated by good design

Space weather:

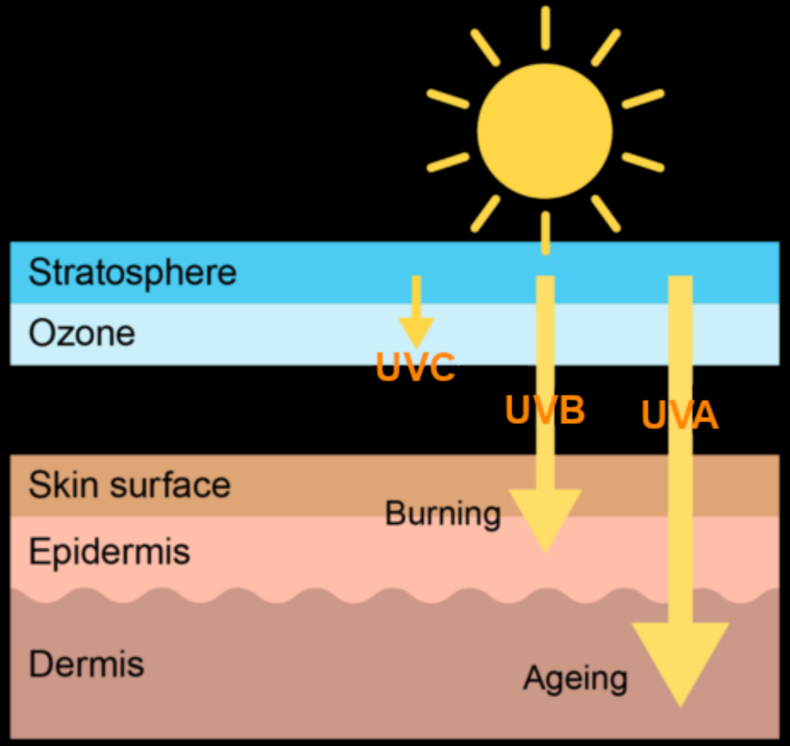
- Variability over minutes to days
- Effects mitigated by design or operational controls
- Design satellites to withstand mean, extreme space weather events that may occur during time on orbit

What is radiation?

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



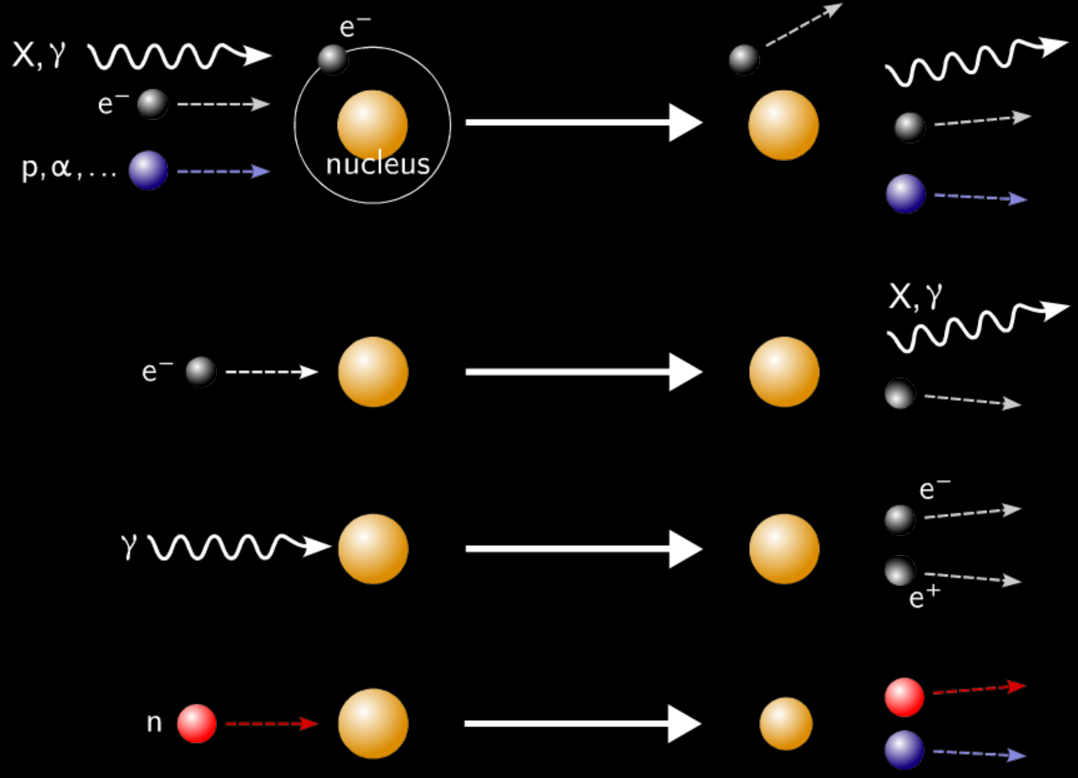
Adapted from American Nuclear Society

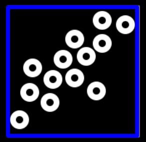


Adapted from Cancer Research UK

How does radiation affect materials?

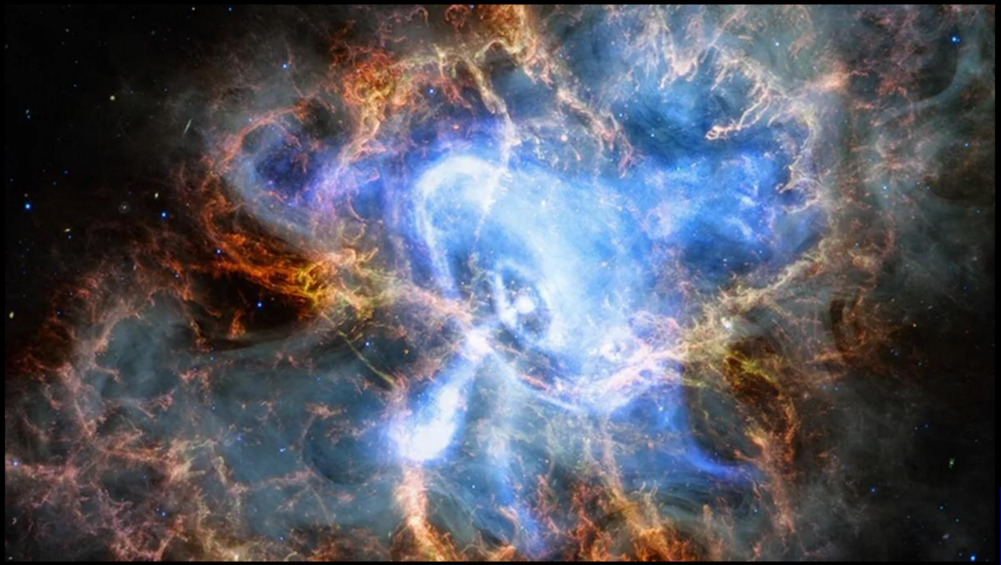
Mostly by ionizing the traversed matter: electrons are stripped out of atoms



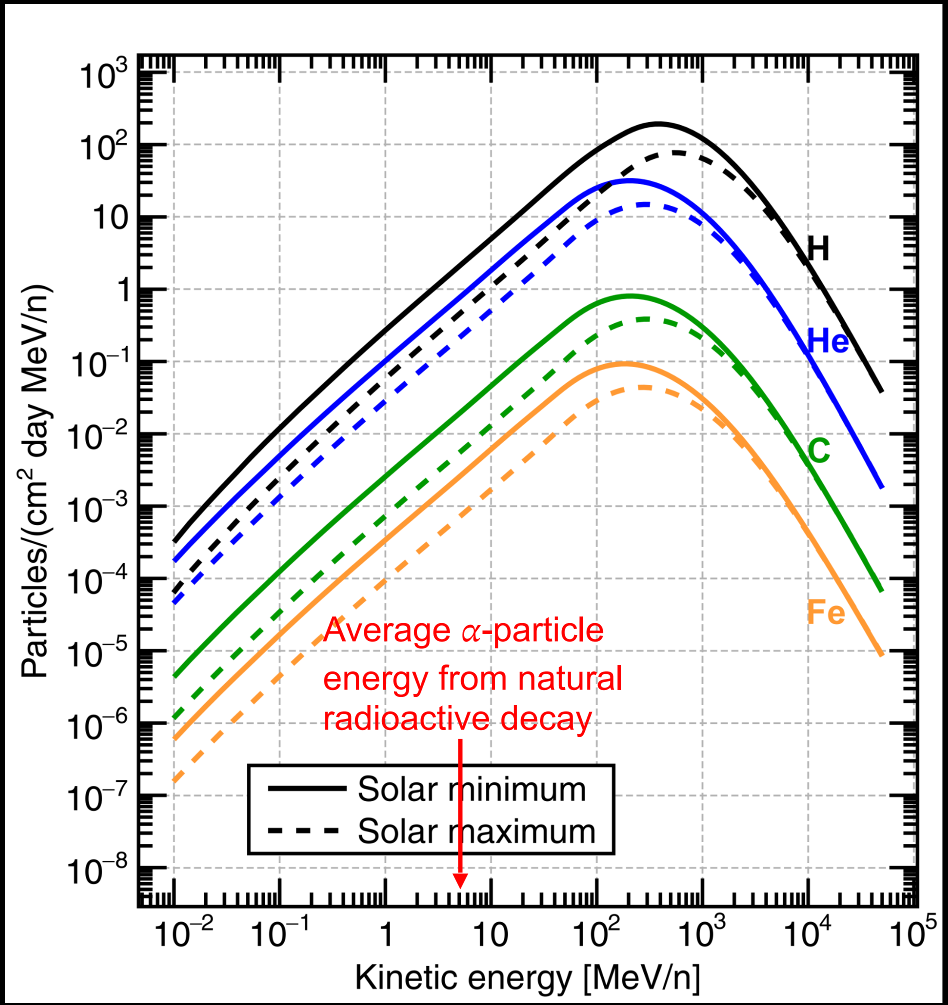


Radiation in space: galactic cosmic rays

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



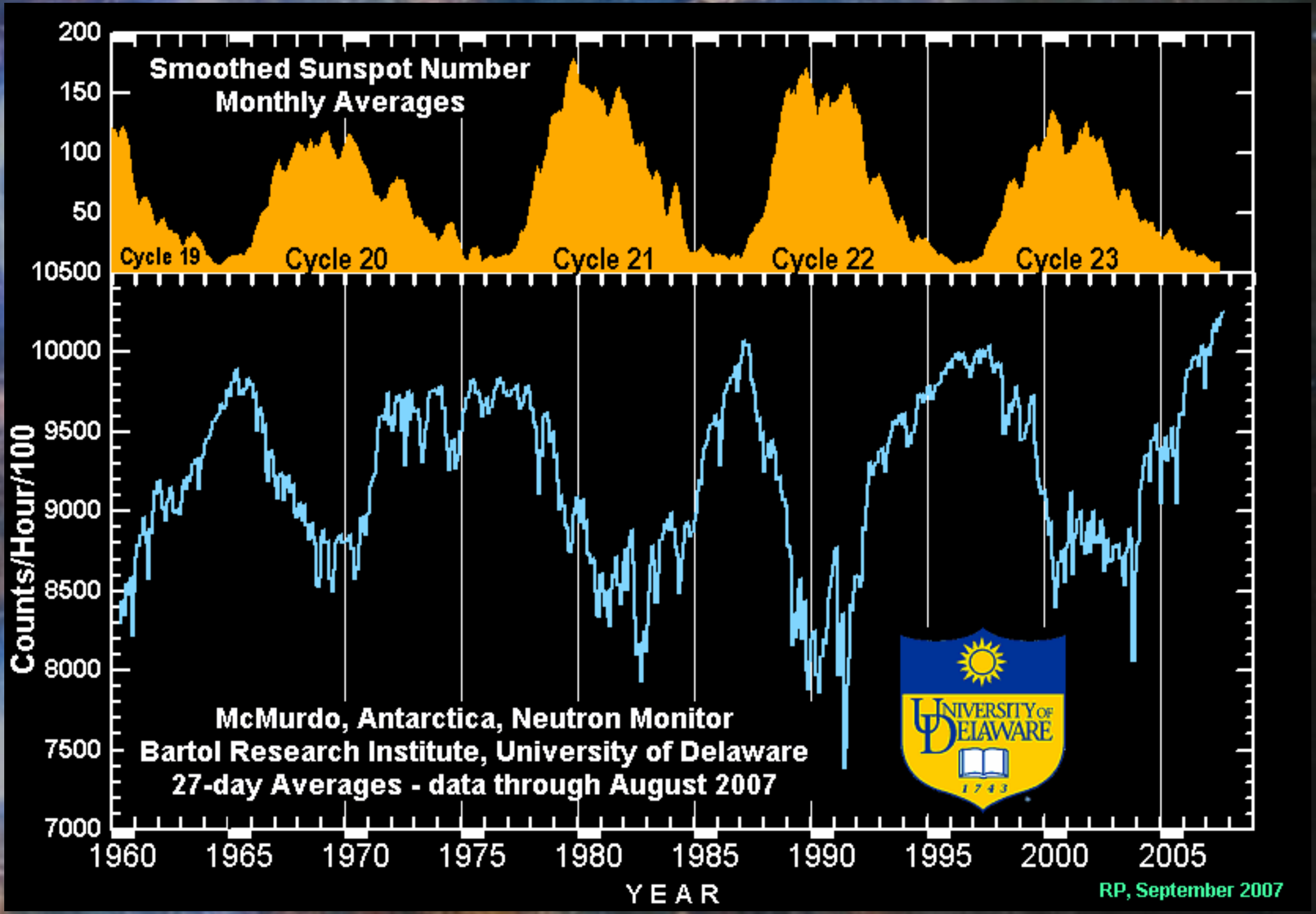
The Crab Nebula, as seen by the James Webb Space Telescope and Chandra X-ray Observatory (Image credit: X-ray, Chandra: NASA/CXC/SAO; Infrared, Webb: NASA/STScI; Image Processing: NASA/CXC/SAO/J. Major)



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

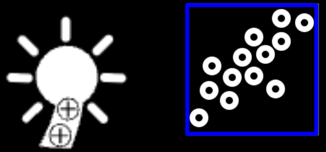
Solar energetic particles (SEPs) are accelerated in solar eruptions

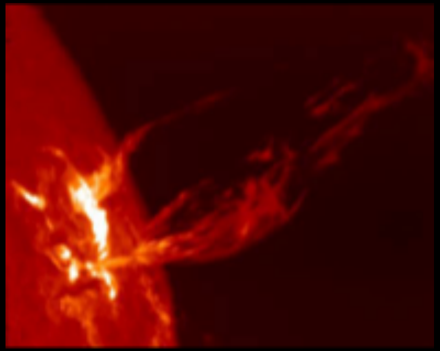
Elemental composition (may vary event by event):

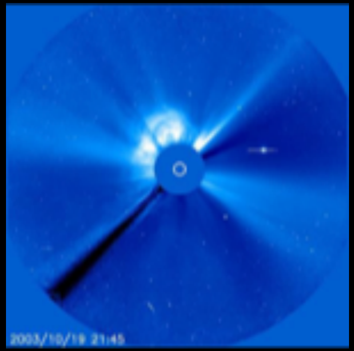
- 96.4% protons
- 3.5% alpha particles
- 0.1% heavier ions (not to be neglected!)

