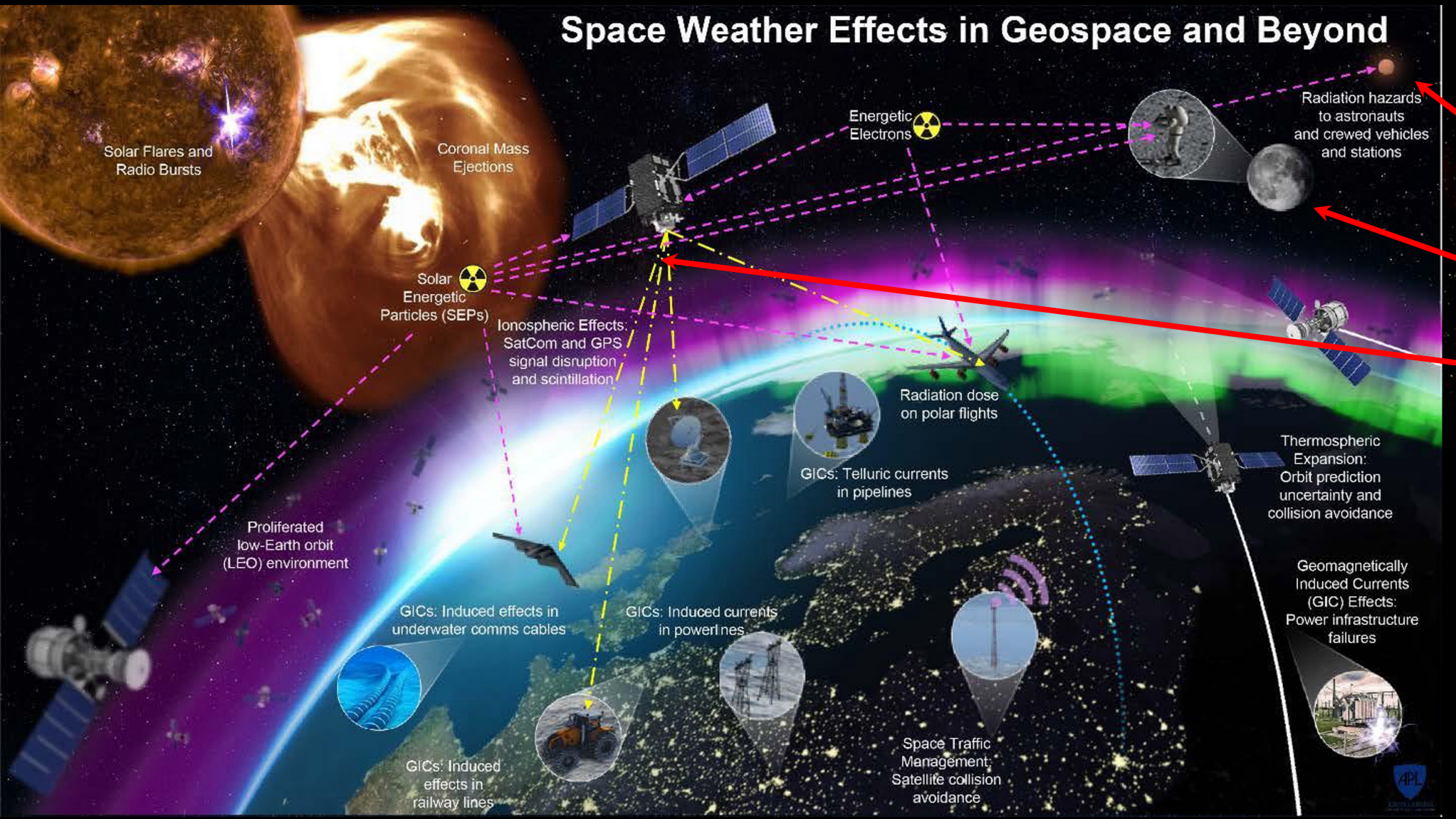
Space Weather Impacts on Satellites

location, location, location…

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



Credits: Vourlidas et al. (2021)

Space Climatology and Space Weather

Space climatology:

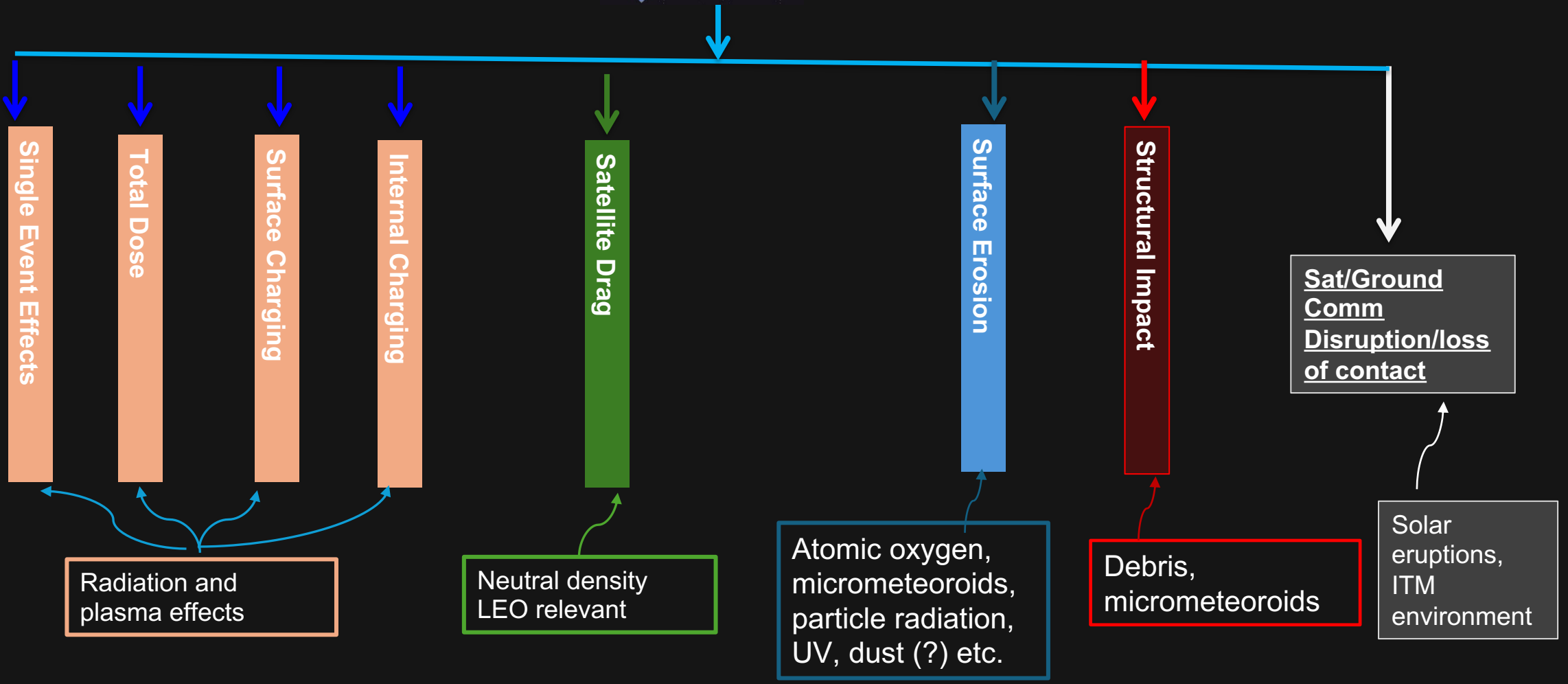
- Variability over months to years
- Space environment effects on both satellites and launch vehicles are best mitigated by good design

Space weather:

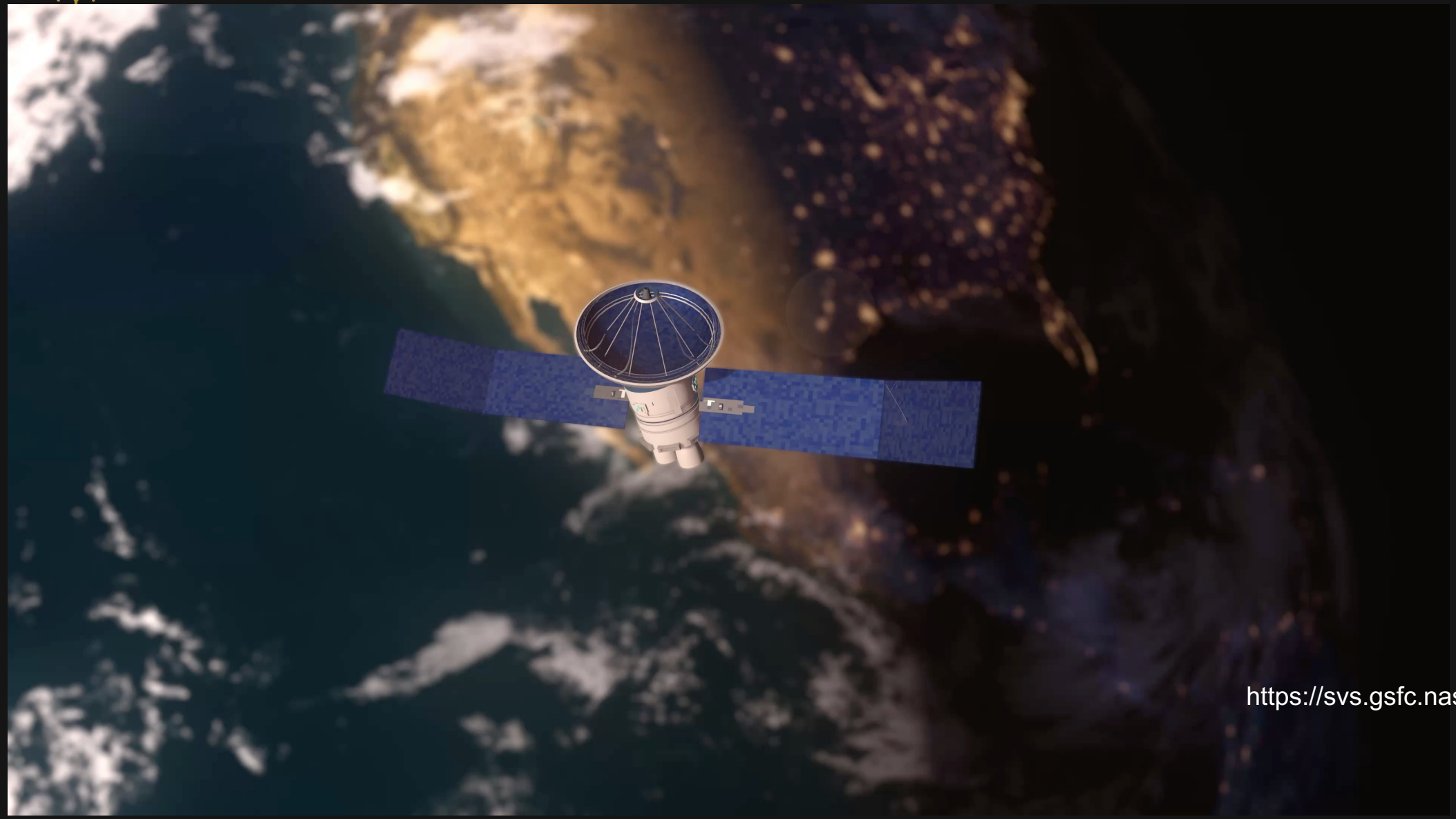
- Variability over minutes to days
- Effects mitigated by design or operational controls
- Design satellites to withstand mean, extreme space weather events that may occur during time on orbit

Space Environments Impacts on Spacecraft Operations





Impacts on Satellite - Illustration



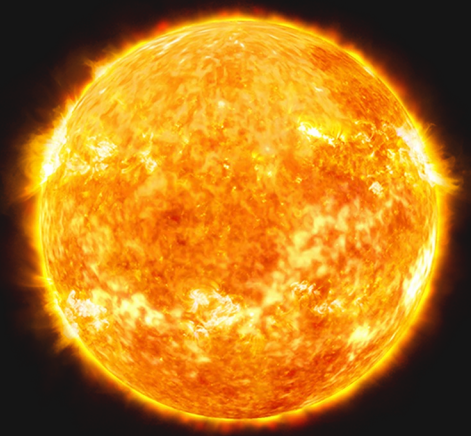
https://svs.gsfc.nasa.gov/14956/

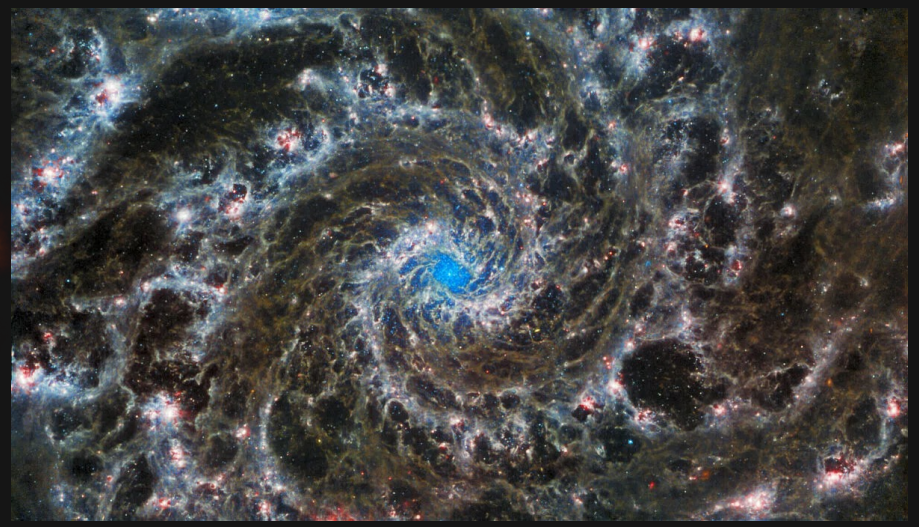
GSFC/SVS

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.