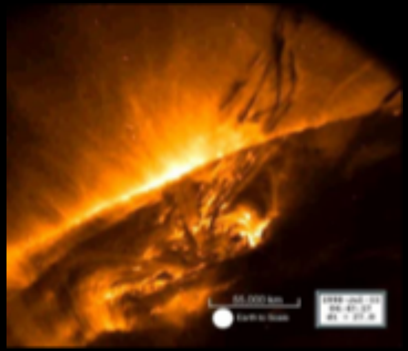
Energies: up to GeV/nucleon

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





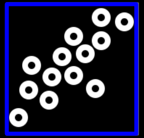


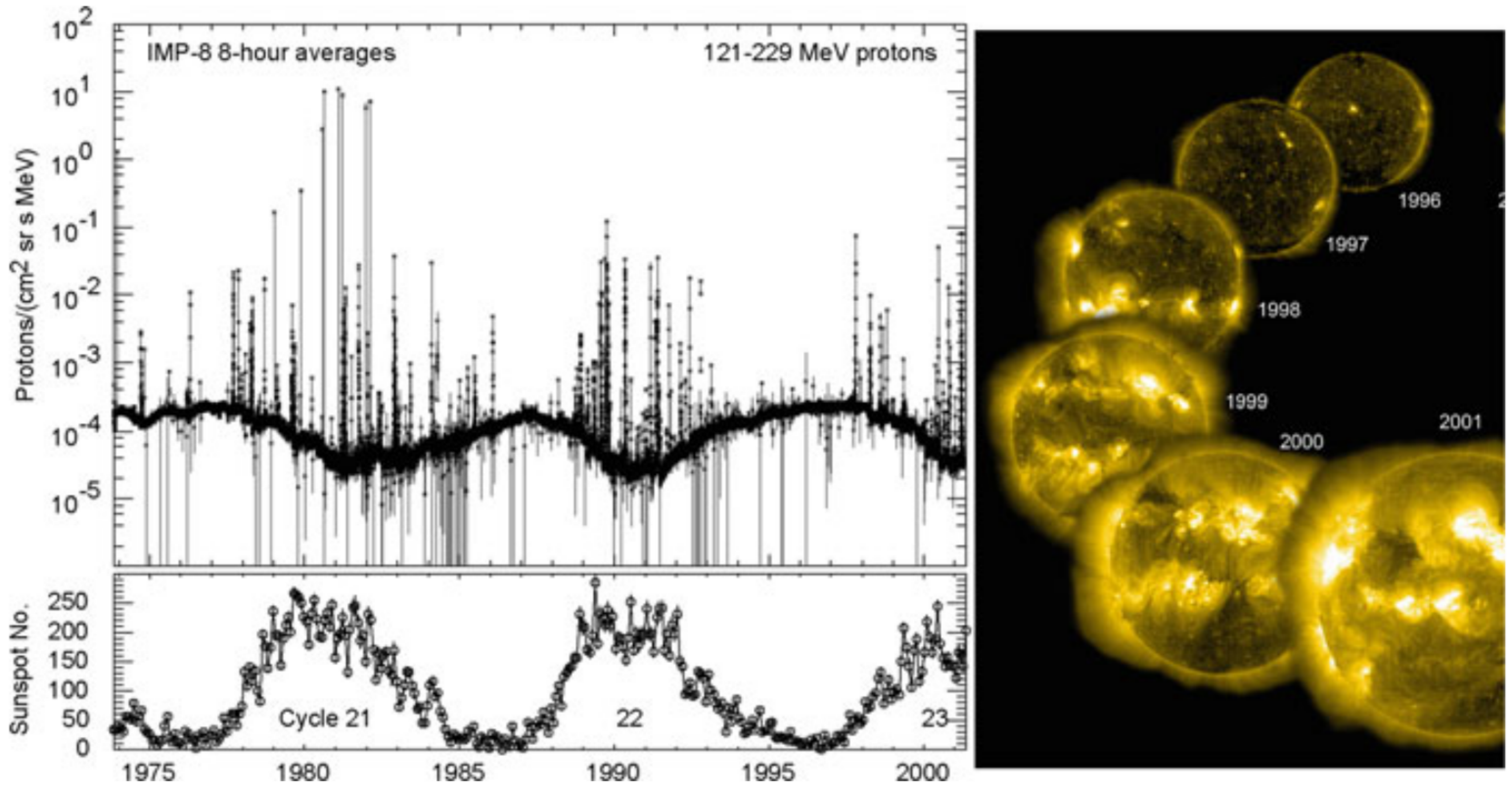


Radiation in space: solar energetic particles

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

Hard to predict!

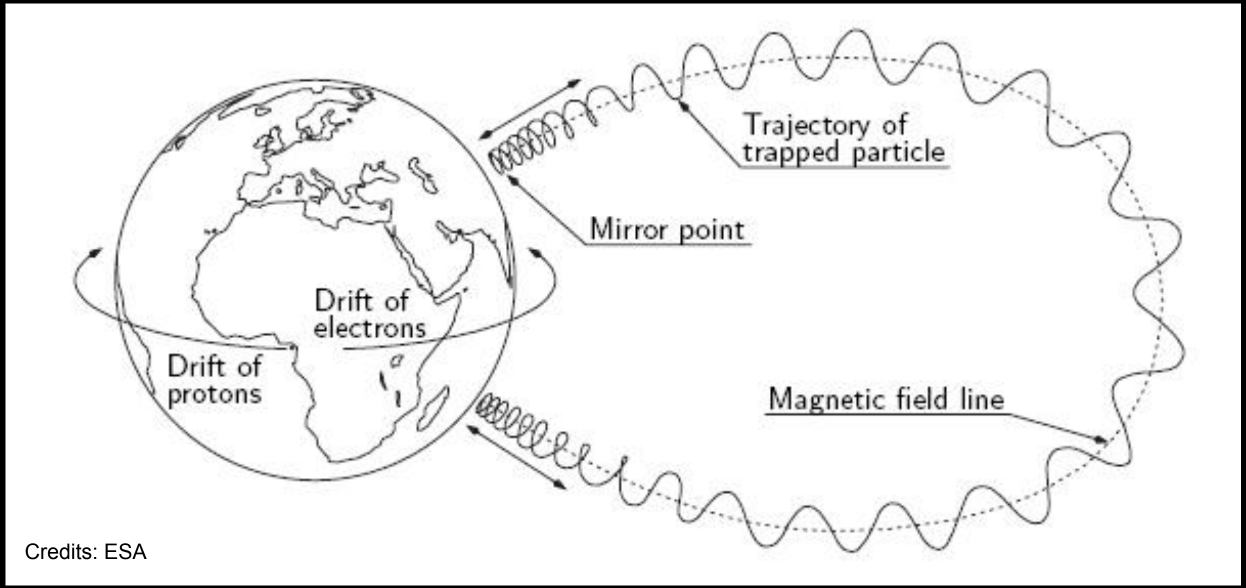




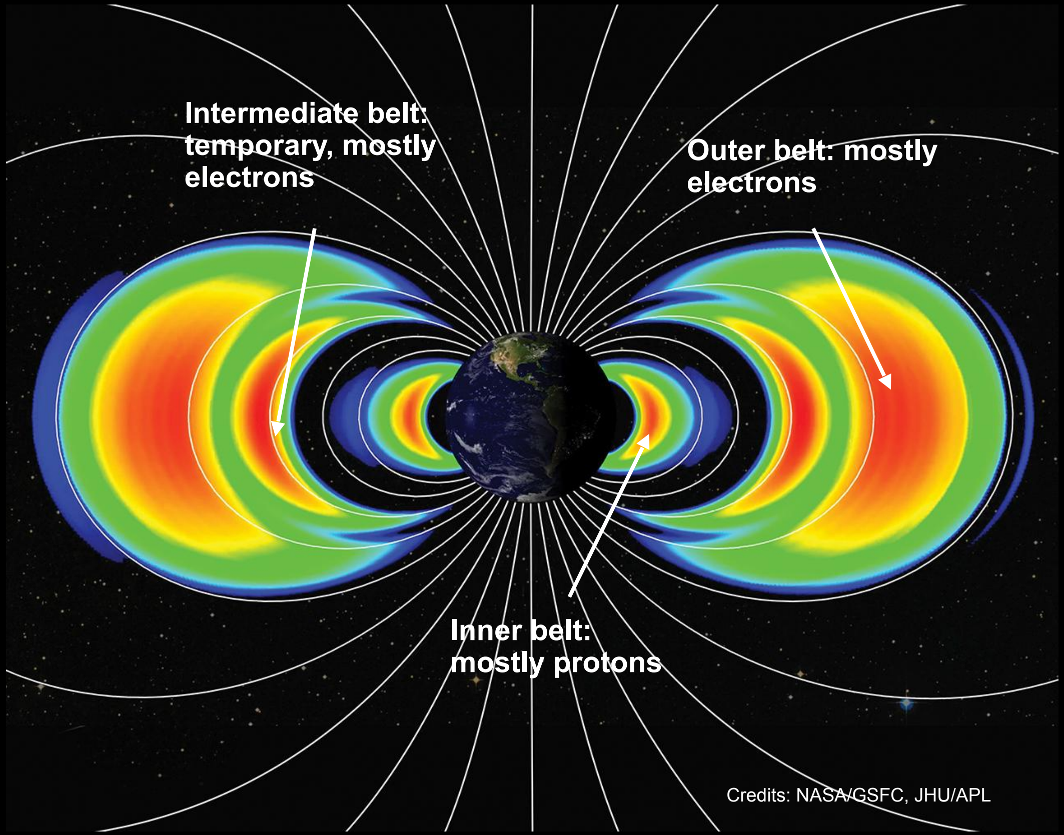
Credits: Reames (2021), DOI:10.1007/978-3-030-66402-2

Radiation in space: Van Allen belts

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



Credits: ESA

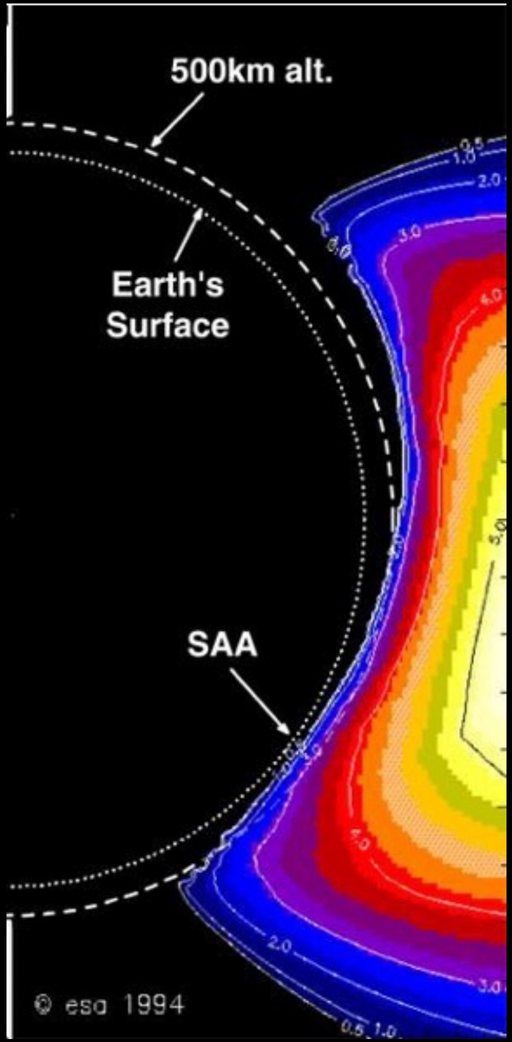


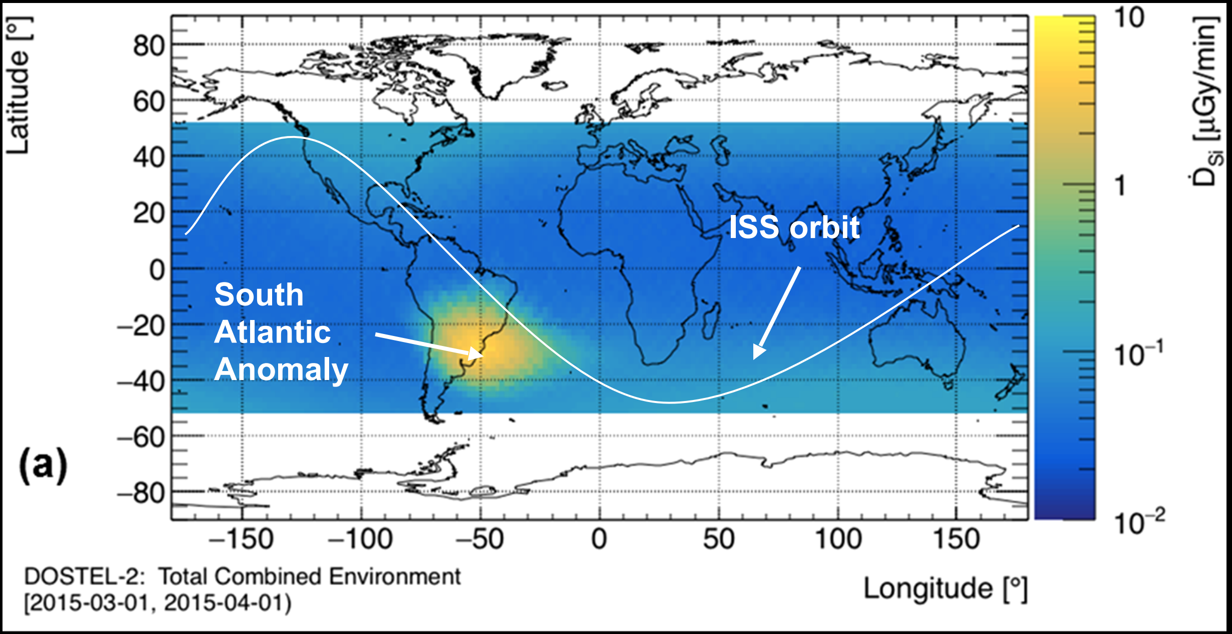
Credits: NASA/GSFC, JHU/APL

At the same time, Earth's magnetic field can deflect SEPs and GCRs up to 15 GeV/n

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:

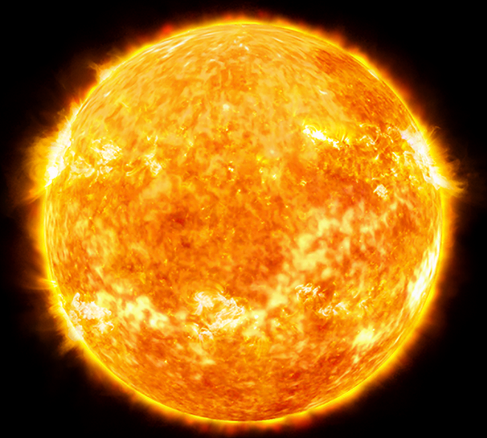
- particle type (electrons, nuclei with different charge number)
- particle energy (how fast particles move)
- particle intensity (how many particles per unit area and time)

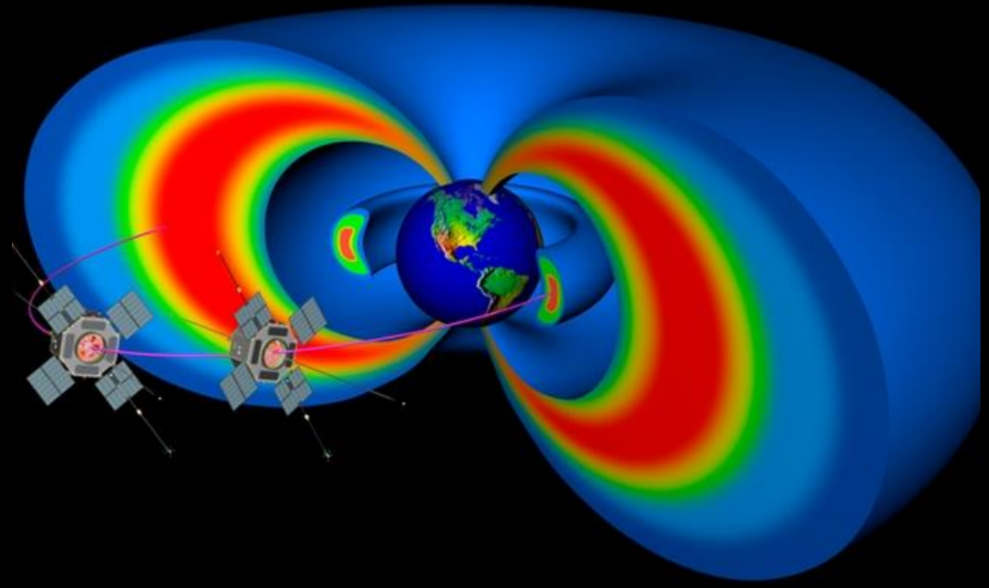
Particle spectrum (intensity vs energy) is a key factor in understanding space radiation effects:

- 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

Quiz: which radiation is where?

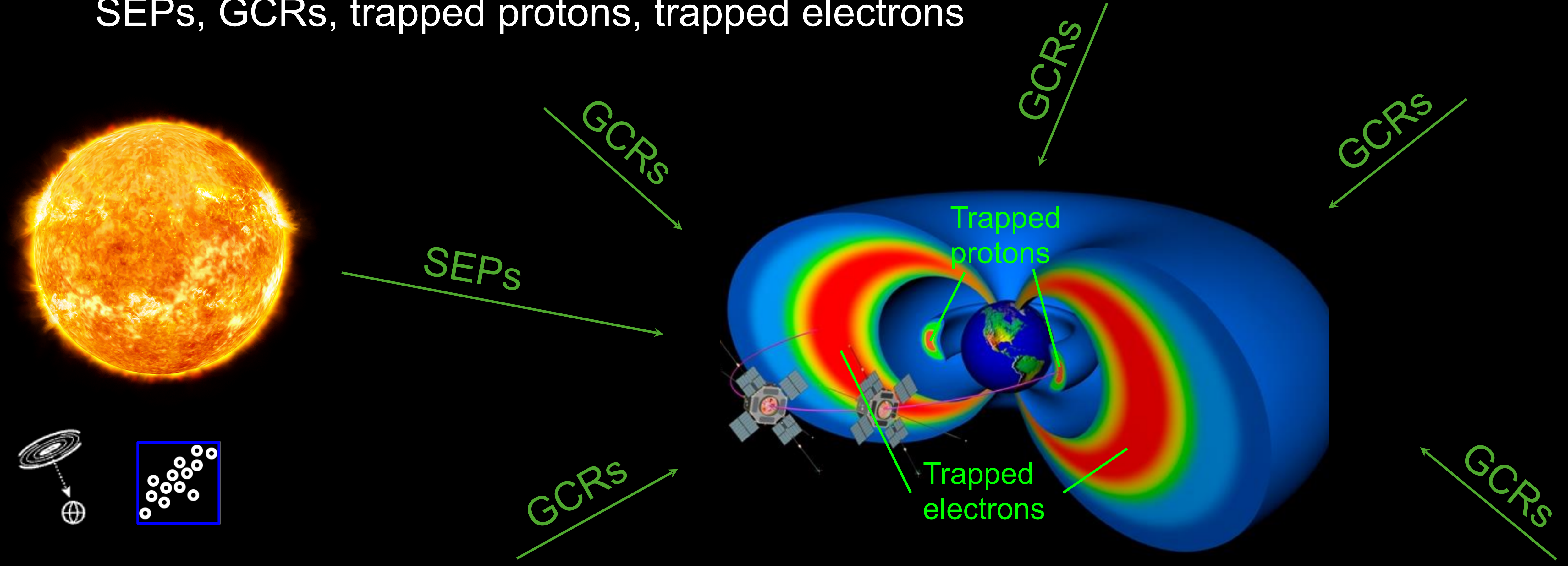
Place the following radiation sources in the appropriate location in space:
SEPs, GCRs, trapped protons, trapped electrons





Quiz: which radiation is where?

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



Satellite impacts

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 charging	• Biasing of instrument readings • Power drains • Physical damage	• Dense, cold plasma • Hot plasma (ring current, aurora population, few eV to 10s keV)
Internal charging	• Biasing of instrument readings • Electrical discharges causing physical damage	• High-energy electrons (>300 keV)

Satellite impacts

Mechanism	Effect	Source
Surface erosion	• Degradation of thermal, electrical, optical properties • Degradation of structural integrity	• Particle radiation • Ultraviolet • Atomic oxygen • Micrometeoroids • Contamination
Structure impacts	• Structural damage • Decompression	• Micrometeoroids • Orbital debris
Satellite drag	• Torques • Orbital decay	• 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)

Single-event effects (SEEs)

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

SEEs: sources in space

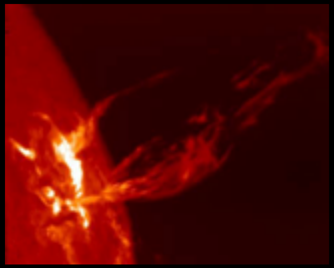
High-energy particle radiation

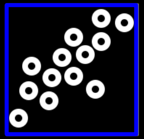
GCRs

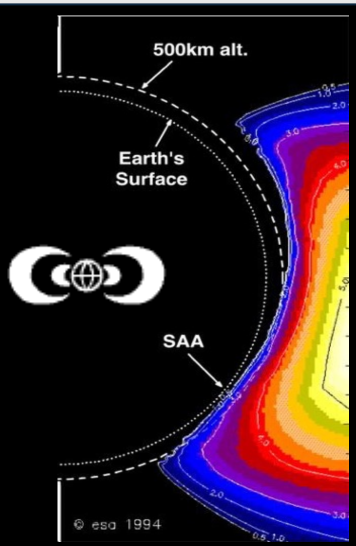
SEPs

SAA

High-energy neutrons





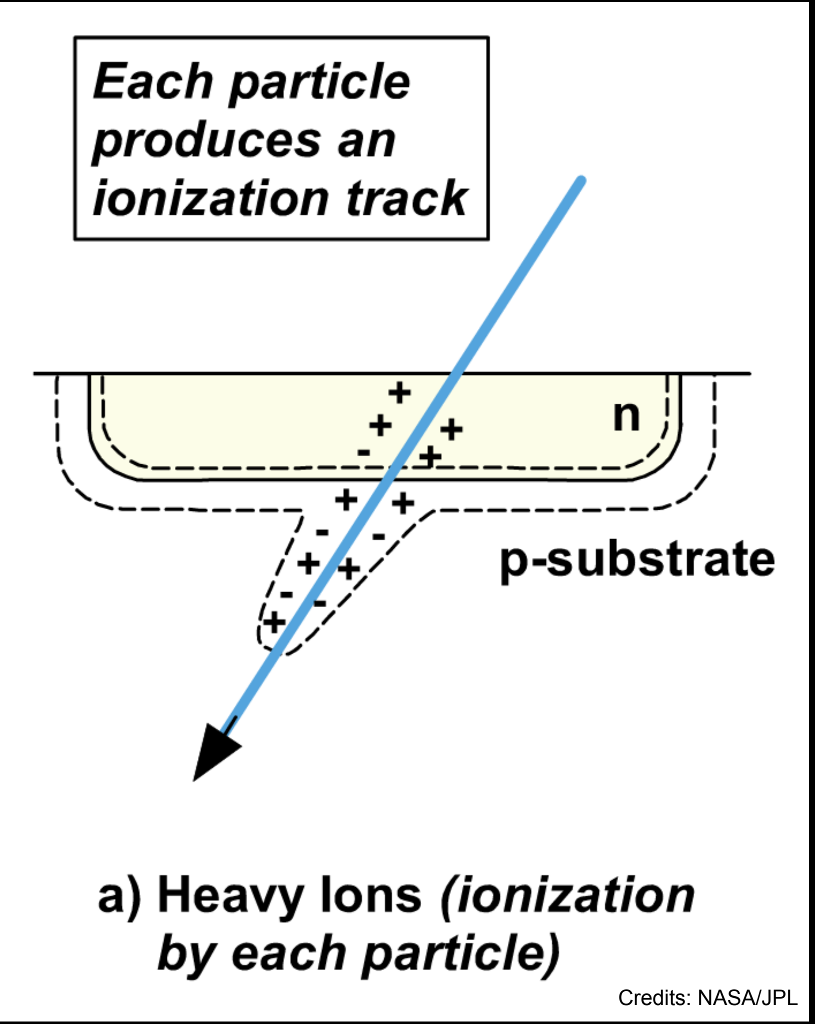


protons/ions from GCR, SEP, and SAA with energy > 30 MeV

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

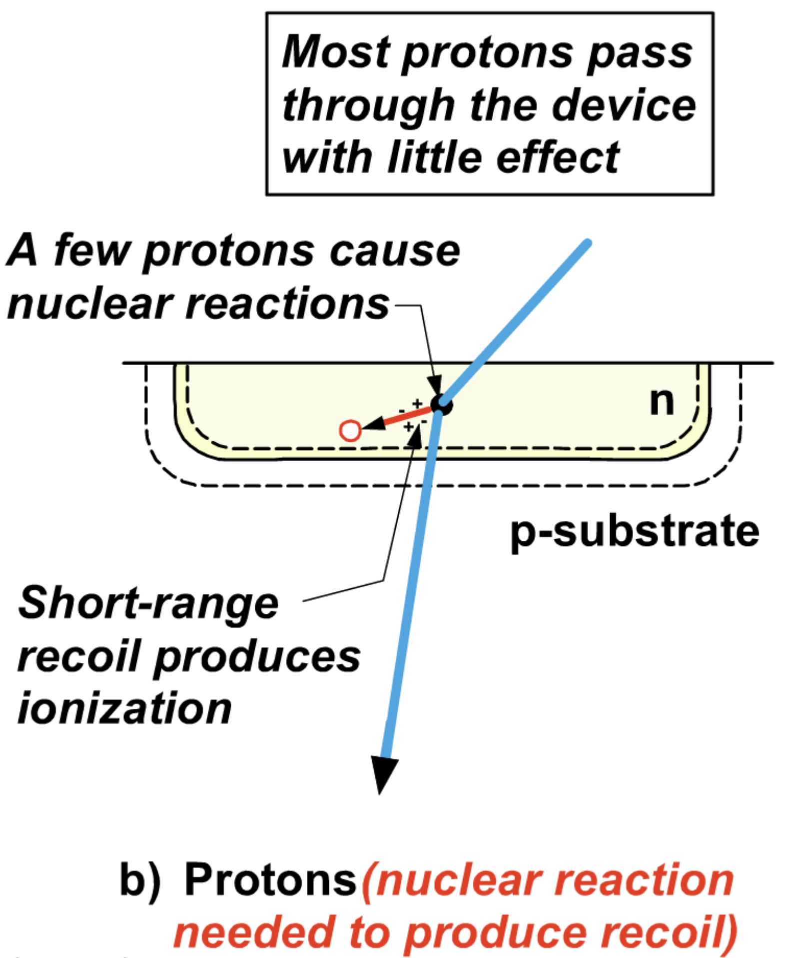
Direct ionization (heavy ions, Z=2-92)
Dense ionization track over a short range produces sufficient charge in sensitive volume to cause SEE



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).