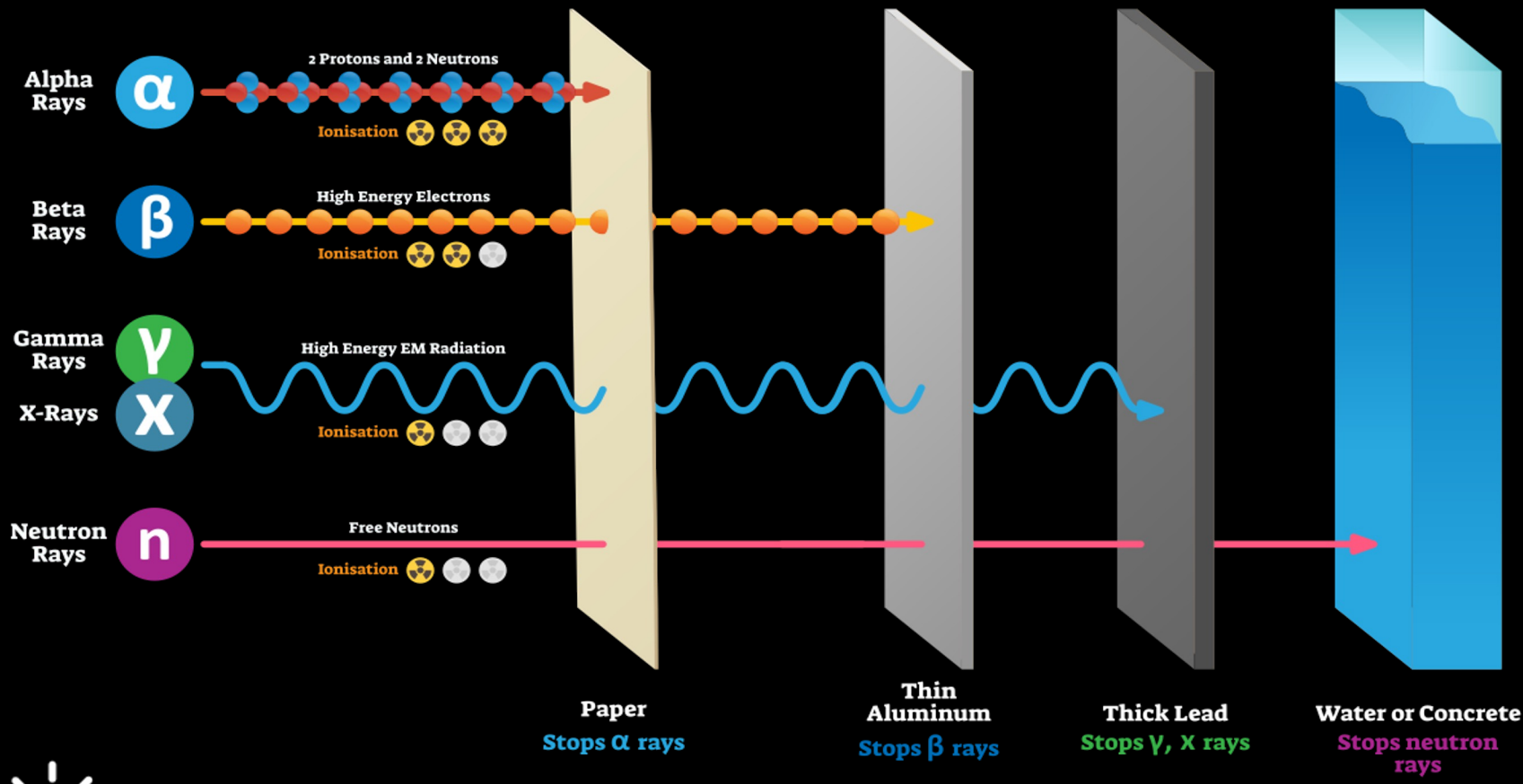






What is radiation?

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



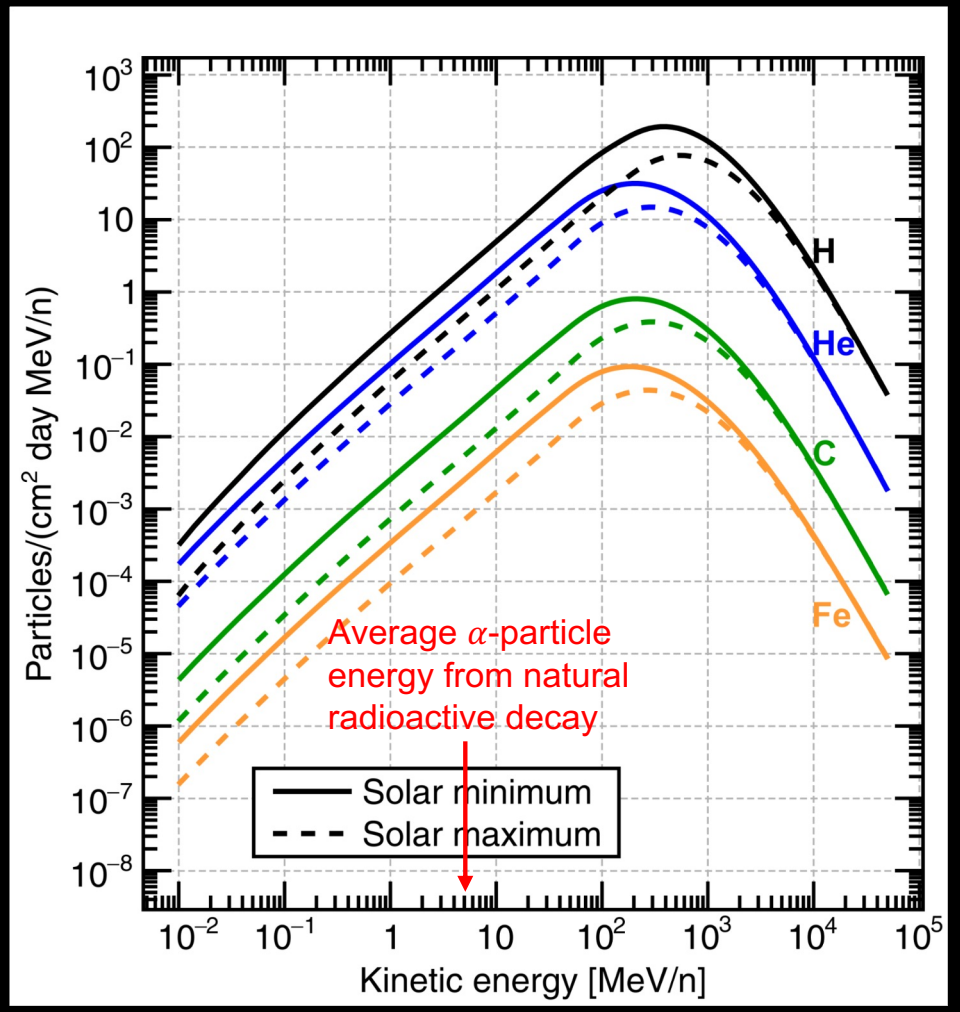
Adapted from American Nuclear Society

Radiation in space: galactic cosmic rays

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



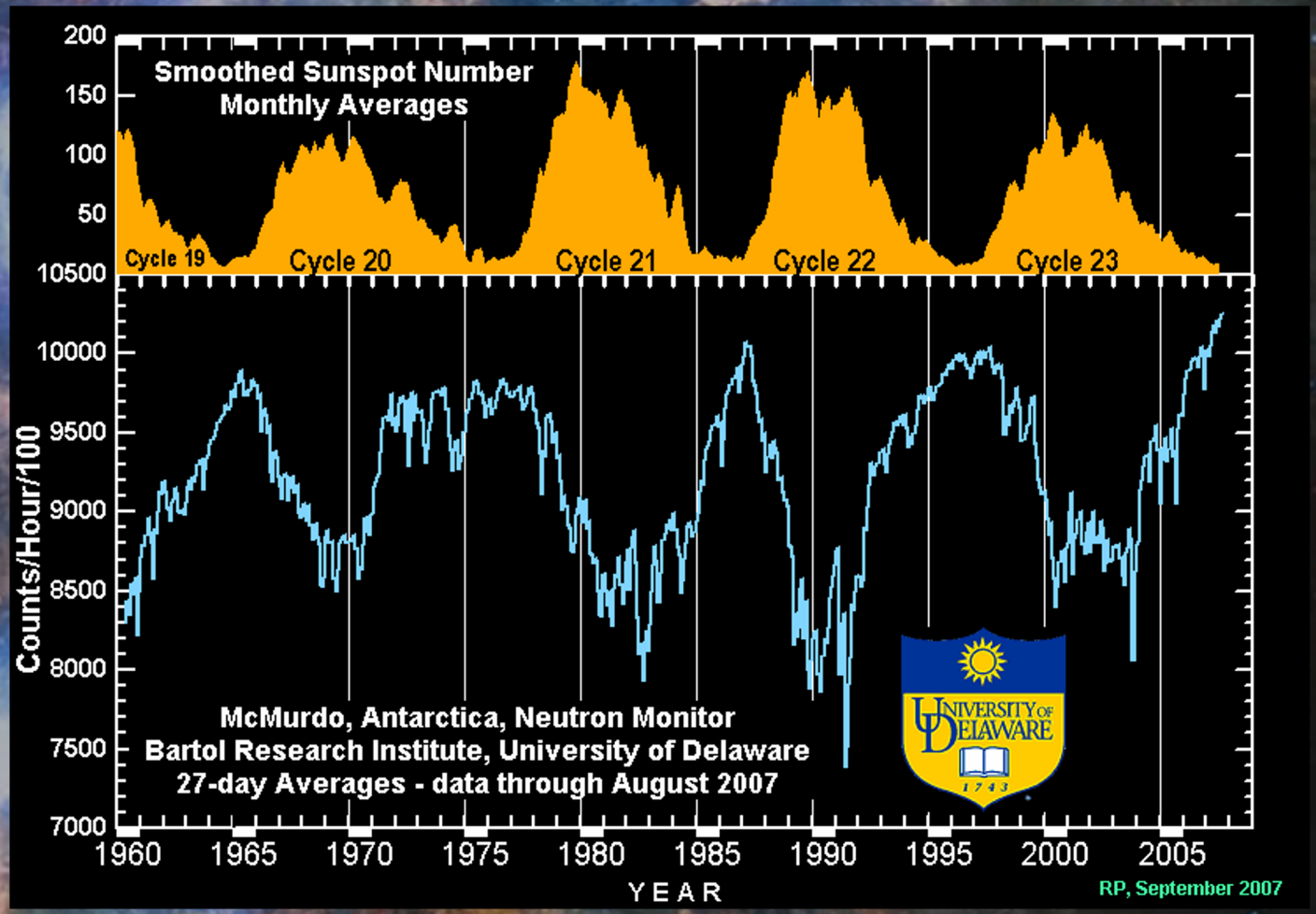
The Crab Nebula, as seen by the James Webb Space Telescope and Chandra X-ray Observatory (Image credit: X-ray, Chandra: NASA/CXC/SAO; Infrared, Webb: NASA/STScI; Image Processing: NASA/CXC/SAO/J. Major)



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

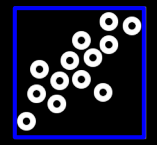
Elemental composition (may vary event by event):

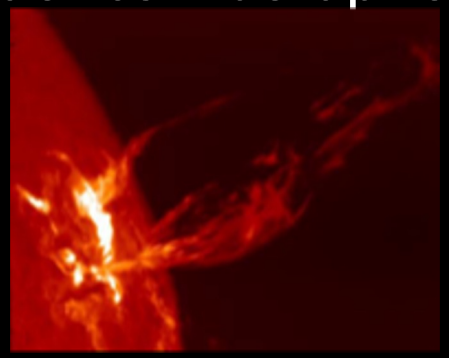
- 96.4% protons
- 3.5% alpha particles
- 0.1% heavier ions (not to be neglected!)

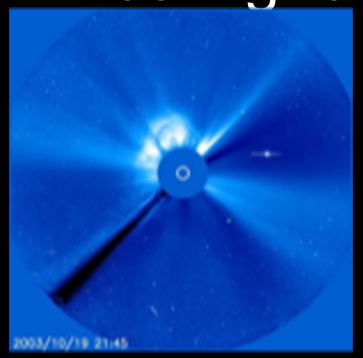
Energies: up to GeV/nucleon

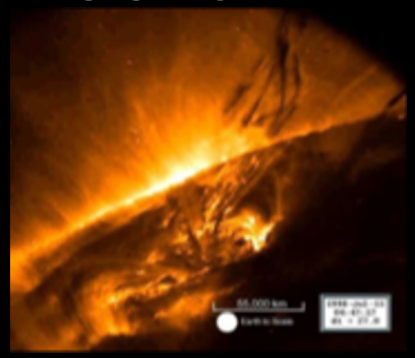
Event magnitude: can be up to 10^5 times higher than GCRs







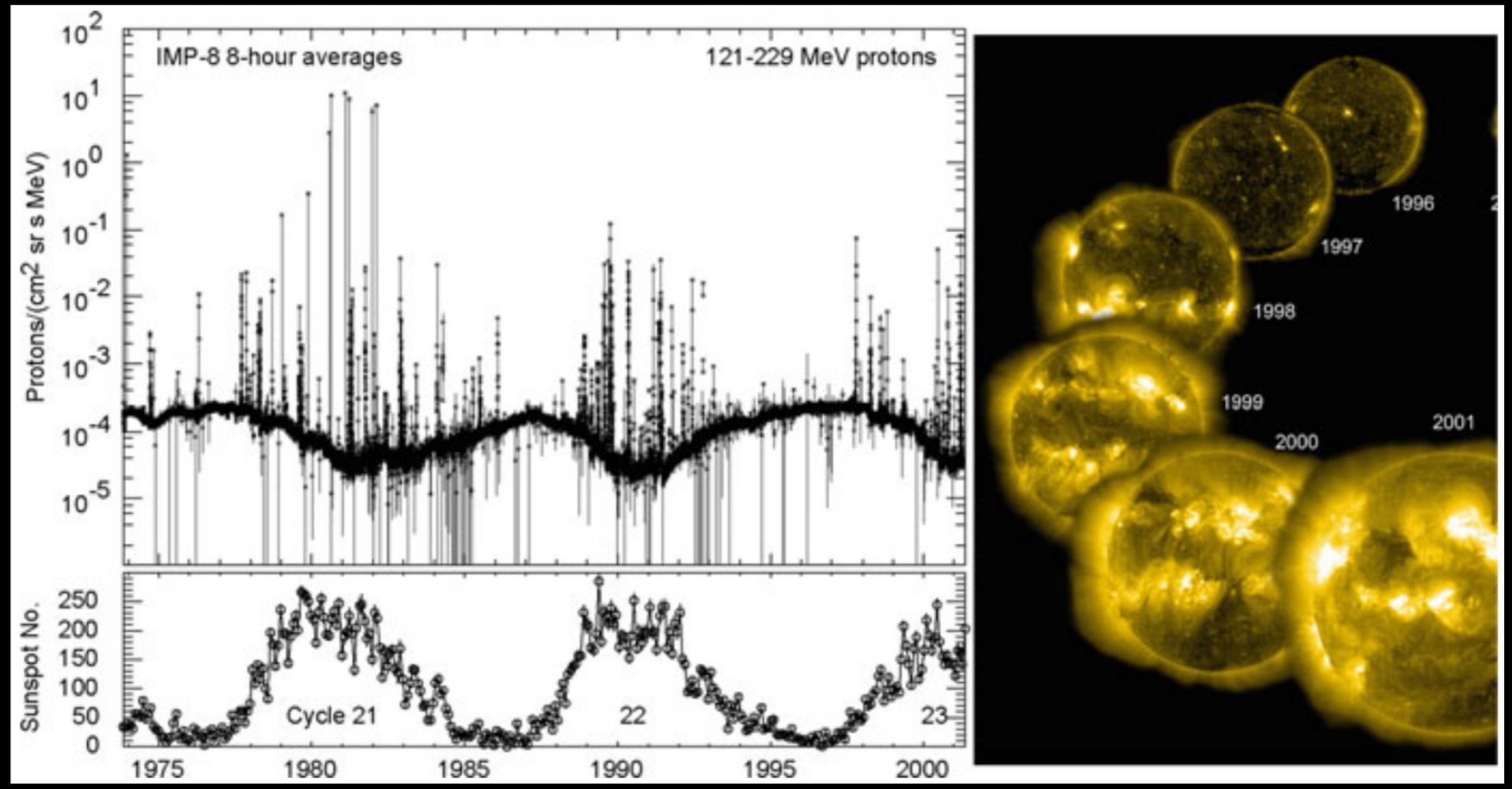




Radiation in space: solar energetic particles

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

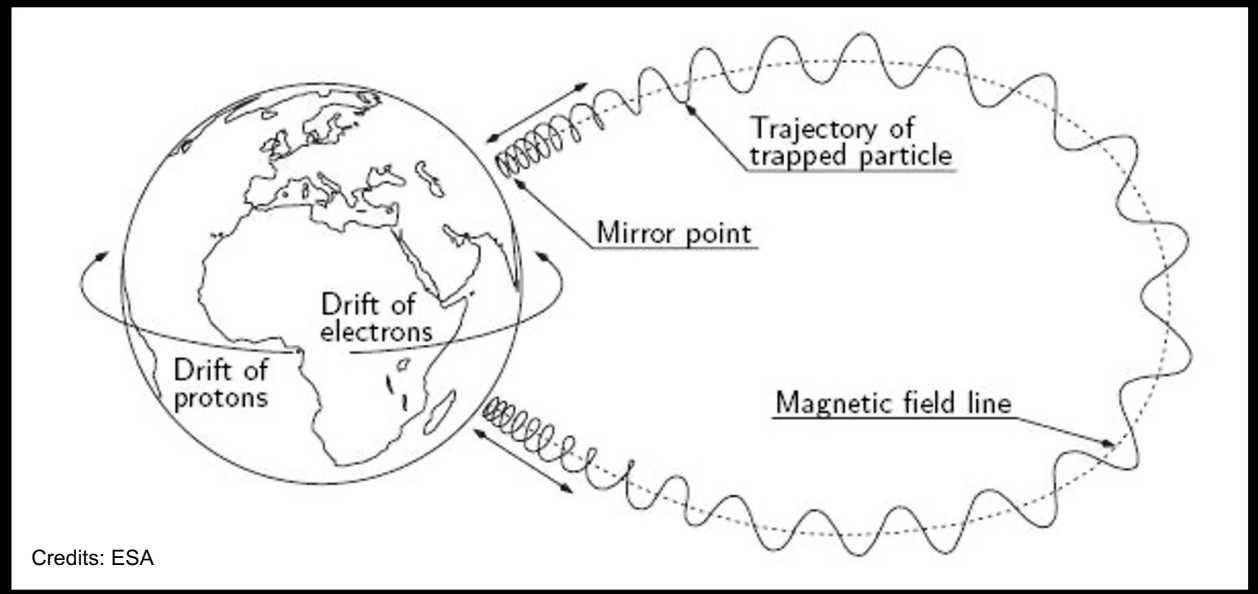
Hard to predict!



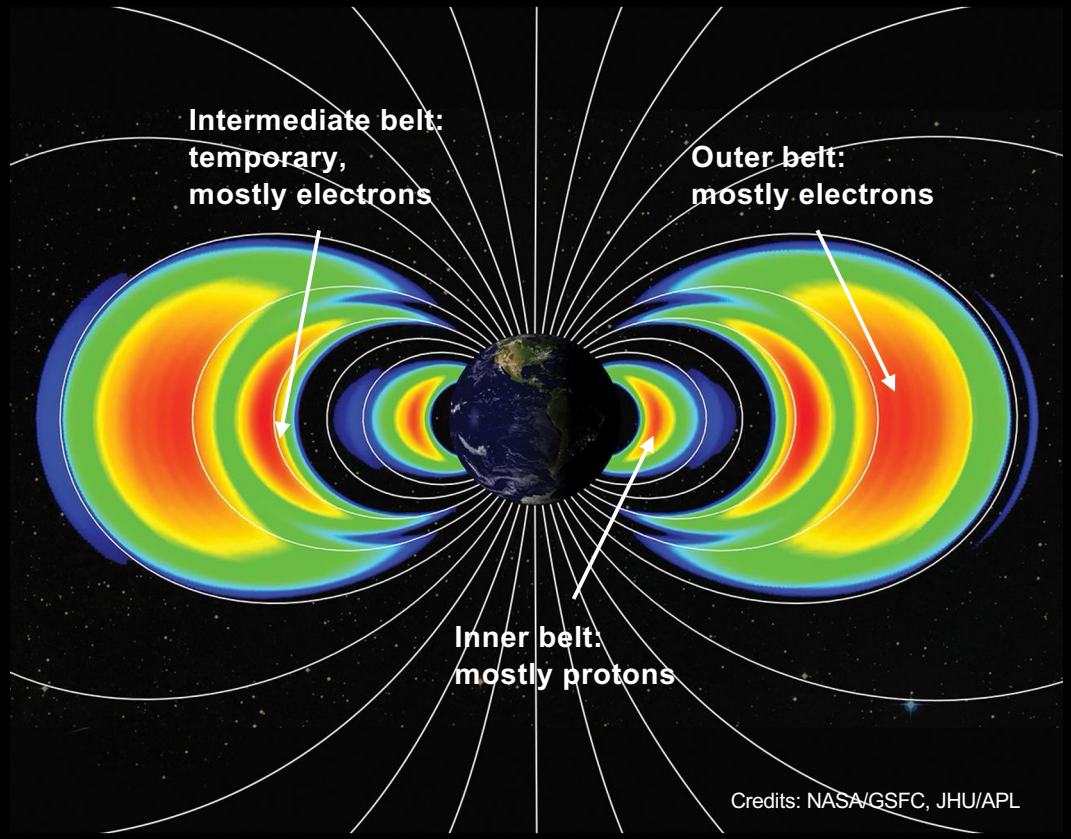
Credits: Reames (2021), DOI:10.1007/978-3-030-66402-2

Radiation in space: Radiation belts

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



Credits: ESA

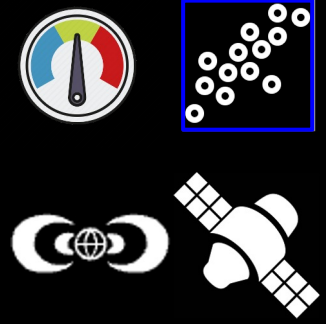


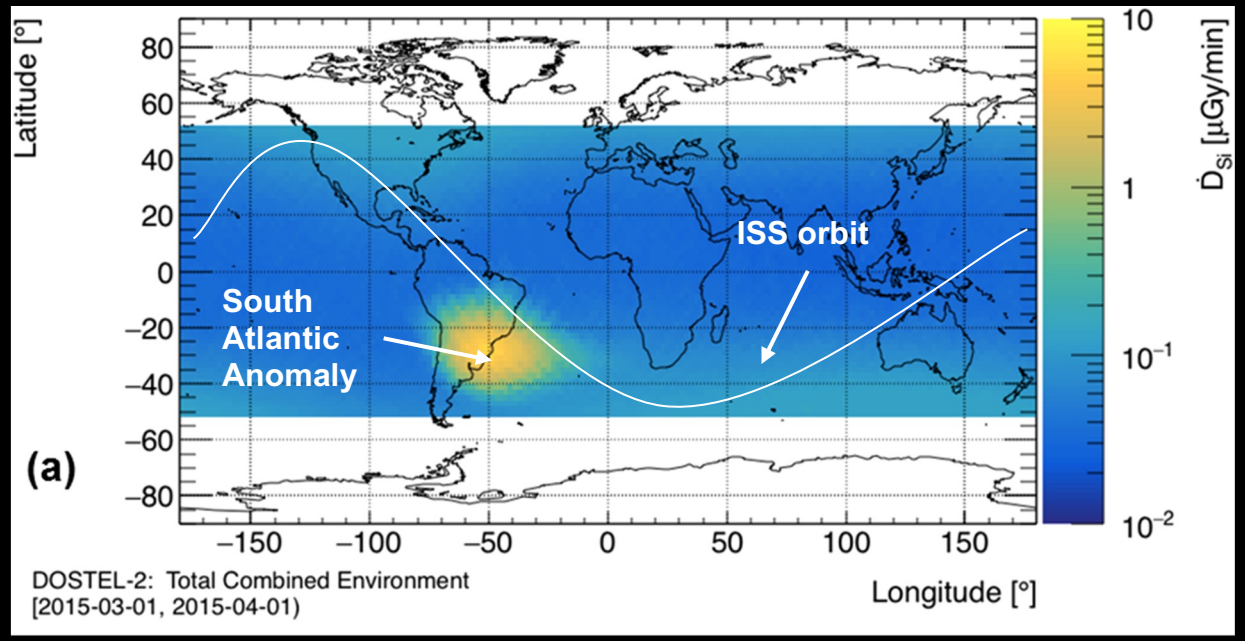
Credits: NASA/GSFC, JHU/APL

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

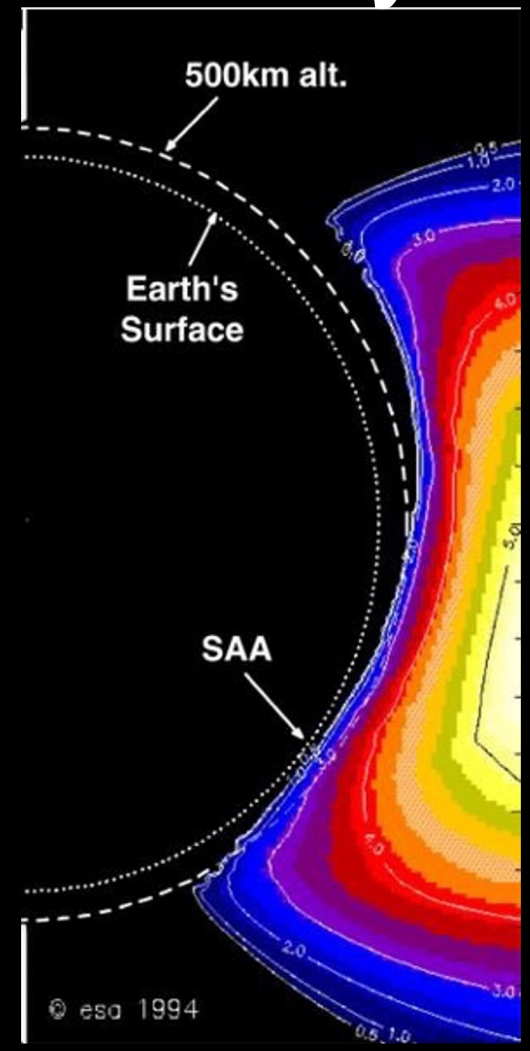
Radiation in space: South atlantic anomaly