Credits: NASA/JPL

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 of by power cycling the affected component/system

Destructive

- Permanent damage to component

Mitigation

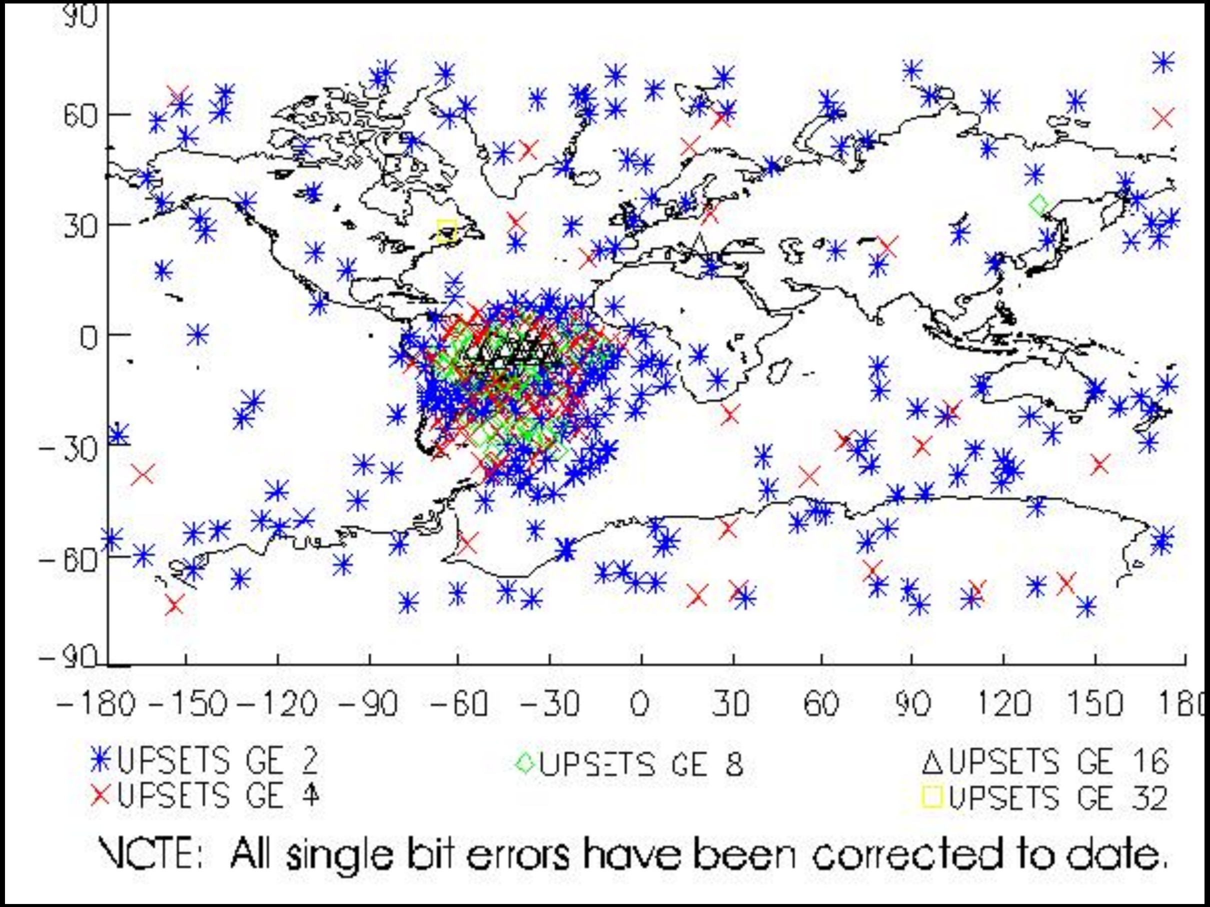
- Radiation hardening (insulating substrates, “simpler” components, …)
- Shielding
- Error correcting code memory, redundancy

Non-destructive SEEs

Soft errors, normally appear as transient pulses in logic or support 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!



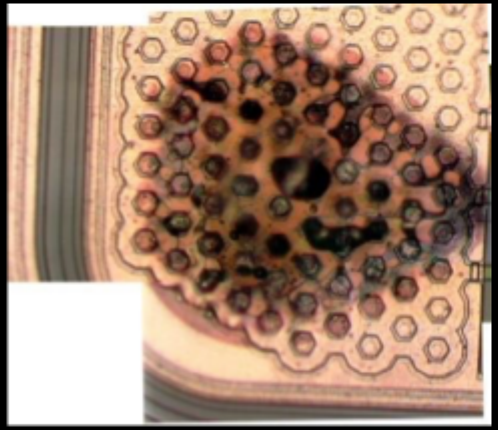
Credits: Seidleck et al. (2003)

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.

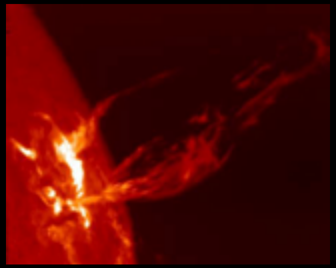
- Destructive SEEs are permanent damages to electronics components
- Bit flips are an instance of SEU
- SEUs are more frequent in the SAA
- Dead pixels can not restored with a power cycle
- Error correction code memory is not a mitigation strategy against SEB

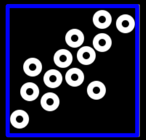
Total dose

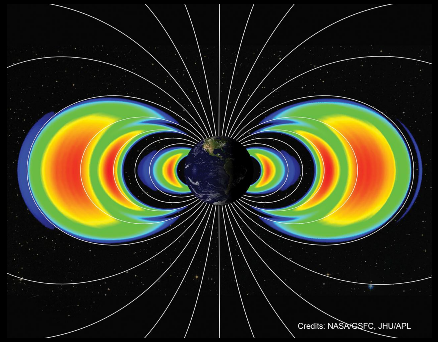
Total dose: sources in space

High-energy particle radiation

- GCRs
- SEPs
- Trapped particles (radiation belts, including SAA)
- High-energy neutrons





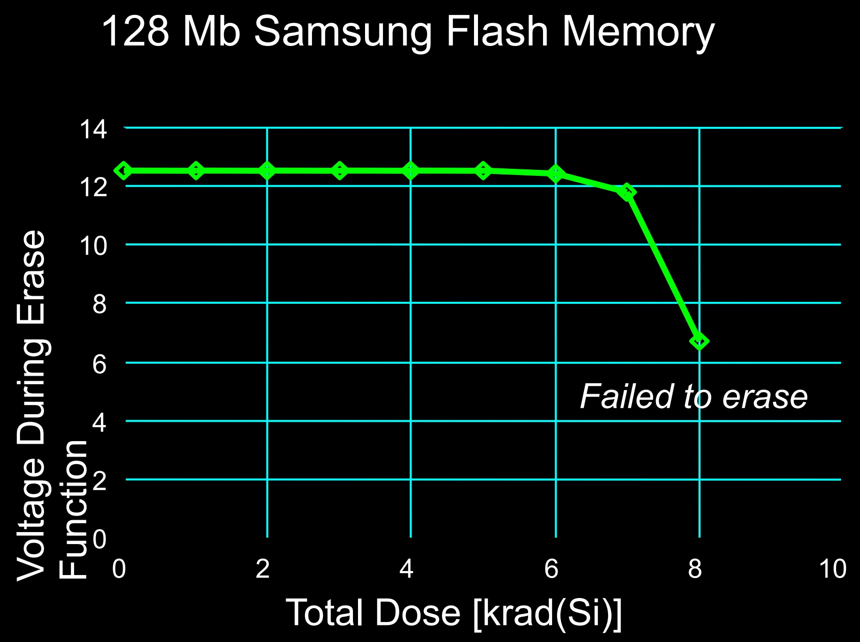


Electrons: >100 keV
Protons: > 1 MeV

Total dose effects: TID

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

- Threshold voltage shifts
- Timing skews
- Leakage currents



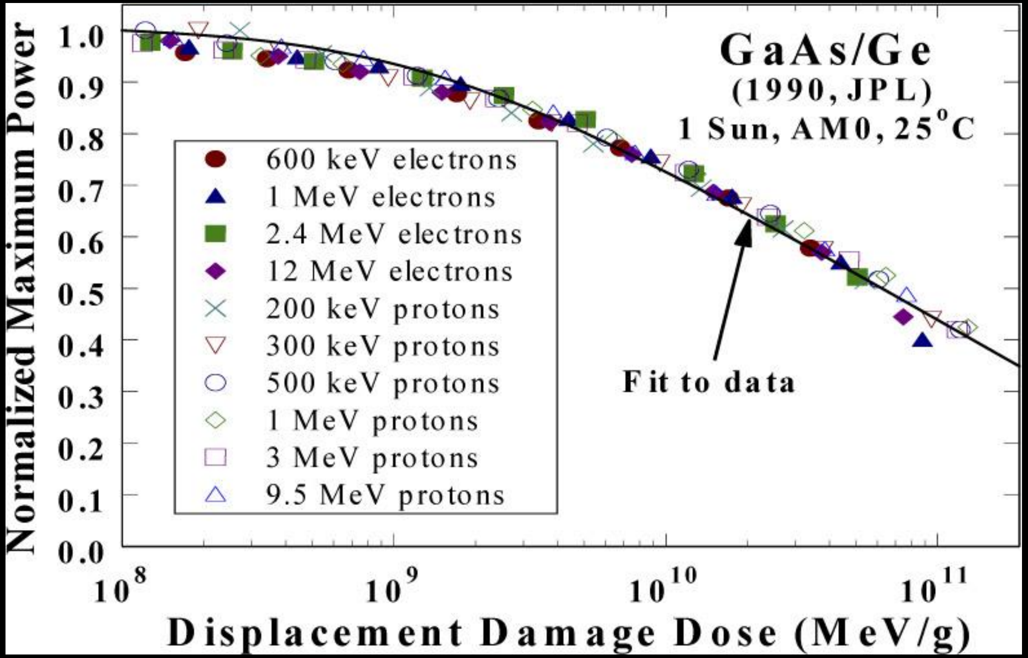
Total dose effects: DDD

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)

Solar Array Degradation



Messenger et al. (2001), DOI: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?

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

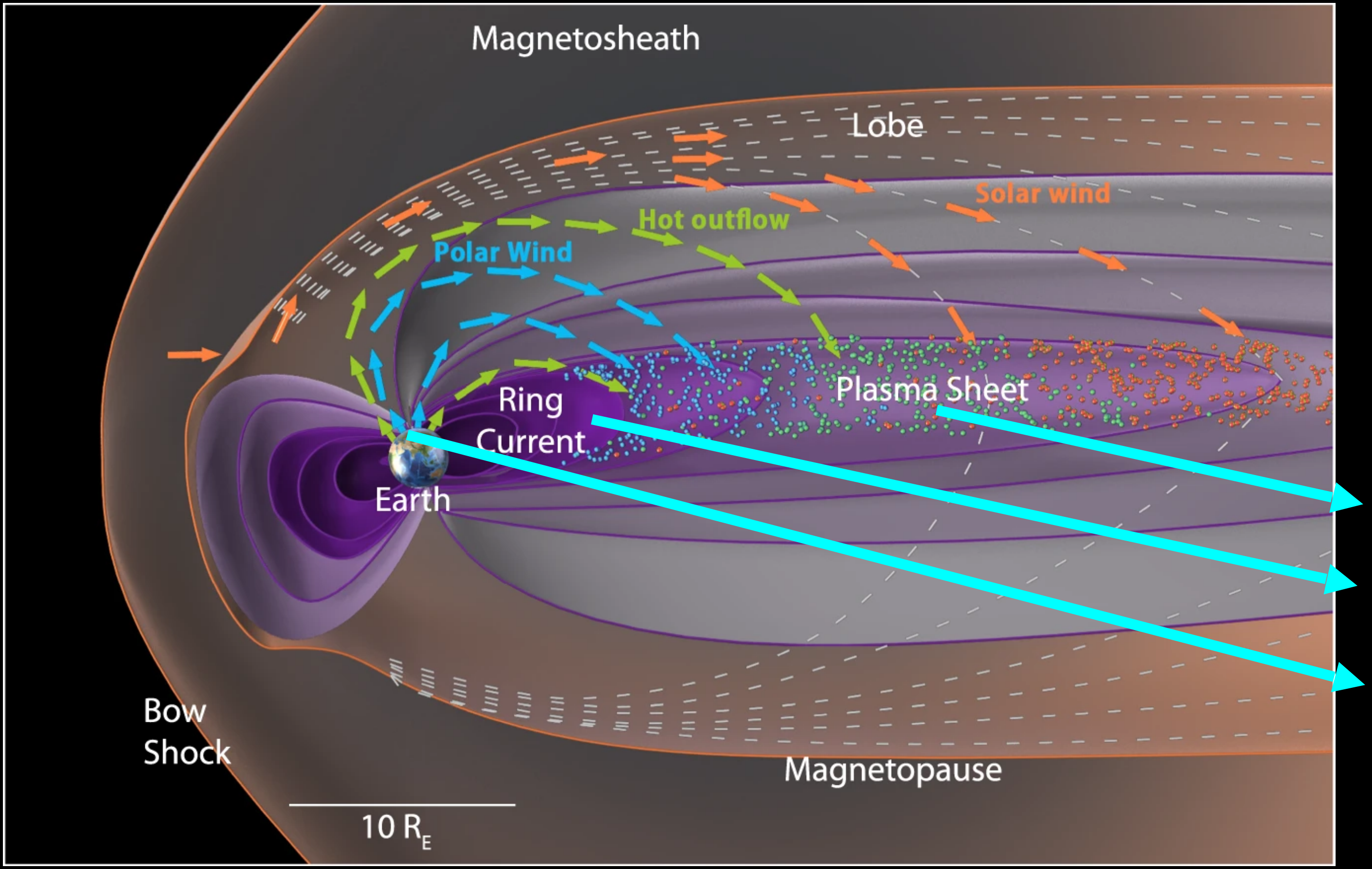
Internal charging:

- 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

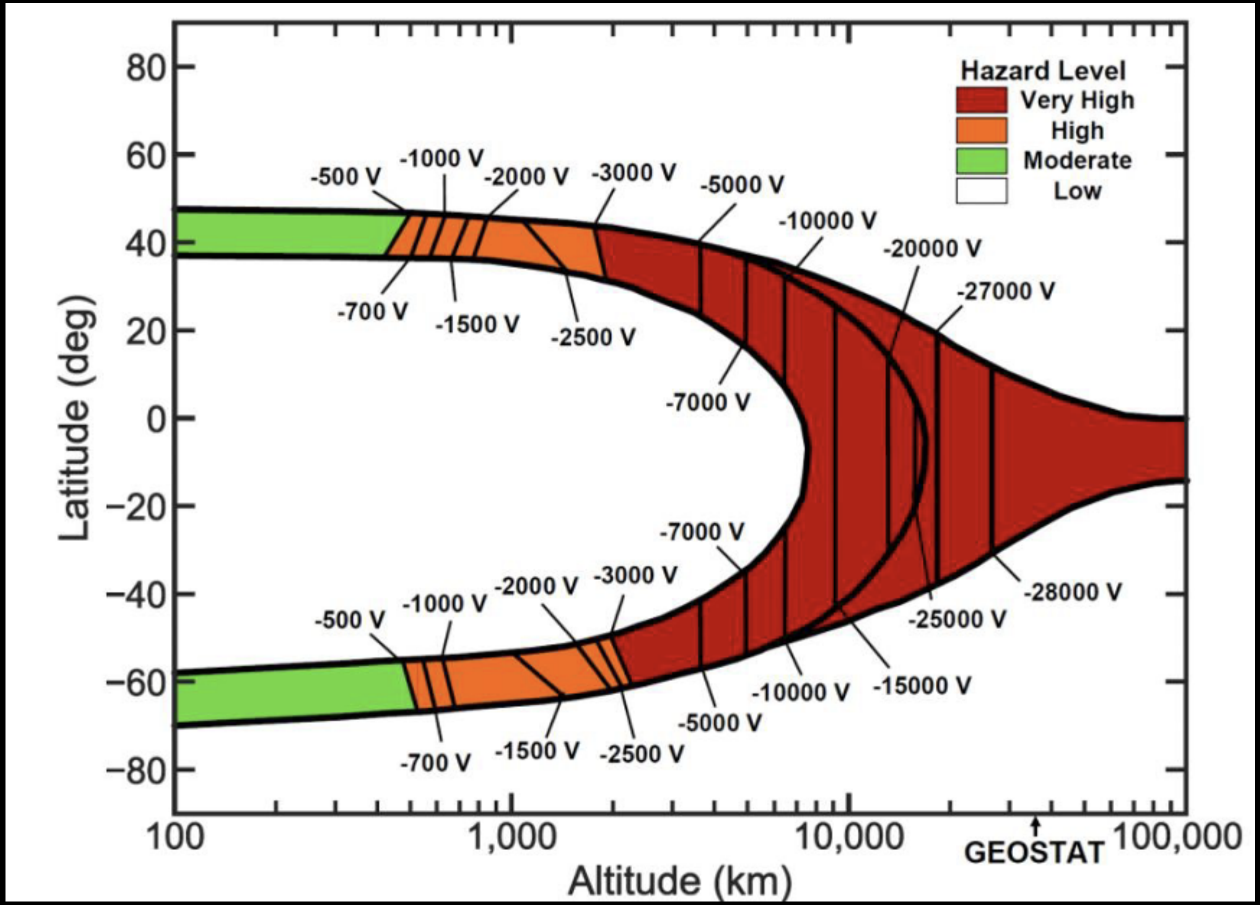
Spacecraft in aurora (polar) regions, ring current, plasma sheet (magnetotail) may be subject to surface charging

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

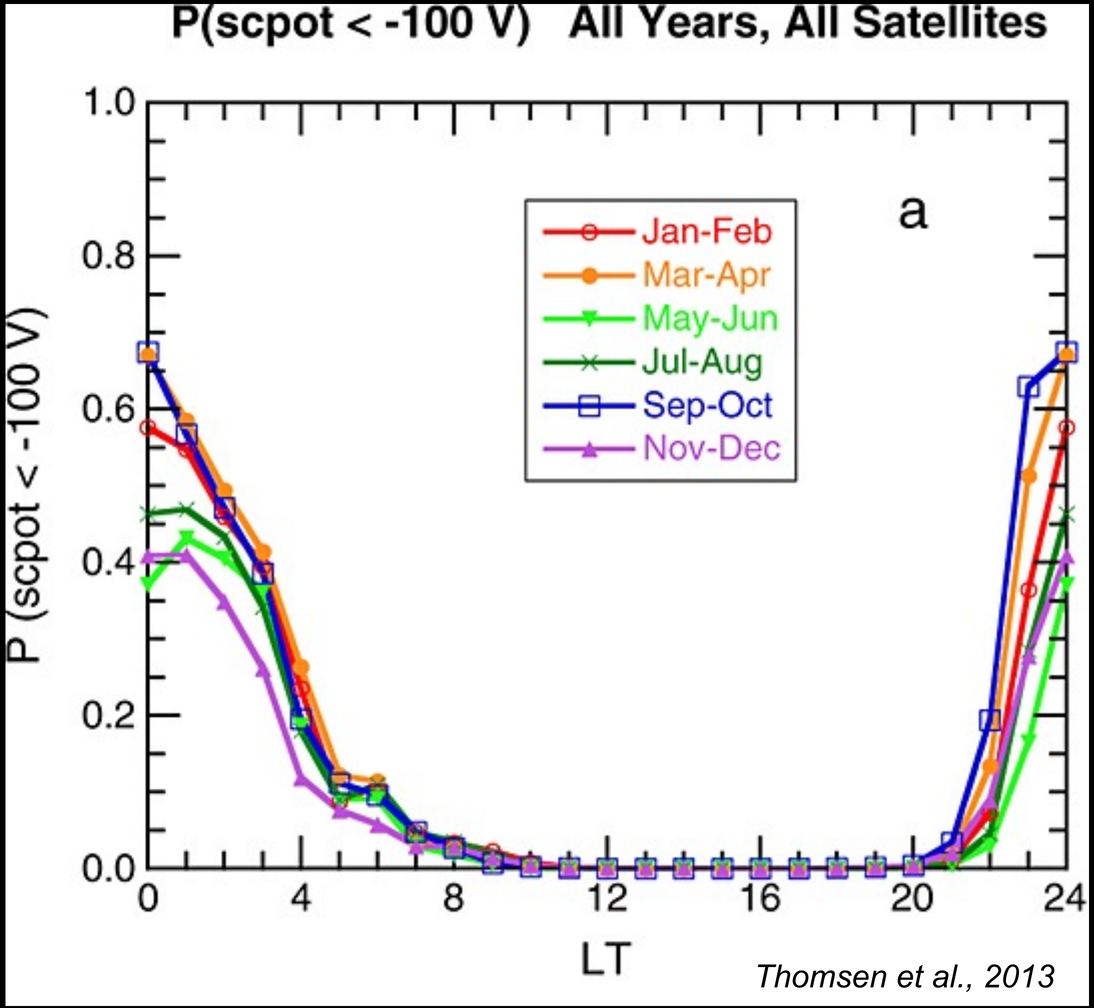


Credits: NASA-HDBK-4002B

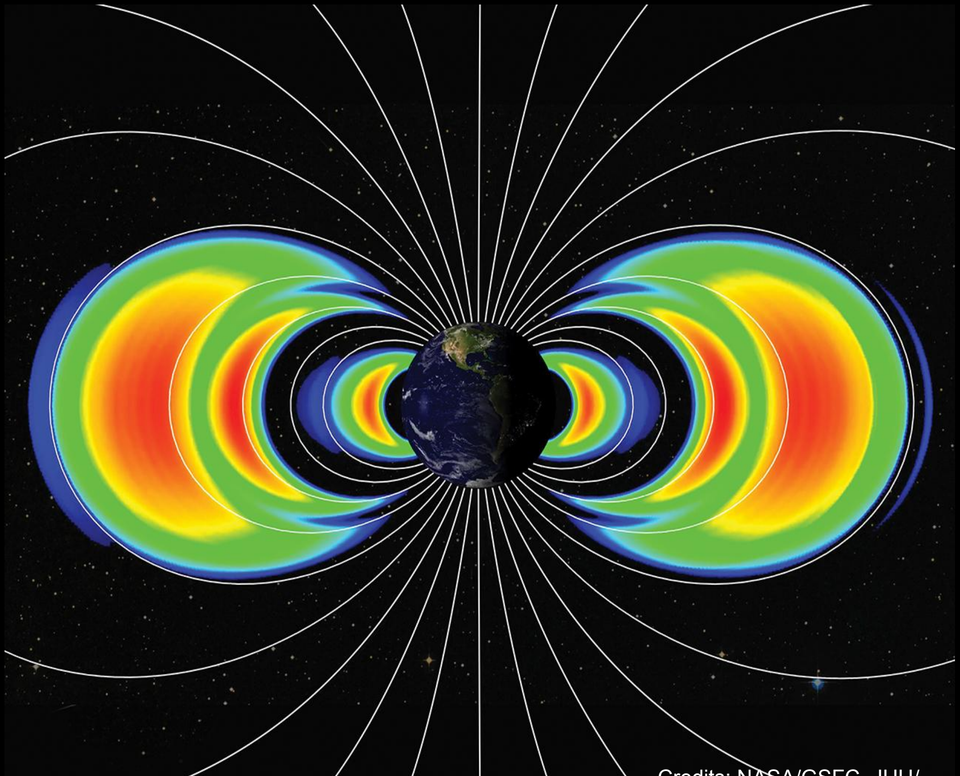
Surface charging: local time dependence

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

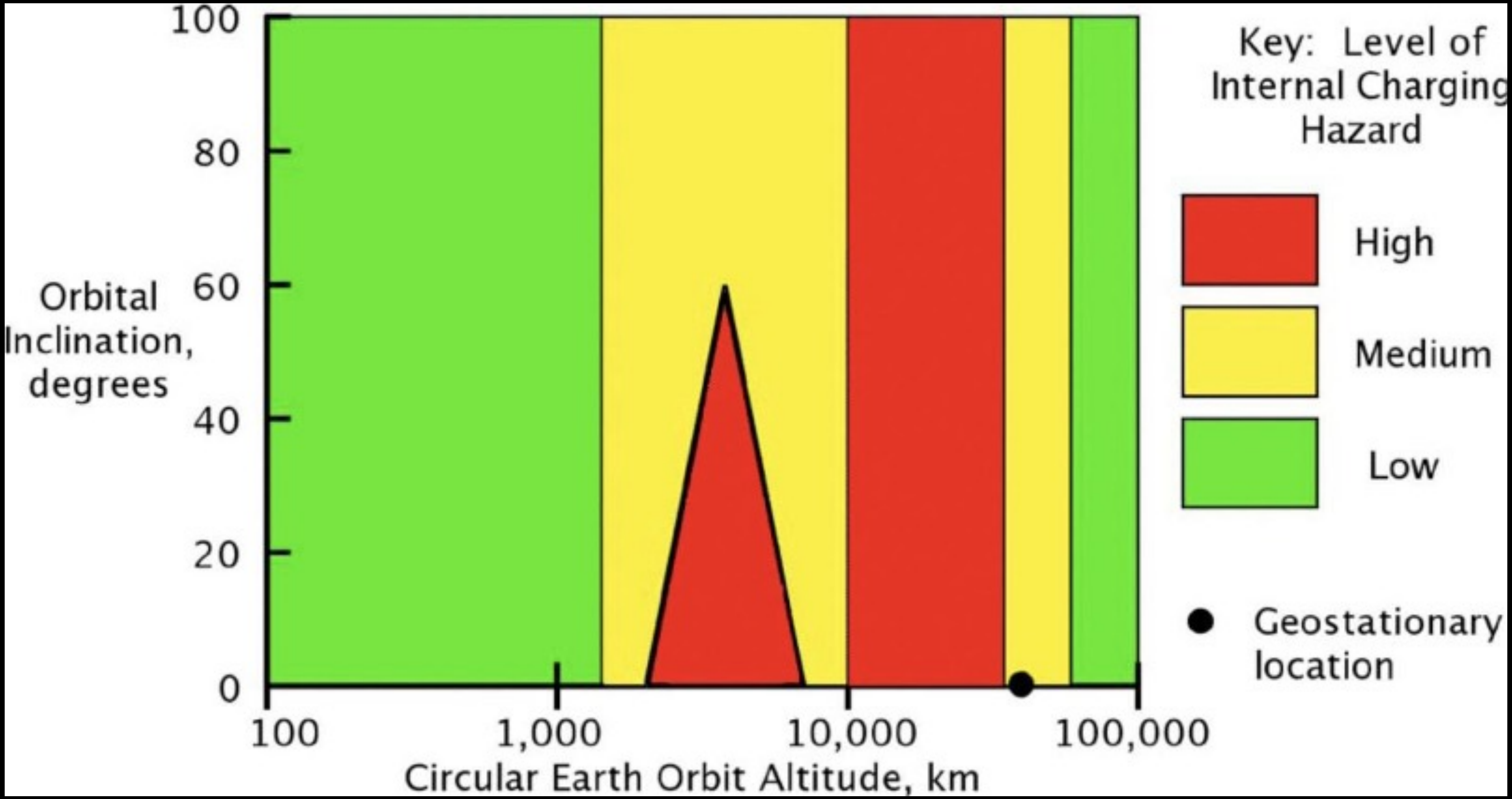

Credits: NASA/GSFC, JHU/APL

>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/(cm^2 s sr)]