- 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



South Atlantic Anomaly



GSFC/SVS

Quantifying radiation effects: particle spectrum

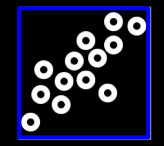
Effects of space radiation depend on:

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

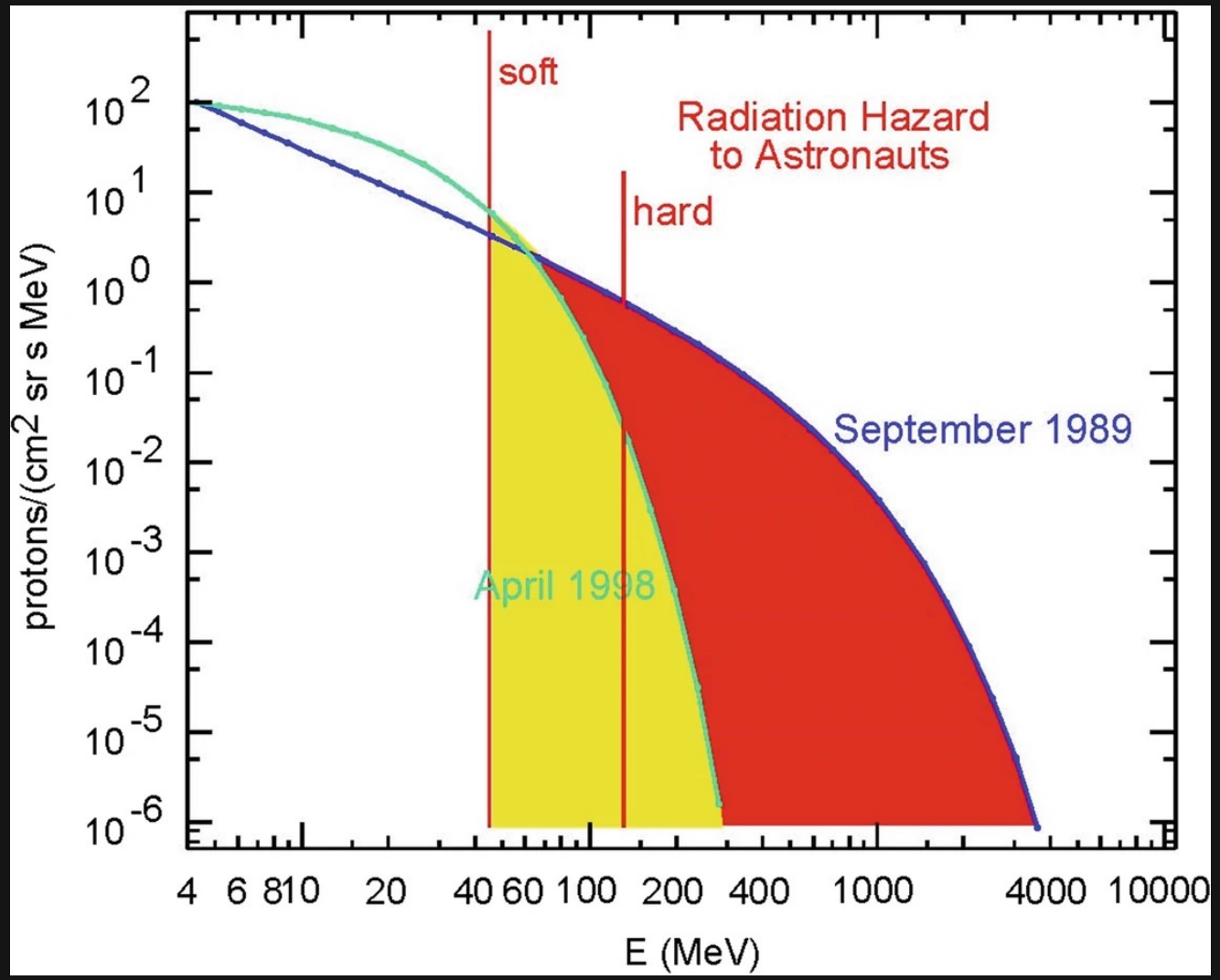
Particle spectrum (intensity vs energy) is a key factor in understanding space radiation effects:

- 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

Increasing Energy

Reames, D.V. (2021)

Satellite impacts

	Mechanism	Effect	Source
Radiation	**Total ionizing dose (TID)**	• Degradation of microelectronics	• Trapped protons • Trapped electrons • Solar protons
Radiation	**Displacement damage dose (DDD)**	• Degradation of optical components and some electronics • Degradation of solar cells	• Trapped protons • Trapped electrons • Solar protons • Neutrons
Radiation	**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
Charging	**Surface charging**	• Biasing of instrument readings • Power drains • Physical damage	• Dense, cold plasma • Hot plasma (ring current, aurora population, few eV to 10s keV)
Charging	**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)

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

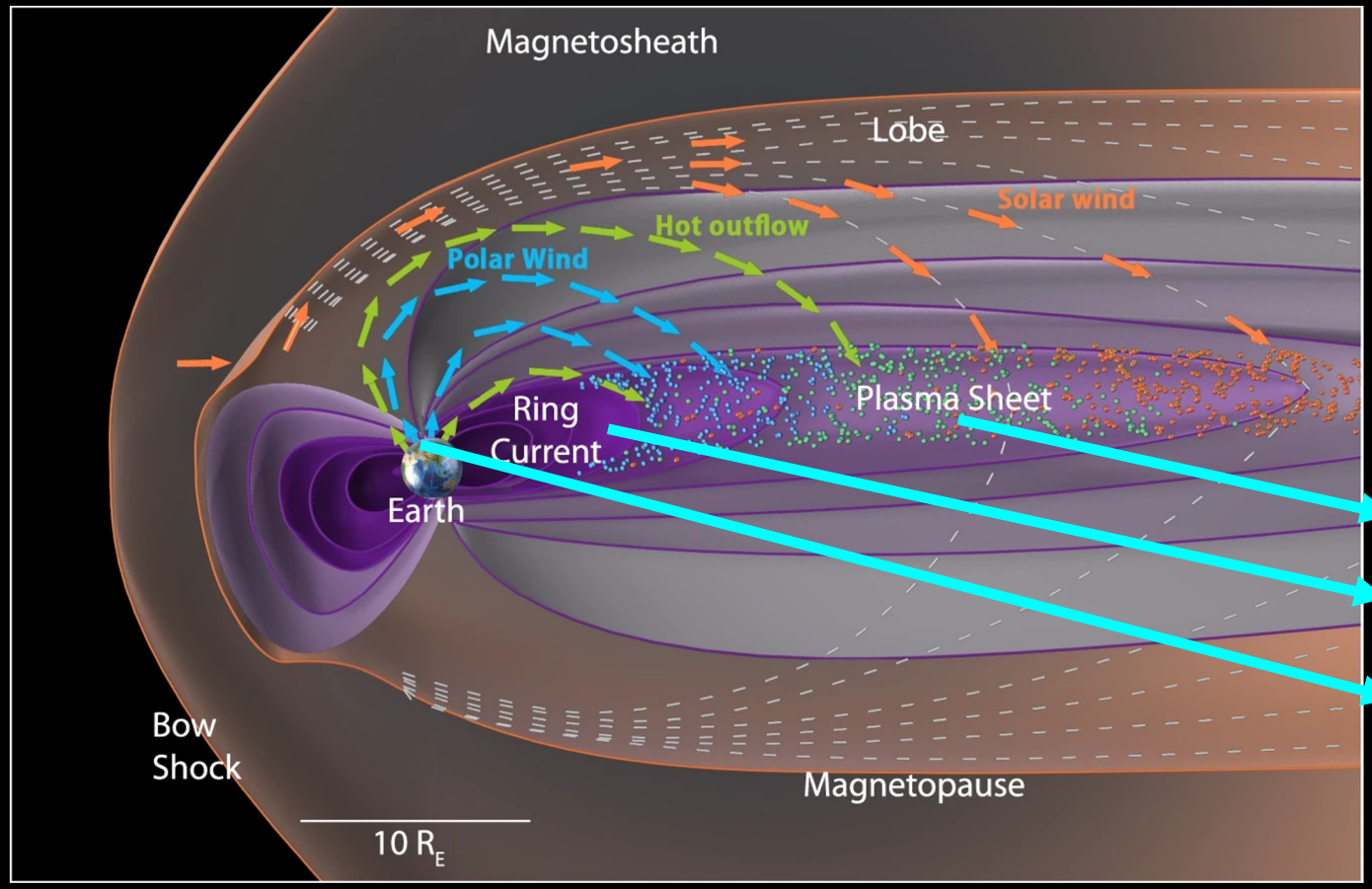
Internal charging:

- 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

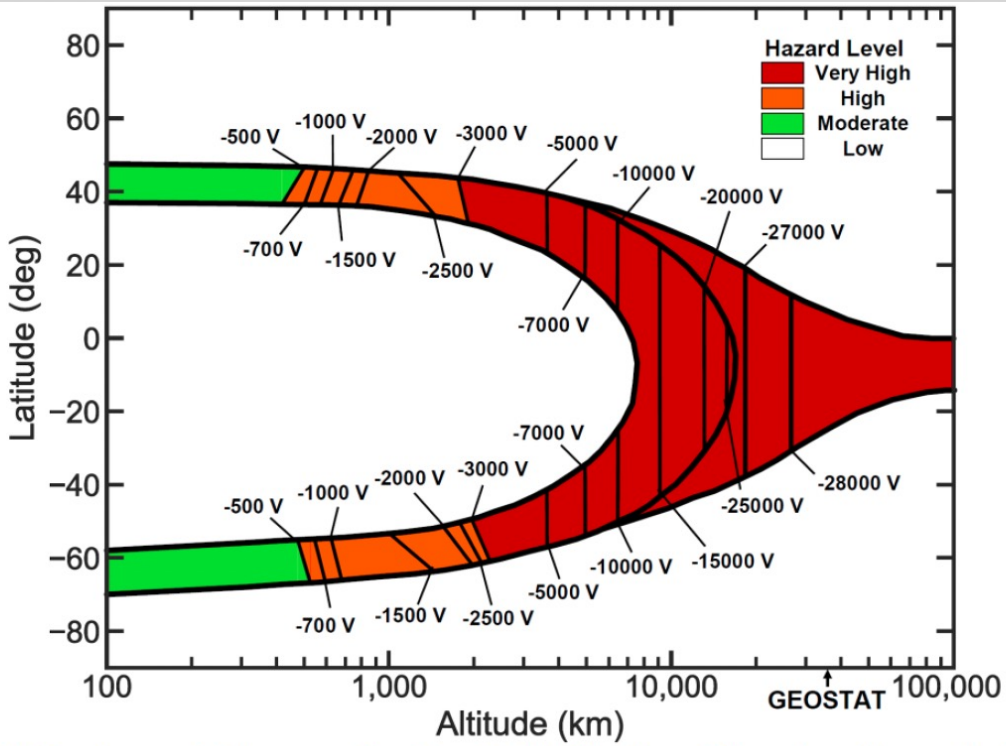


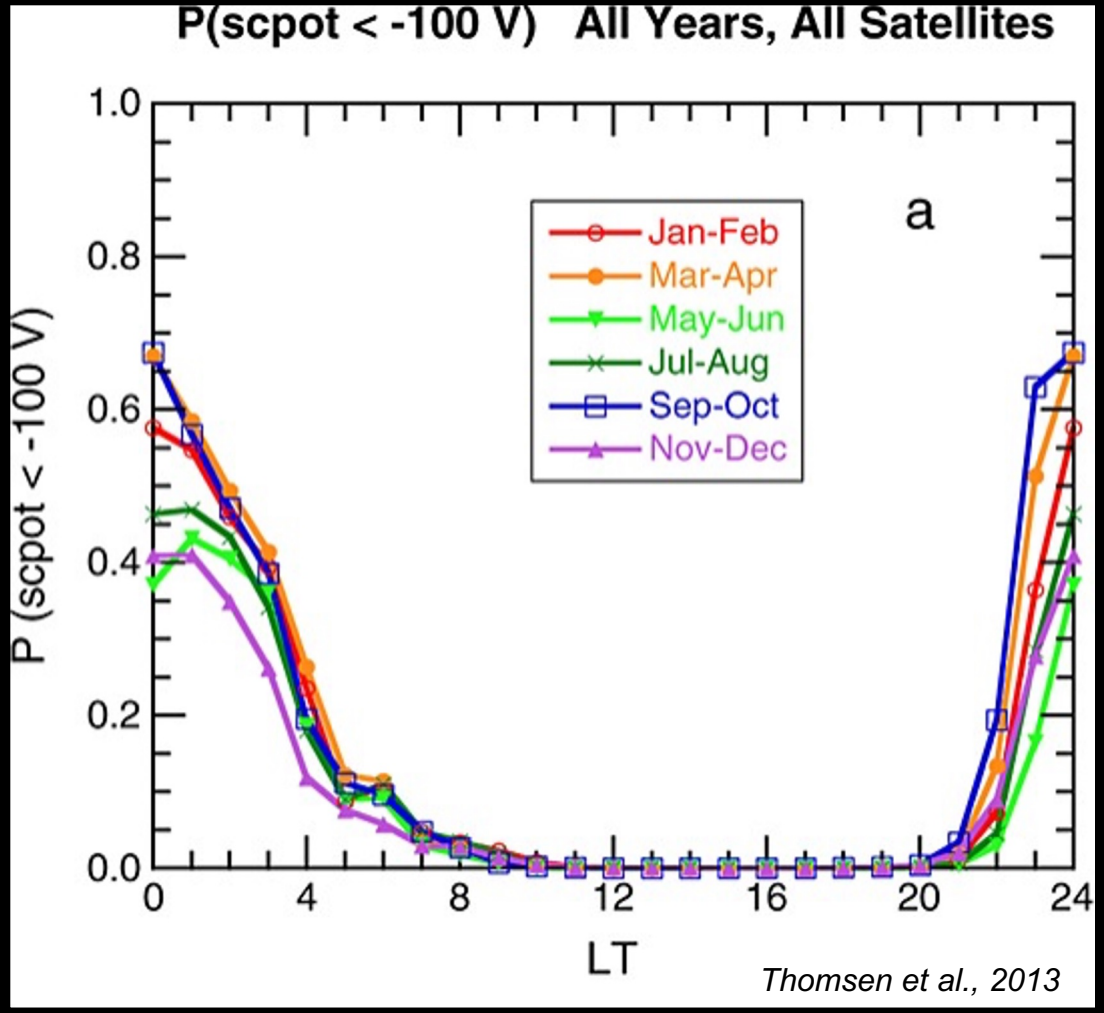
Figure 1—Earth Regimes of Concern for On-Orbit Surface Charging Hazards for Spacecraft Passing Through Indicated Latitude and Altitude Based on DMSP and Freja Observations, et al.

Credits: NASA-HDBK-4002B

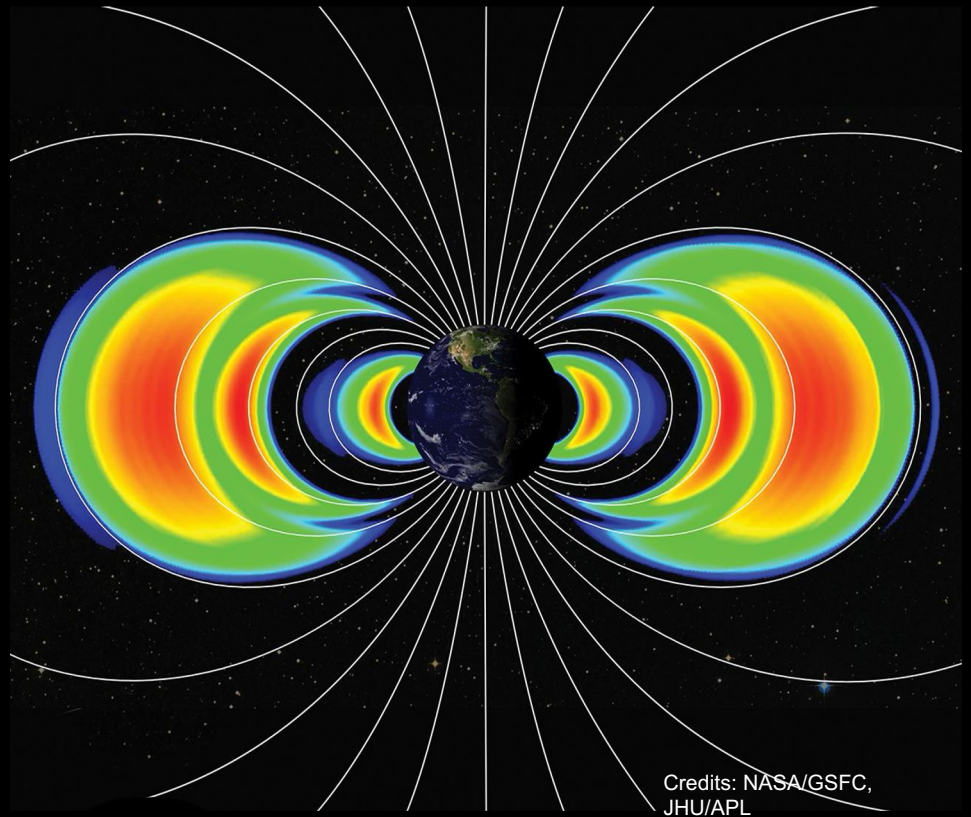
Surface charging: local time dependence

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 = $1/(cm^2\ s\ sr)$]

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

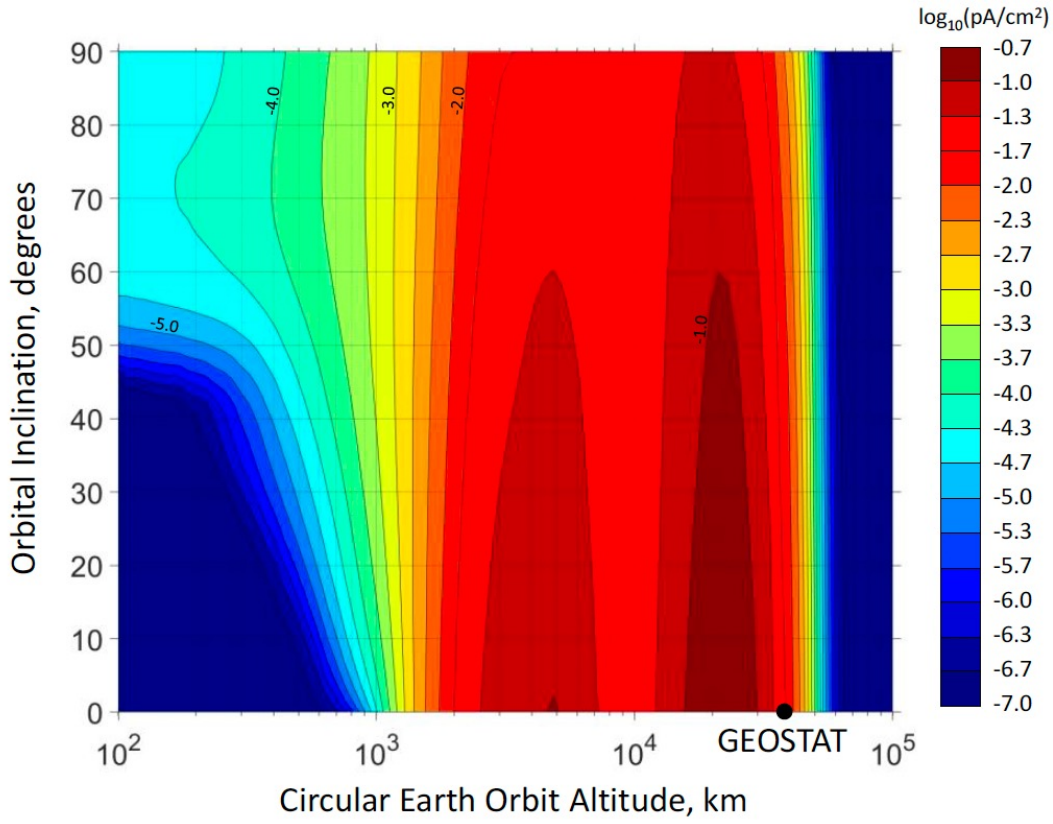


Figure 2—Earth Regimes of Concern for On-Orbit Internal Charging Hazards for Spacecraft with Circular Orbits, the Charging Flux under 30 mil Al Shielding is Plotted

NASA-HDBK-4002B

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)

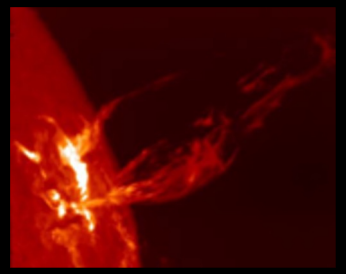
Any measurable effect in a circuit caused by a single incident ion

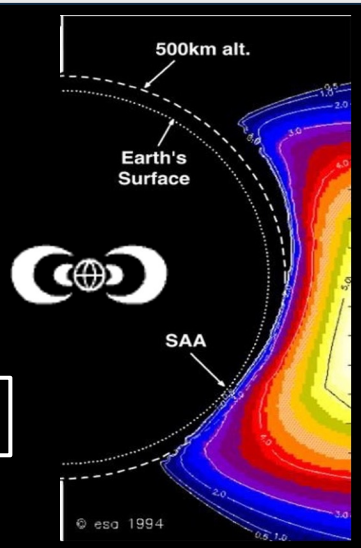
SEEs: sources in space

High-energy particle radiation

- GCRs
- SEPs
- SAA
- High-energy neutrons

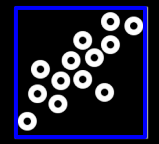








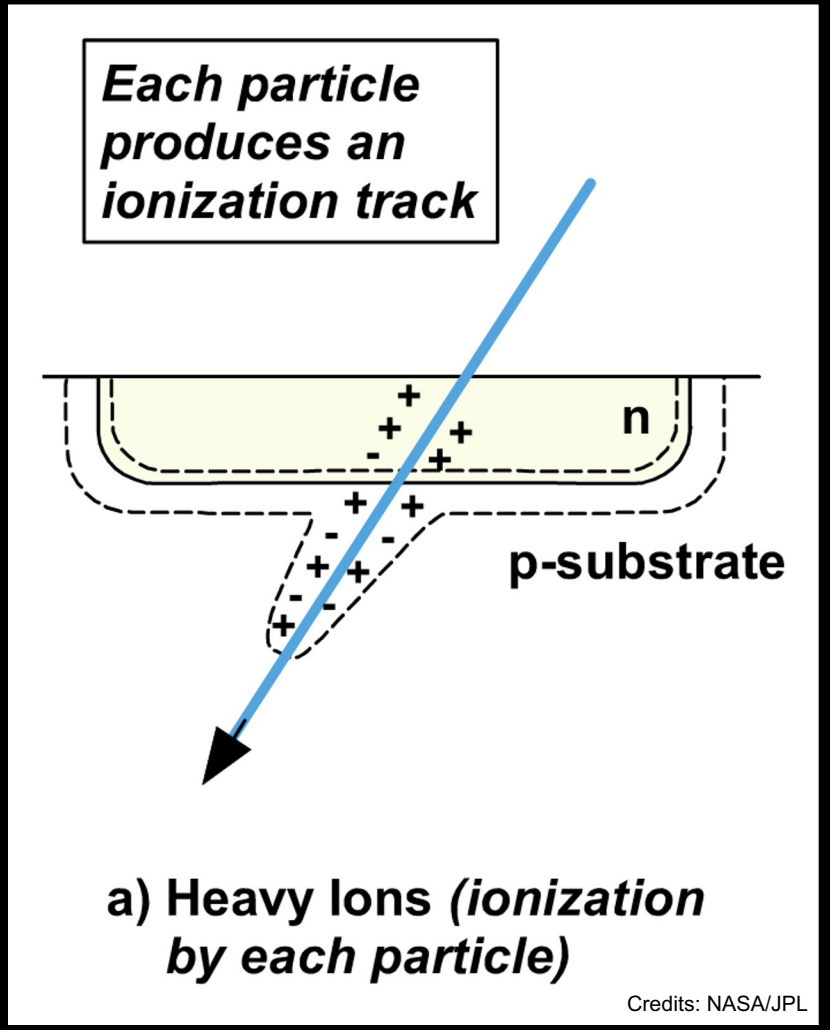
protons/ions from GCR, SEP, and SAA with energy > 30 MeV



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

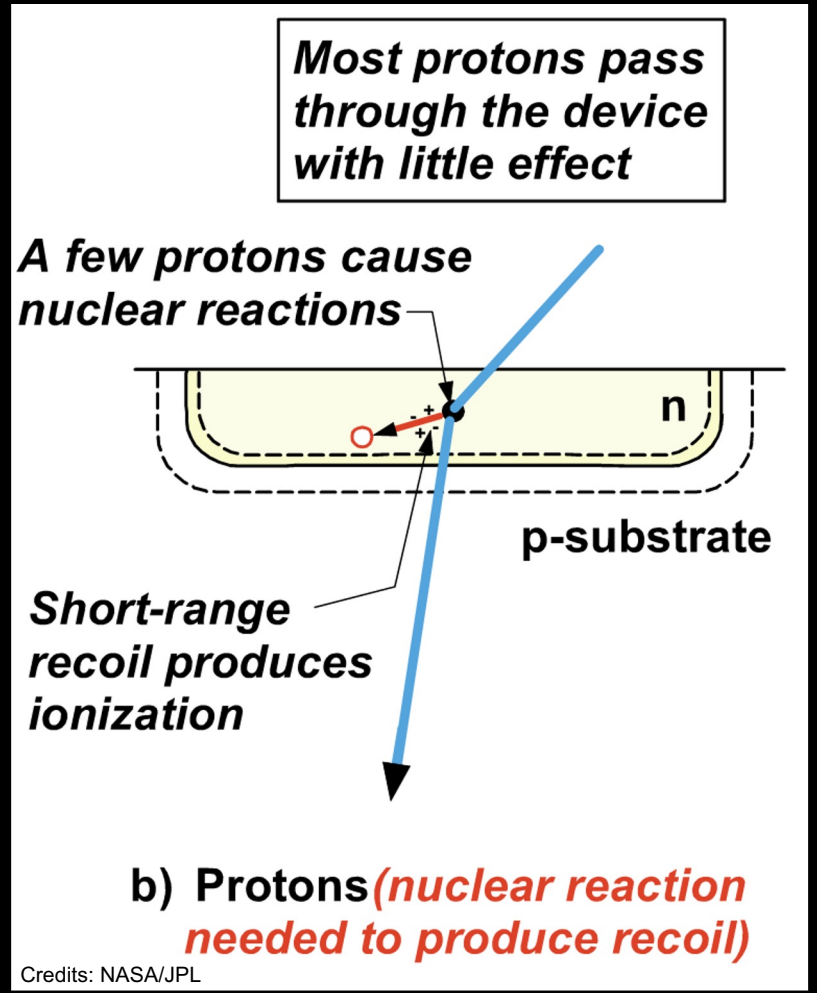
Direct ionization (heavy ions, Z=2-92)
Dense ionization track over a short range produces sufficient charge in sensitive volume to cause SEE



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).