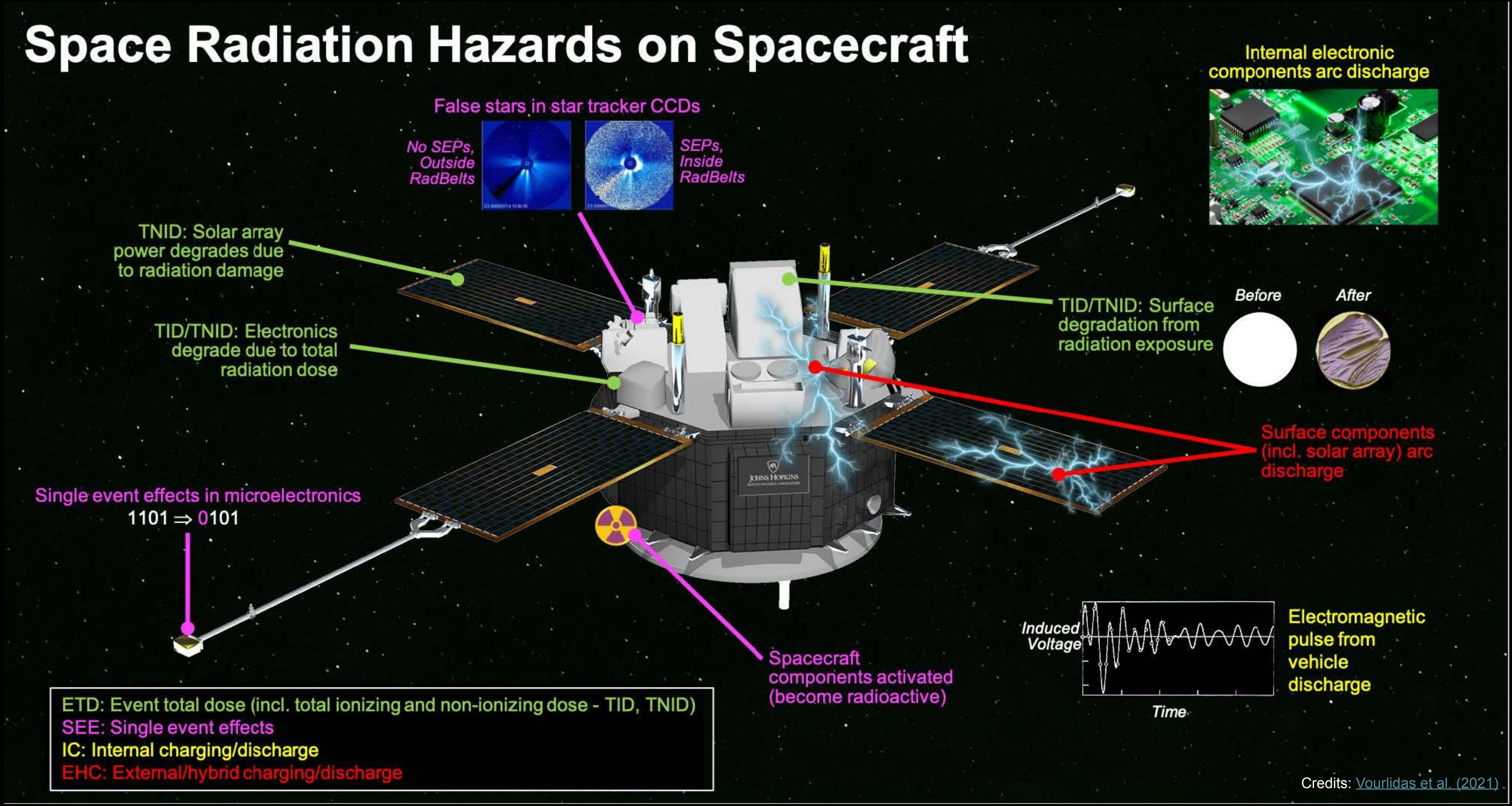
Internal charging: hazard distribution

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



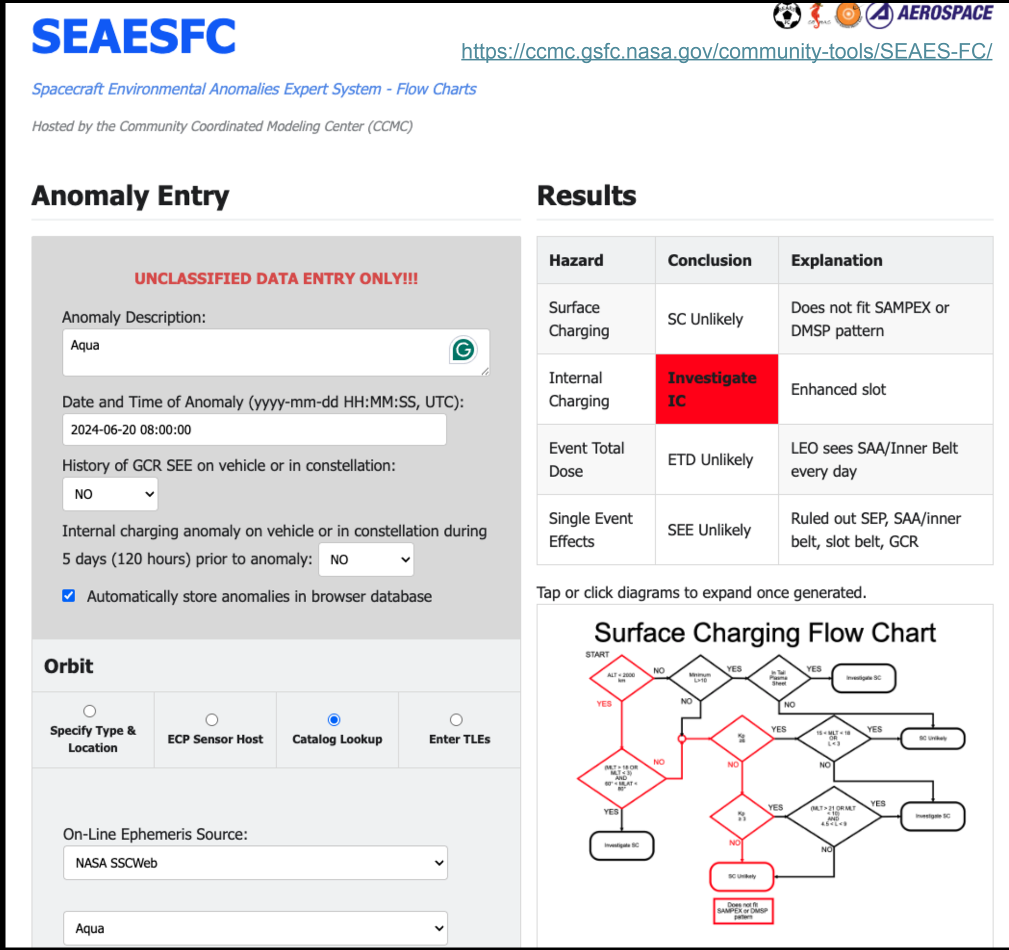
Quiz: Spacecraft charging

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


Space Radiation Hazards on Spacecraft
Internal electronic components arc discharge
False stars in star tracker CCDs
No SEPs, Outside RadBelts
SEPs, Inside RadBelts
TNID: Solar array power degrades due to radiation damage
TID/TNID: Electronics degrade due to total radiation dose
TID/TNID: Surface degradation from radiation exposure
Before
After
Surface components (incl. solar array) arc discharge
Single event effects in microelectronics
1101 ⇒ 0101
Spacecraft components activated (become radioactive)
Induced Voltage
Time
Electromagnetic pulse from vehicle discharge
ETD: Event total dose (incl. total ionizing and non-ionizing dose - TID, TNID)
SEE: Single event effects
IC: Internal charging/discharge
EHC: External/hybrid charging/discharge
Credits: Vourlidas et al. (2021)

SEAS-FC tool at CCMC

Spacecraft Environmental Anomalies Expert System - Flow Chart



- Used by Moon-to-Mars 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

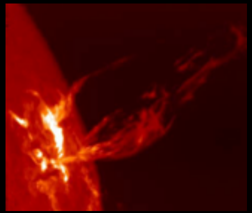
On June 20, Aqua and Aura came within minutes of having to go into safe mode.

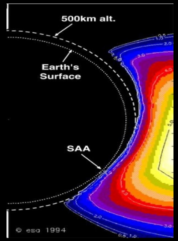
Aviation impacts

Radiation effects at aviation altitudes

Sources

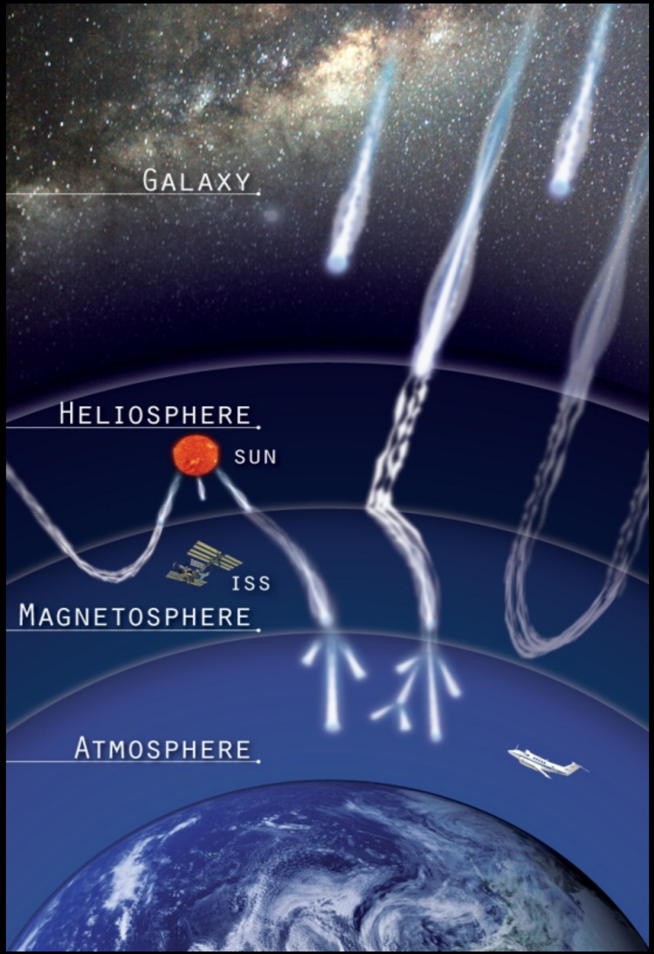
- GCRs
- SEPs
- SAA
- Radiation belt electrons





? – lacks community consensus

- 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)

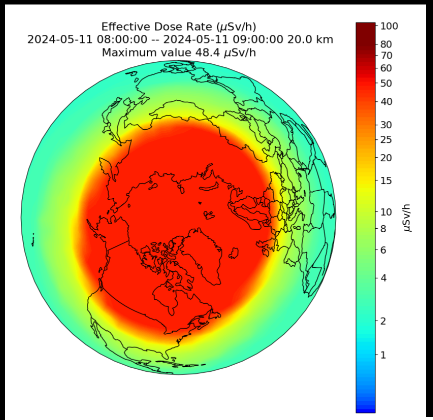
- **Output products**: dose quantities for assessing human radiation exposure and radiation flux quantities for characterizing single event effects (SEE) in flight electronic systems
- **Model Domain**: Earth's surface to cislunar (at Mars too)
- **Output availability: (1)** real-time atmospheric radiation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

Recent News:

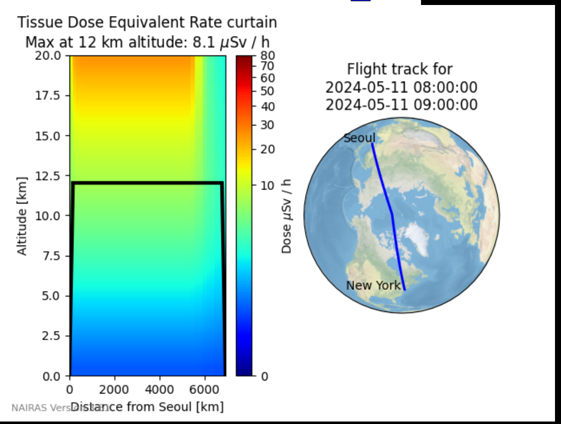
- U.S. Space Force (USSF) using NAIRAS predictions at 20 km in operations to support U2 pilot exposure.
- USSF used NAIRAS predictions to recall operational U2 flight during the May 10-12, 2024 SEP event: pilot descended to lower altitude and returned to base
- **Forecasting:** 3-7 hours SEP forecast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

May 10-12, 2024 SEP Event

Altitude: 20 km



Commercial Altitude



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)	1MeV 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