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

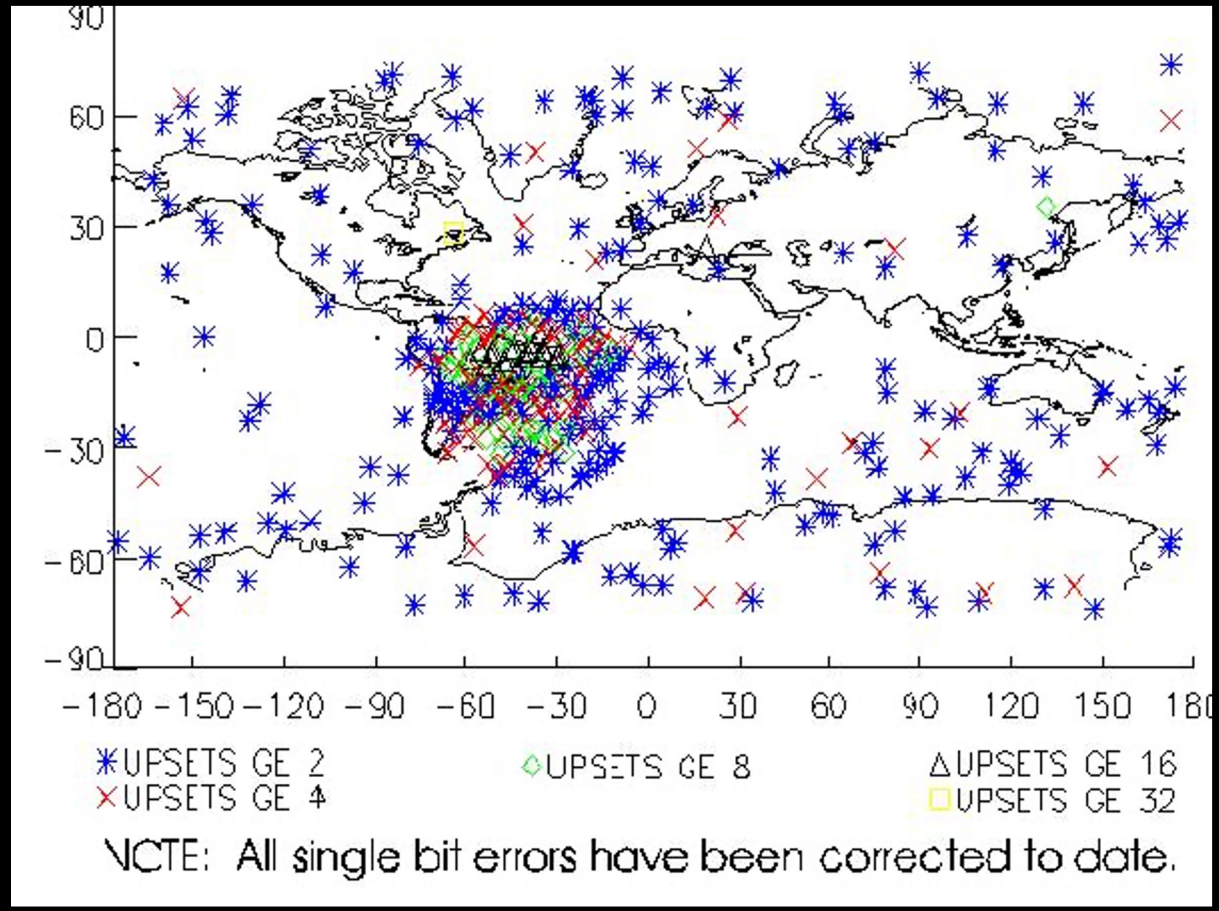
- Radiation hardening (insulating substrates, “simpler” components, …)
- Shielding
- Error correcting code memory, redundancy

Non-destructive SEEs

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



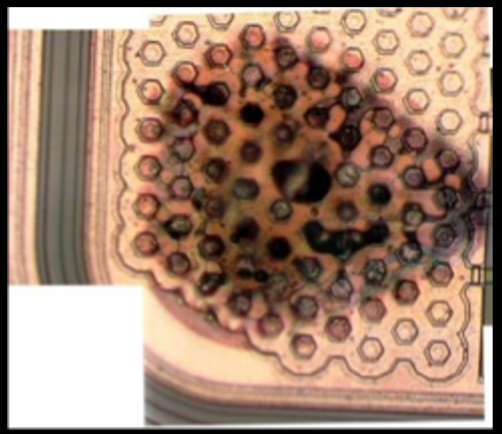
Credits: Seidleck et al. (2003)

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

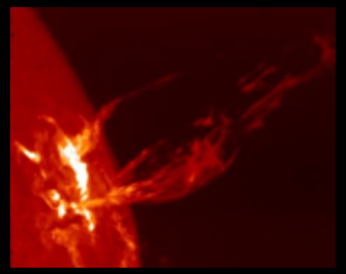
Total dose: sources in space

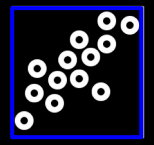
High-energy particle radiation

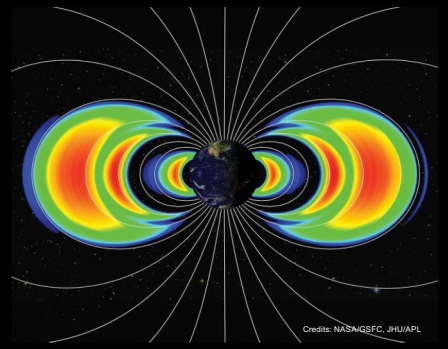
- GCRs
- SEPs
- Trapped particles (radiation belts, including SAA)
- High-energy neutrons













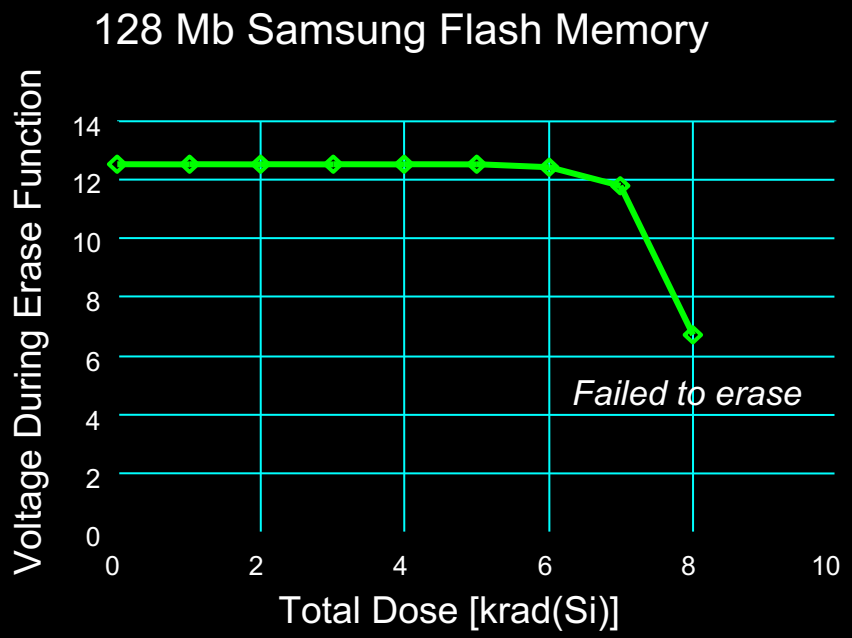
Electrons: >100 keV
Protons: > 1 MeV

Total dose effects: TID

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

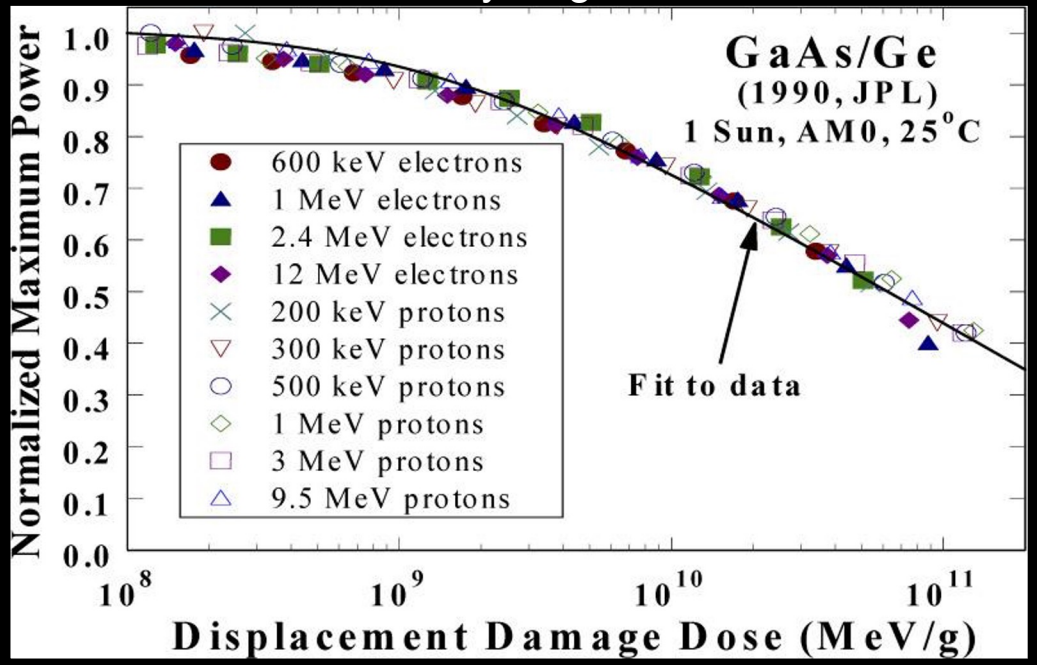
Displacement Damage Dose (DDD): cumulative damage resulting from displacement of atoms in semiconductor lattice structure causing:

- Carrier lifetime shortening
- Mobility degradation

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



Solar Array Degradation



Messenger et al. (2001), DOI:10.1002/pip.357

SEE vs TID



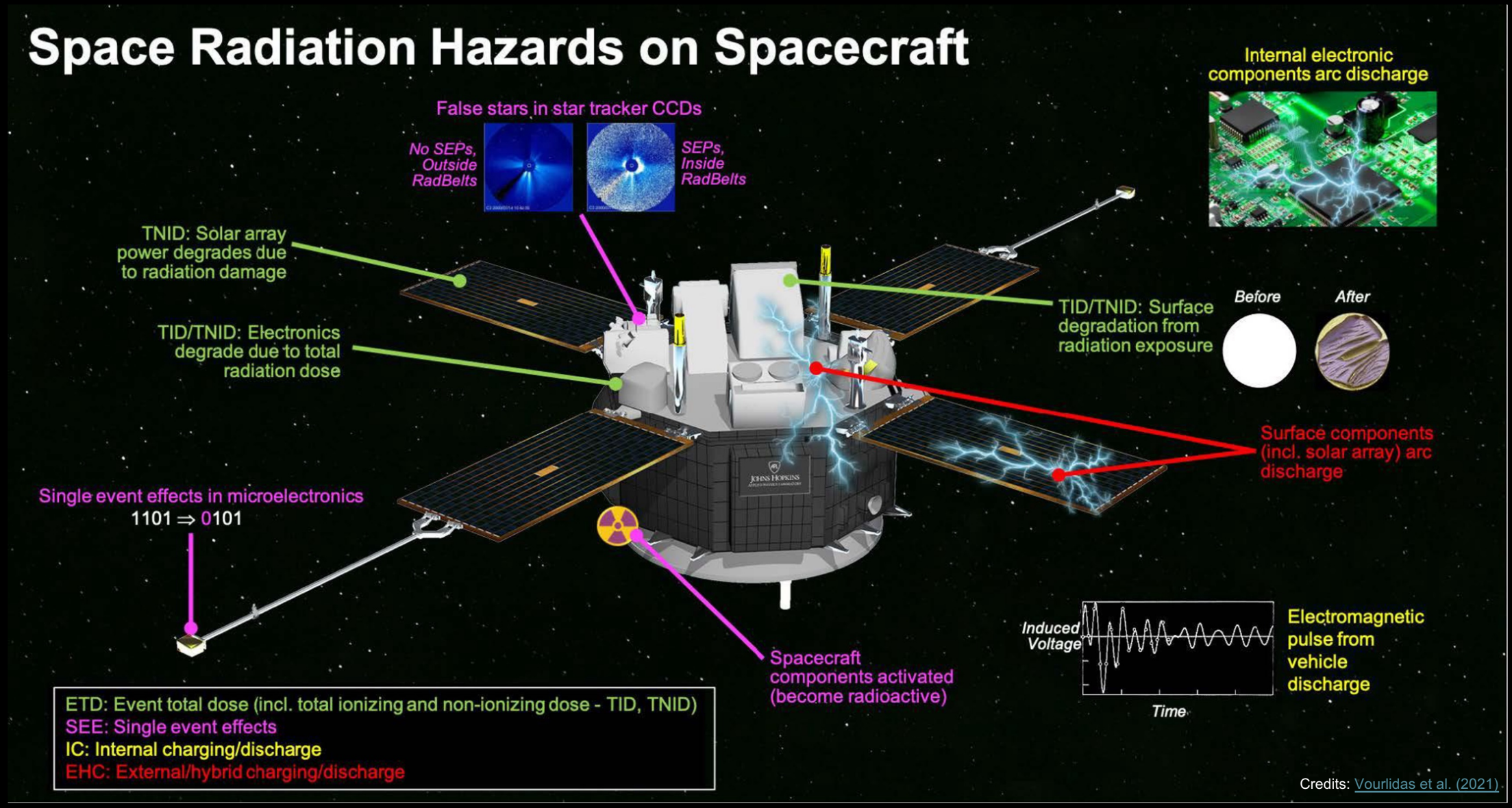
TID: lightly ionizing particles are important if abundant enough to **collectively** produce an effect

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?