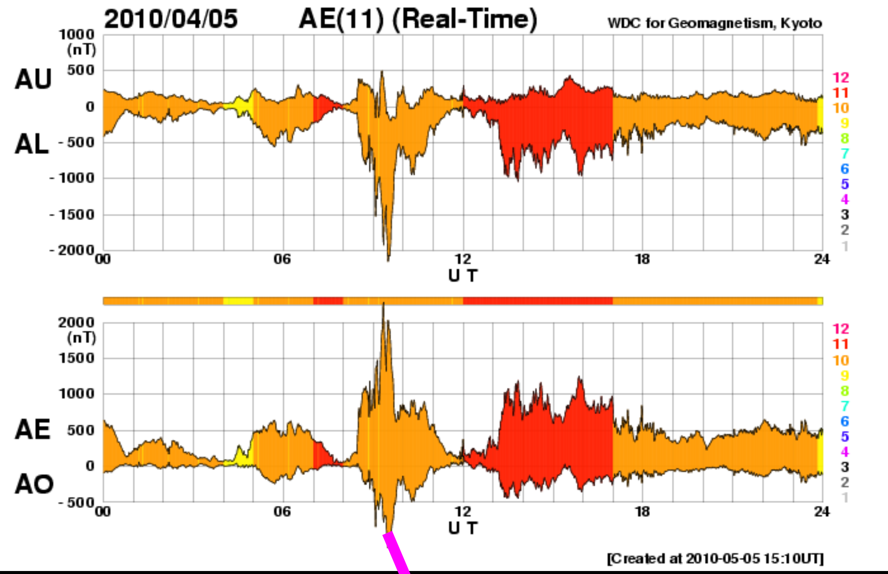
Exercises

Exercise 1: Galaxy 15 failure on April 5, 2010

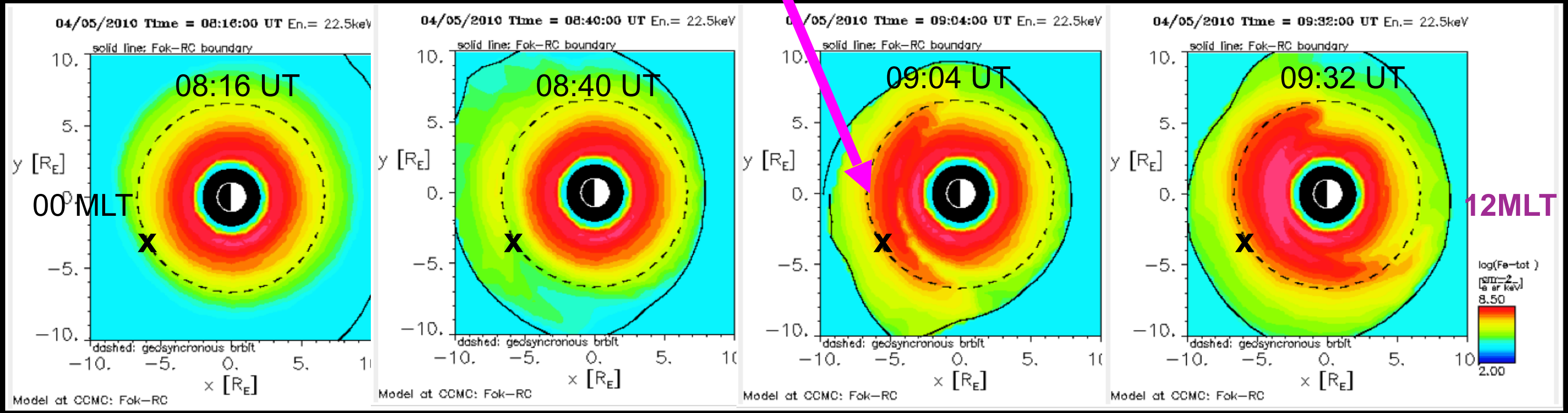
AU/AL/AE: indices for substorm activity

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

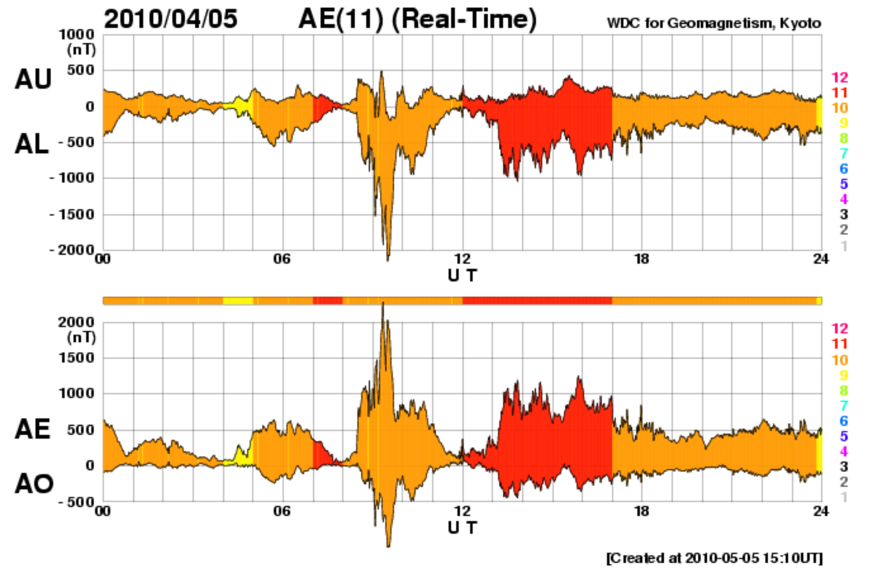
The color-bar is flux in logarithmic values

Exercise 1: Galaxy 15 failure on April 5, 2010

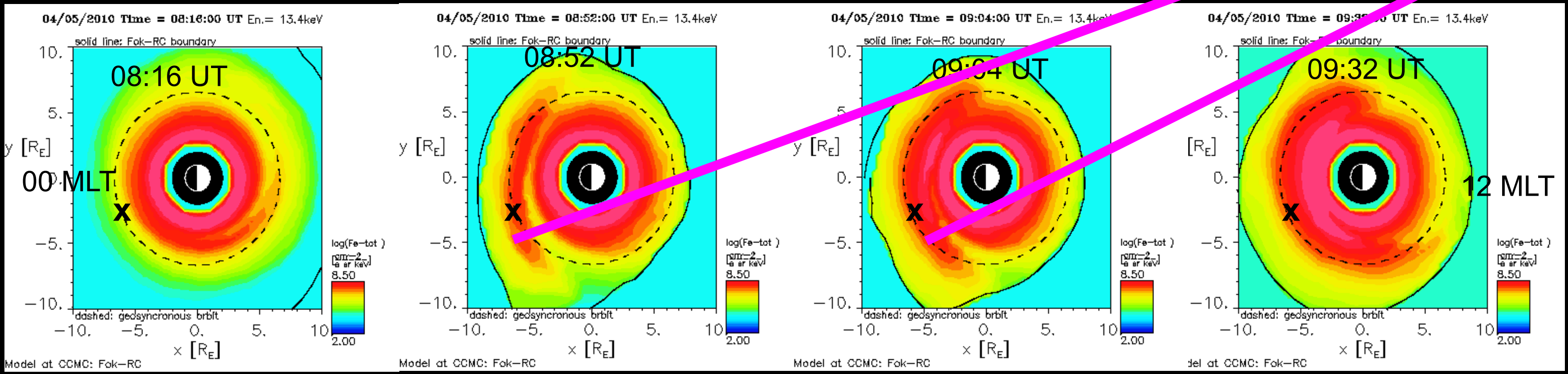
AU/AL/AE: indices for substorm activity

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

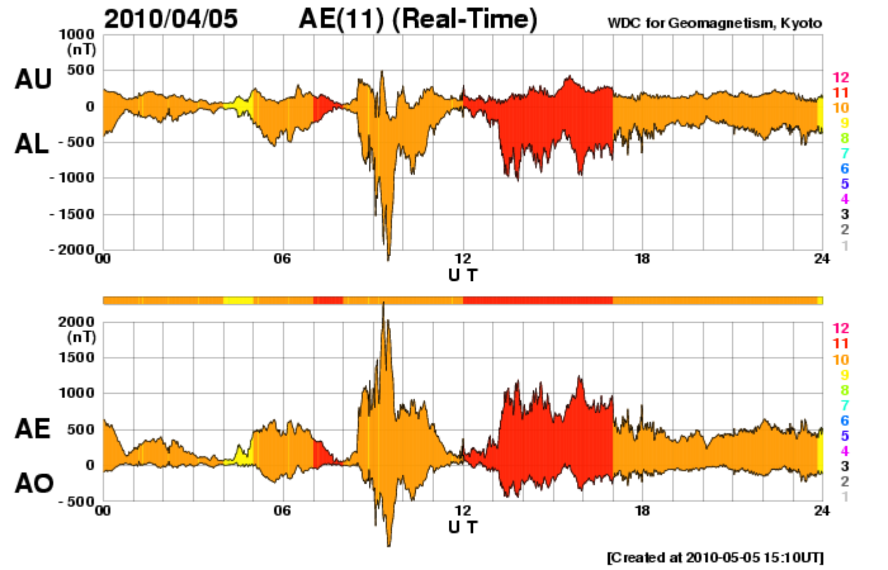
The color-bar is flux in logarithmic values

Exercise 1: Galaxy 15 failure on April 5, 2010

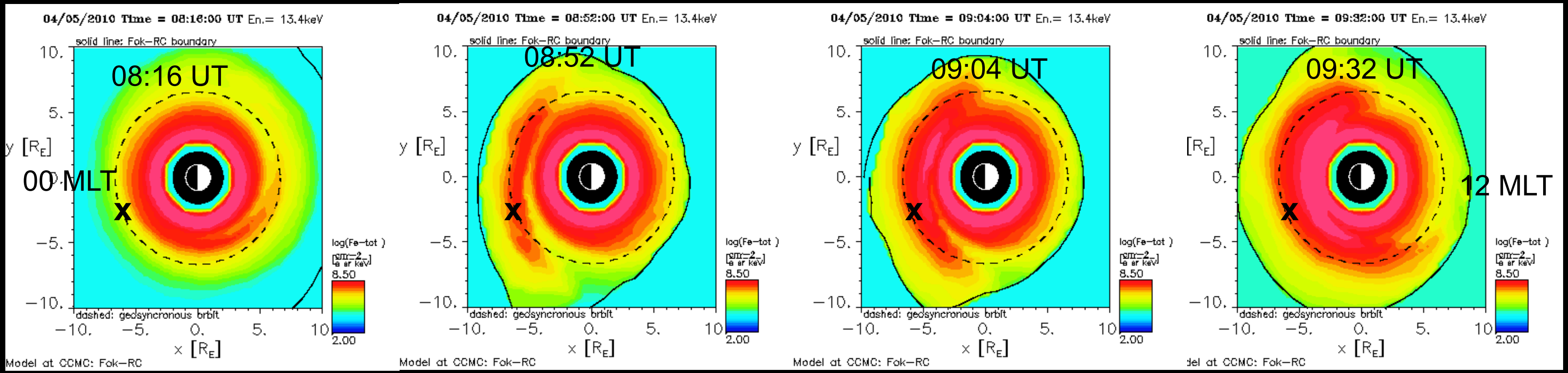
AU/AL/AE: indices for substorm activity

super substorm (AL: -2200 nT)!

nominal AL intensity (-200 nT)



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



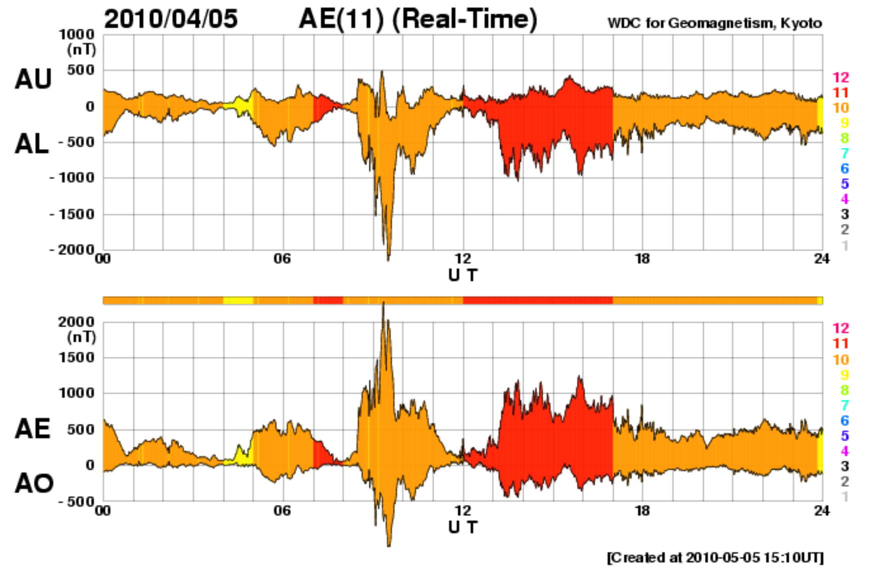
Galaxy 15 failed approx 9:48 UT, located around 01 MLT

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

AU/AL/AE: indices for substorm activity

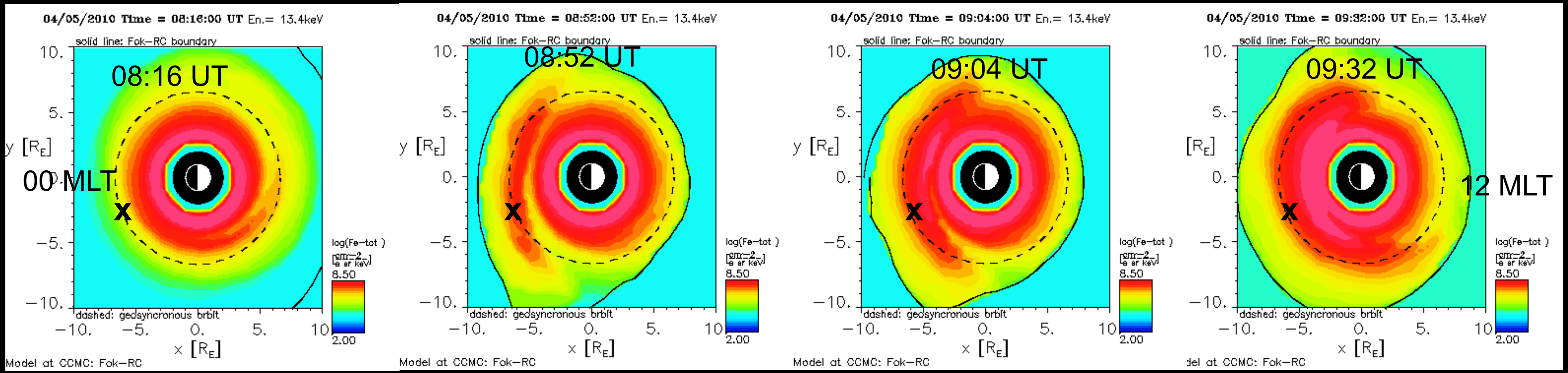
super substorm (AL: -2200 nT)!