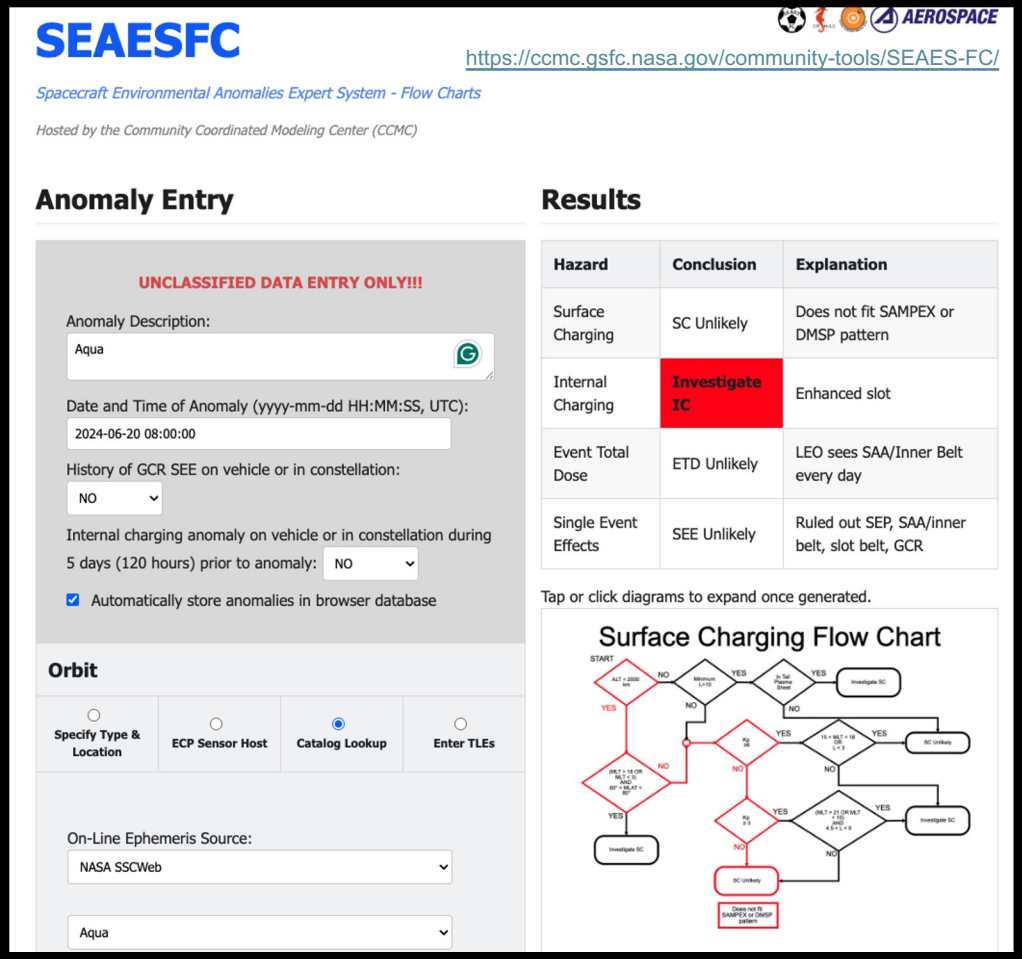
Space Radiation Hazards on Spacecraft



Credits: Vourlidas et al. (2021)

SEAES-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

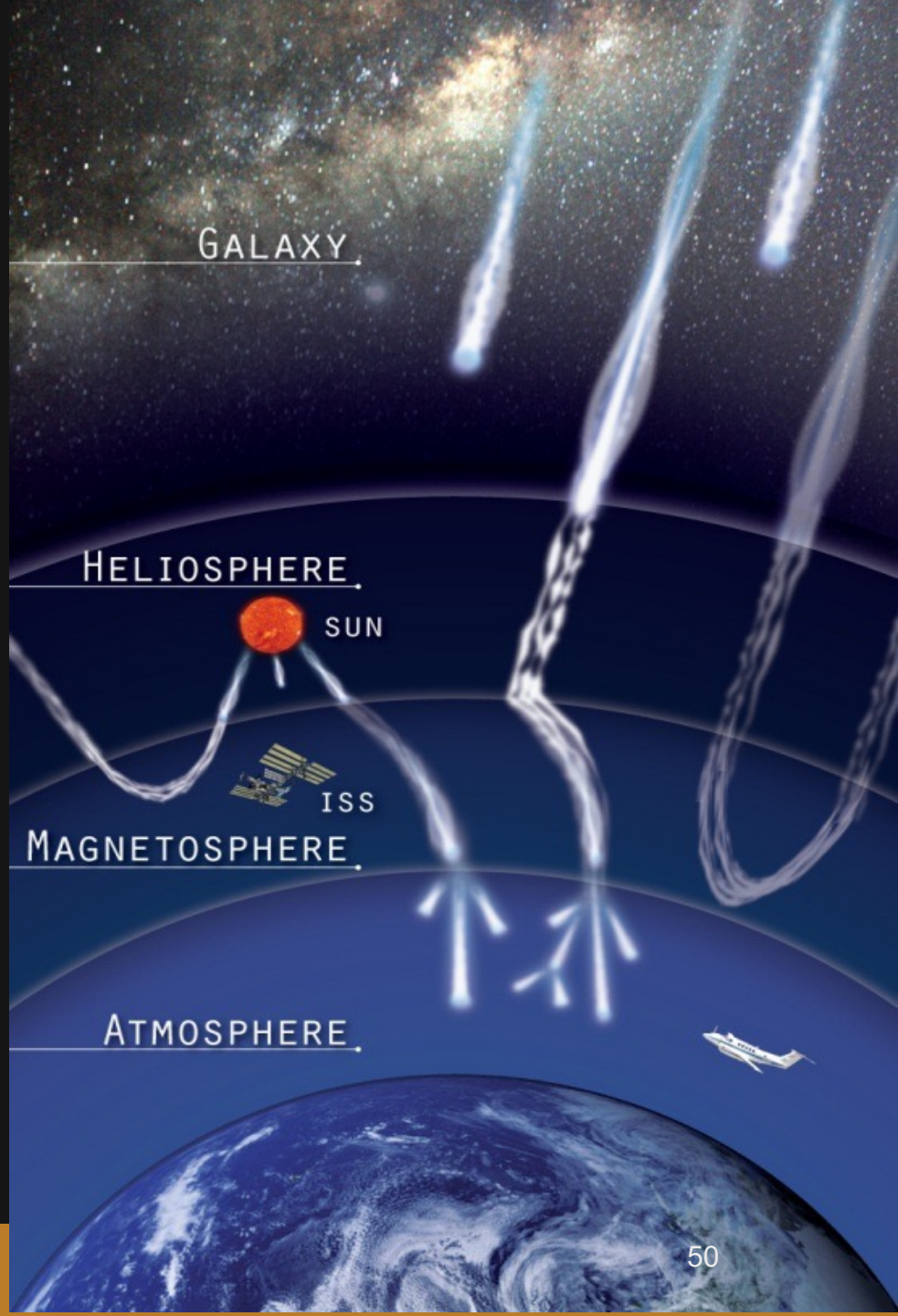


On June 20, Aqua and Aura came within minutes of having to go into safe mode.

Aviation impacts

NAIRAS Model

- **Key (Vintage) Model Features**
  - Physics-based **HZETRN** (High Charge (Z) and Energy TRaNsport) code
  - Real-time inclusion of solar energetic particle (**SEP**) radiation
  - Real-time solar-magnetospheric effects on radiation (cutoff model *by Kress et al.* [*2004, 2010*])
- **New/Current Model Developments**
  - Extend from atmosphere to space environment, now including trapped protons (**TRP-p**) and electrons (**TRP-e**)
  - SEP heavy-ions (Z=2-92, A=4-238) added
  - Single-Event Effects (**SEE**) radiation risk assessment quantities added (differential/integral flux/fluence)
  - Real-time products at 20 km to support military high-flyers
  - Run-on-Request (**RoR**) @ CCMC
  - Relevant for aviation, satellite anomalies, launch, and pre-launch assessments



NAIRAS model at CCMC

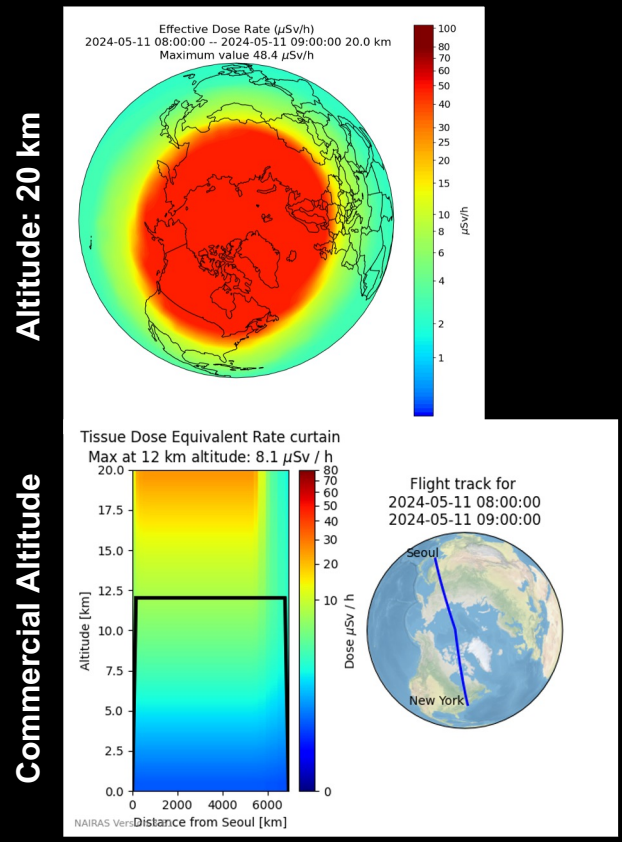
Nowcast of Aerospace Ionizing RAdiation System (NAIRAS)

- **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)

Highlights:

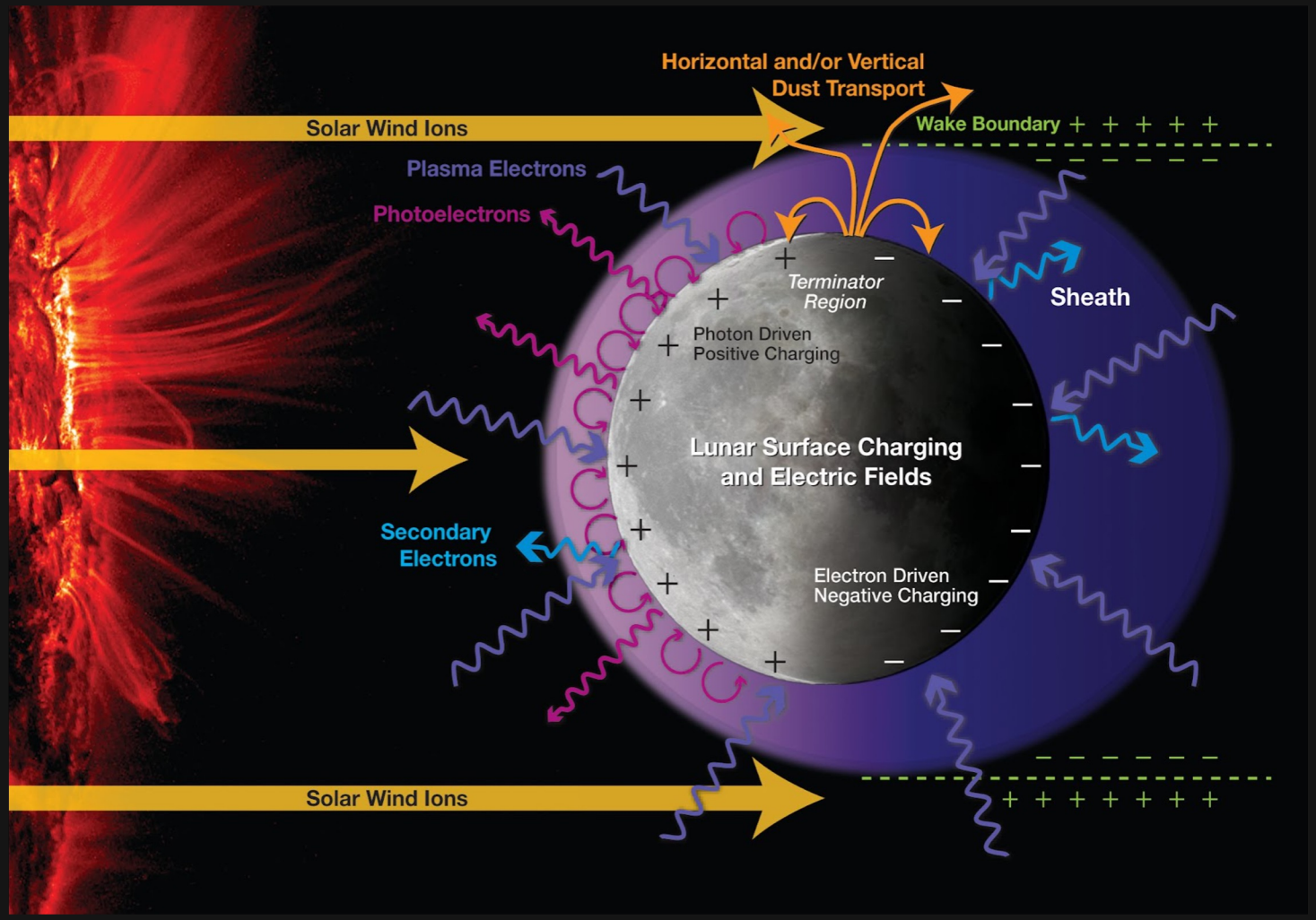
- U.S. Space Force (USSF) using NAIRAS predictions at 20 km in operations to support U2 pilot exposure.
- USSF used NAIRAS predictions to recall operational U2 flight during the May 10-12, 2024 SEP and Nov 2025 events
- **Forecasting:** 3-7 hours SEP forecast of peak dose after event onset by coupling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

May 10-12, 2024 SEP Event



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

Lunar Charging



Courtesy: T. Stubbs

Charging Hazards

- Electrostatic discharge (ESD) from differential charging of surfaces
- Mobilization and adhesion of charged dust (Stubbs et al., 2007; Gaier, 2005) — with direct implications for EVA safety, rover hardware, and landed infrastructure.