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**.



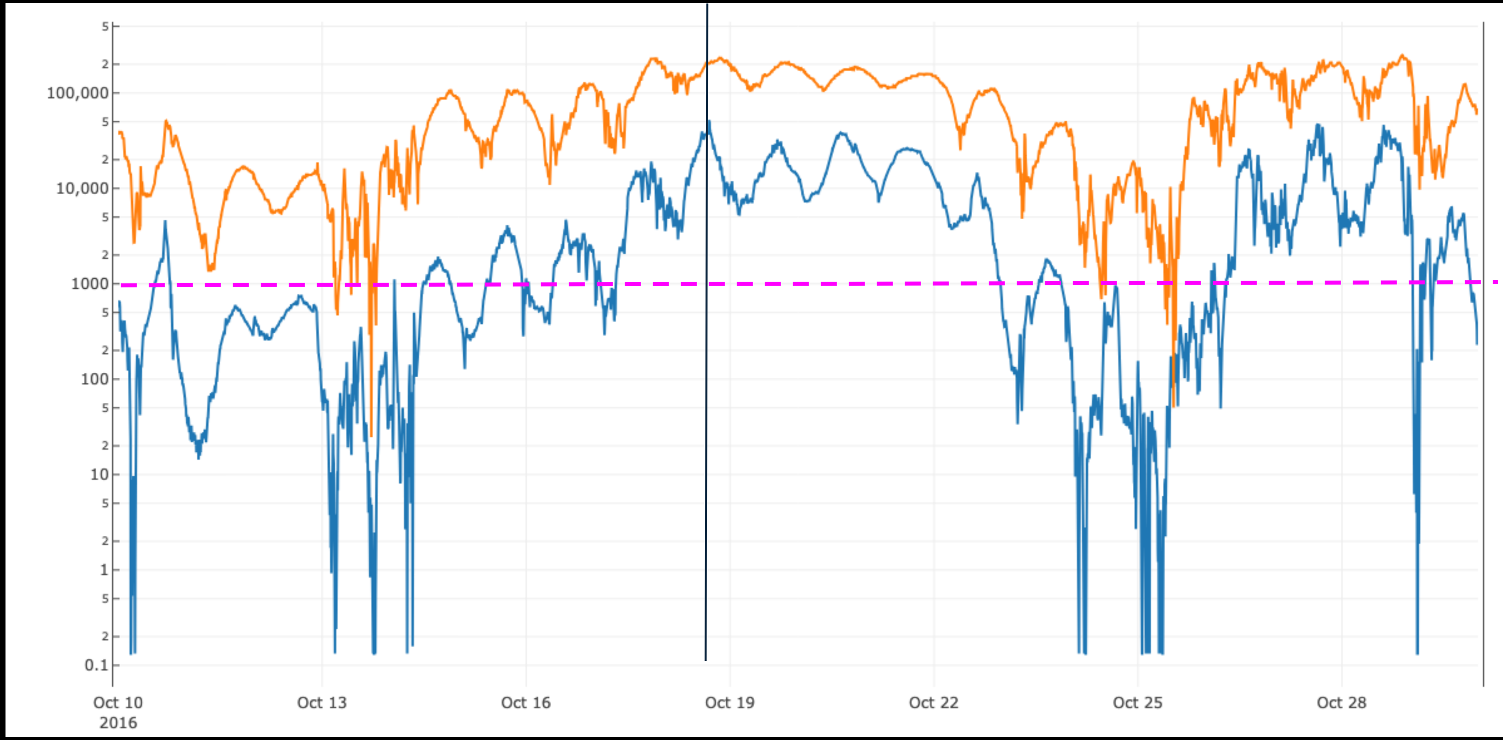
Galaxy 15 failed approx 9:48 UT, located around 01 MLT

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

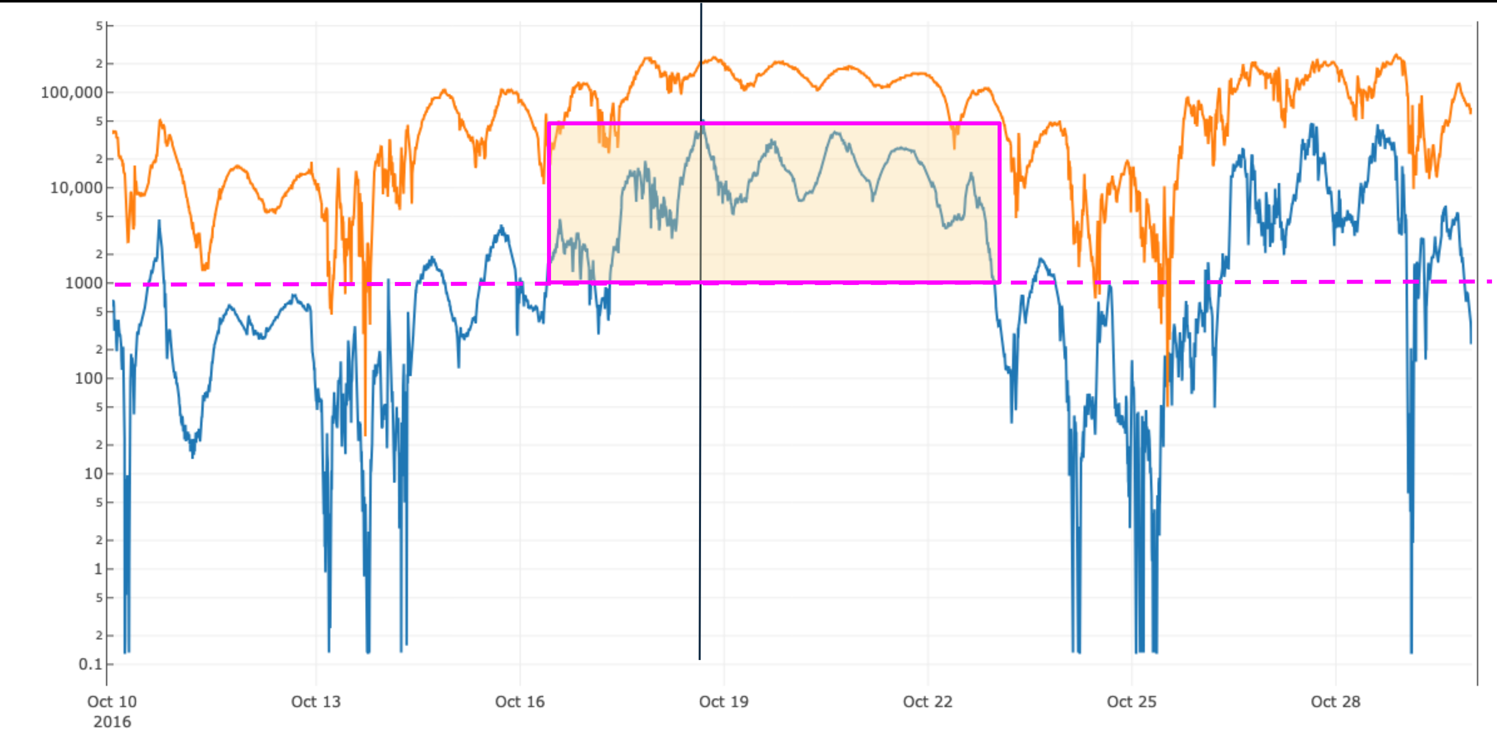
Q: A spacecraft experiencing these conditions on 2016-10-18T16:00Z might experience anomalies due to what spacecraft impact?

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

AEROSPACE

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

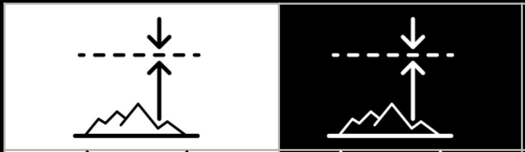
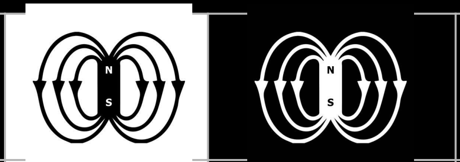
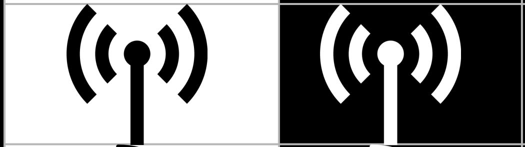
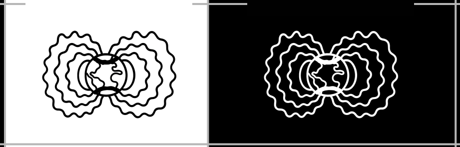
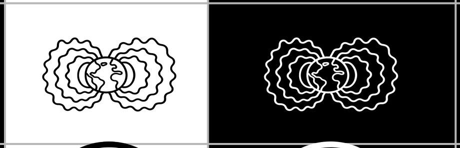
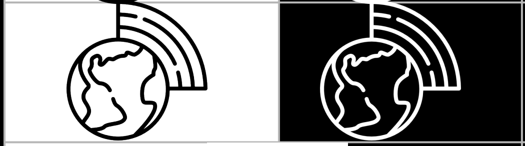
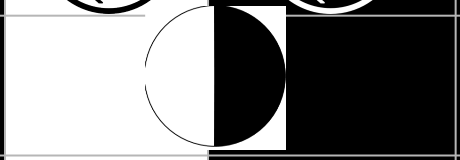
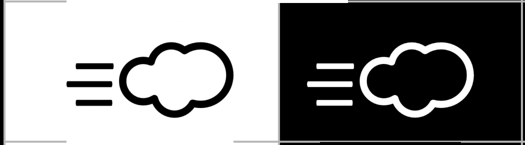
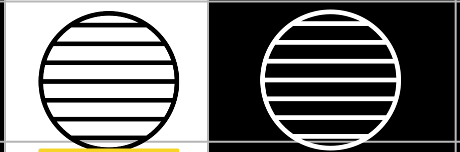
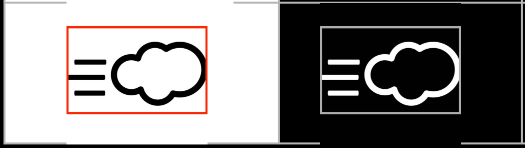
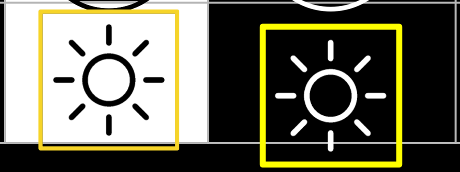
satellite: GOES 15

IC: Internal Charging

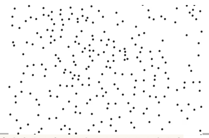
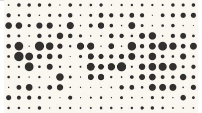
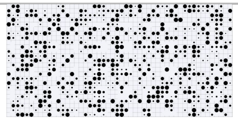
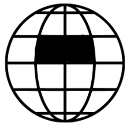
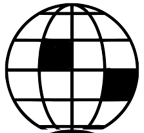
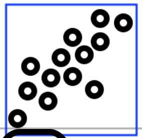
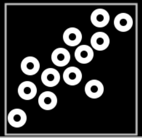
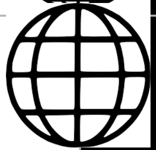
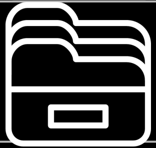
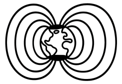
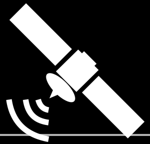
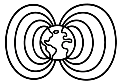
https://ccmc.gsfc.nasa.gov/seaesfc/

Backup slides

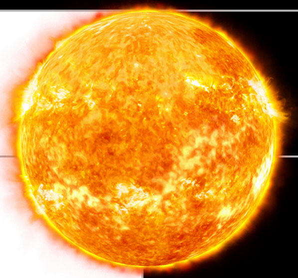
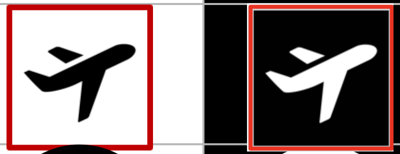
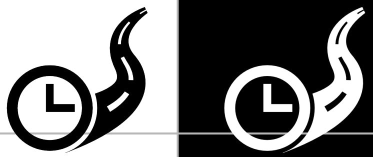
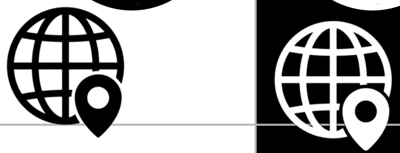
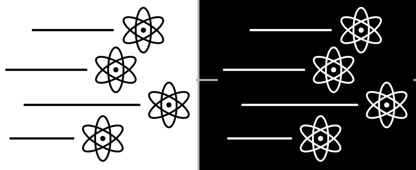
Icons

	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

Icons

		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

Icons

		mass			sun!
		plane			
		polar caps			transmit time
		position earth			fast particles 2
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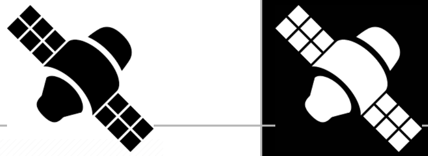		satellite			
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