Models in the pipeline to CCMC

Stubbs et al. 2014, 1-D Lunar Charging Model

Another model: Janet Green, Linda Parker et al. Lunar Charging Model

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



Exercises

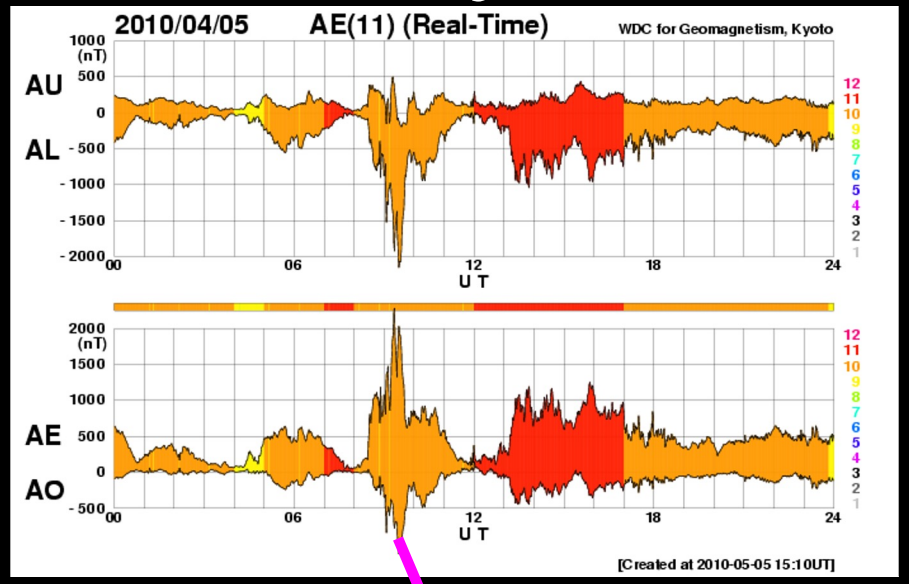
An ISWA layout:
https://iswa.ccmc.gsfc.nasa.gov/app/?layout=ringcurrent_fok_2010april_galaxy_training

Exercise 1: Galaxy 15 failure on April 5, 2010

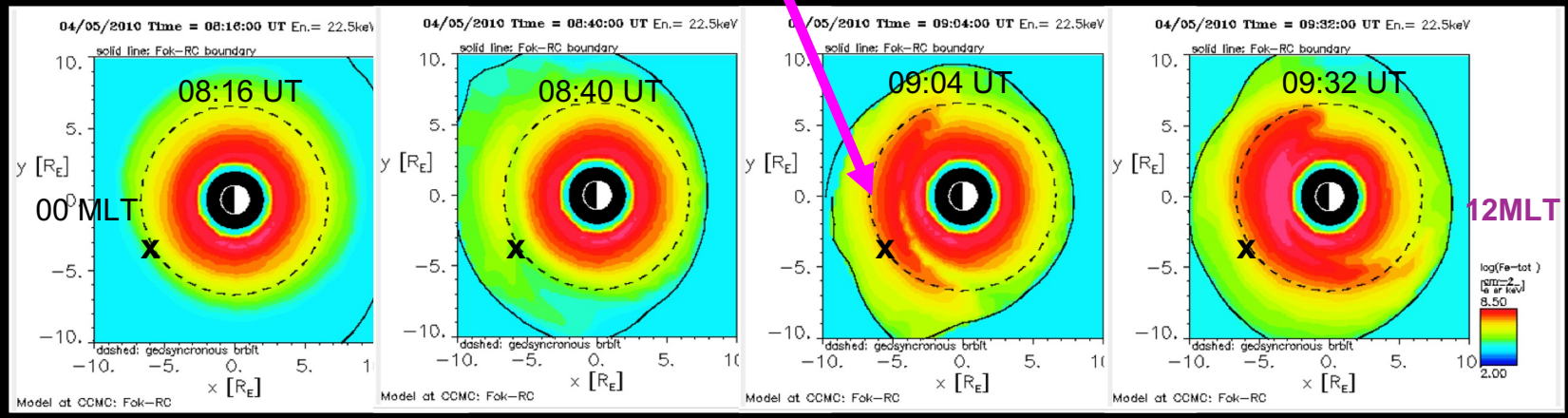
AU/AL/AE: indices for substorm activity

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

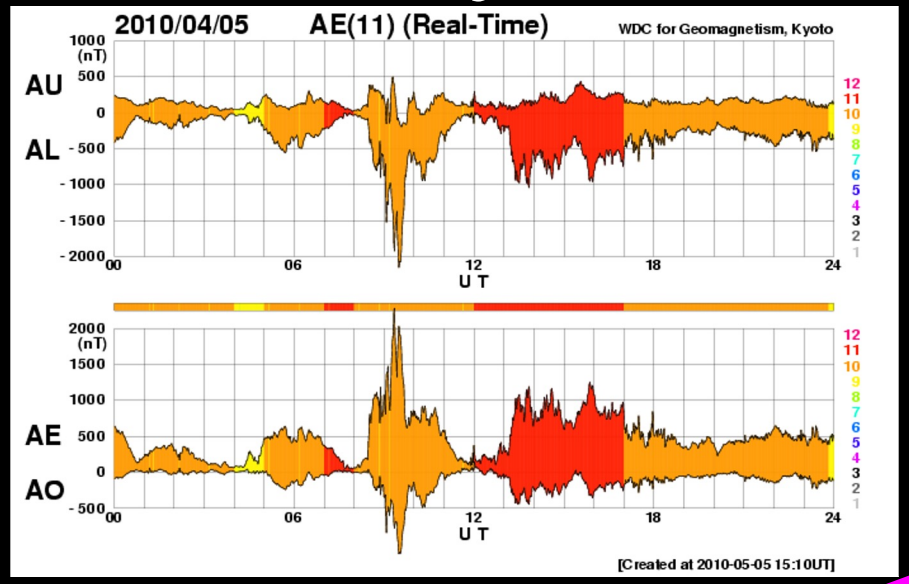
The color-bar is flux in logarithmic values

Exercise 1: Galaxy 15 failure on April 5, 2010

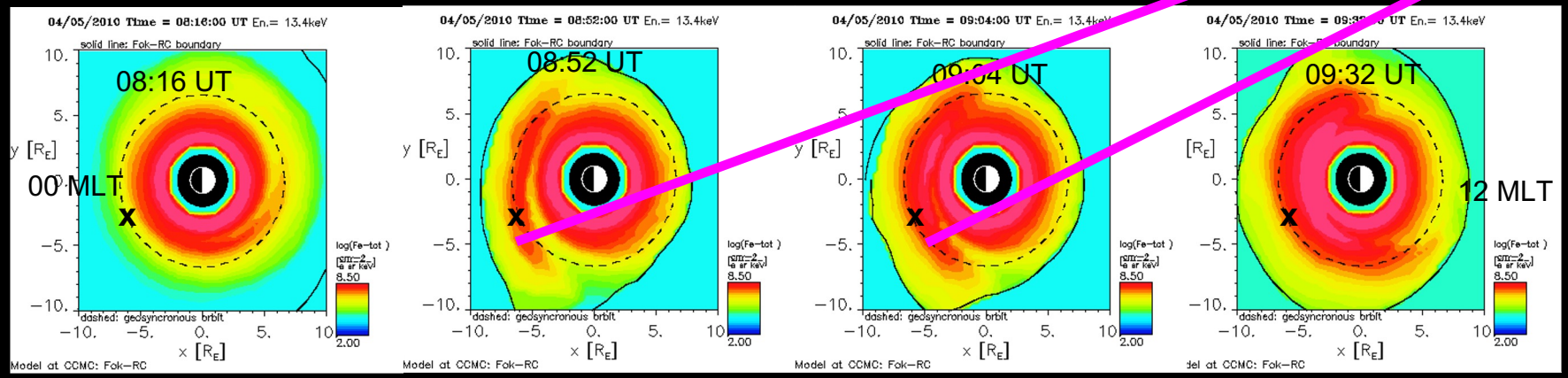
AU/AL/AE: indices for substorm activity

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

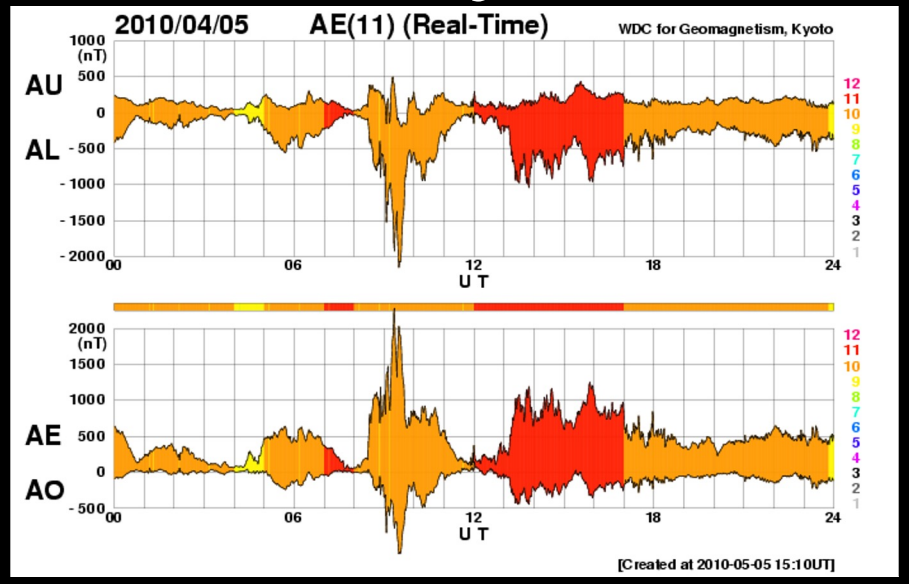
The color-bar is flux in logarithmic values

Exercise 1: Galaxy 15 failure on April 5, 2010

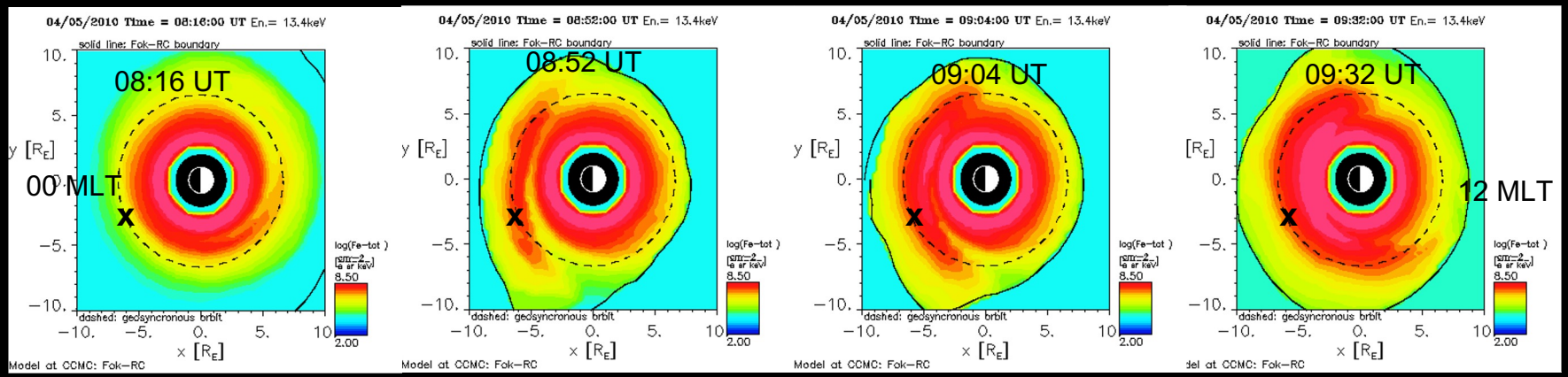
AU/AL/AE: indices for substorm activity

super substorm (AL: -2200 nT)!

nominal AL intensity (-200 nT)



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



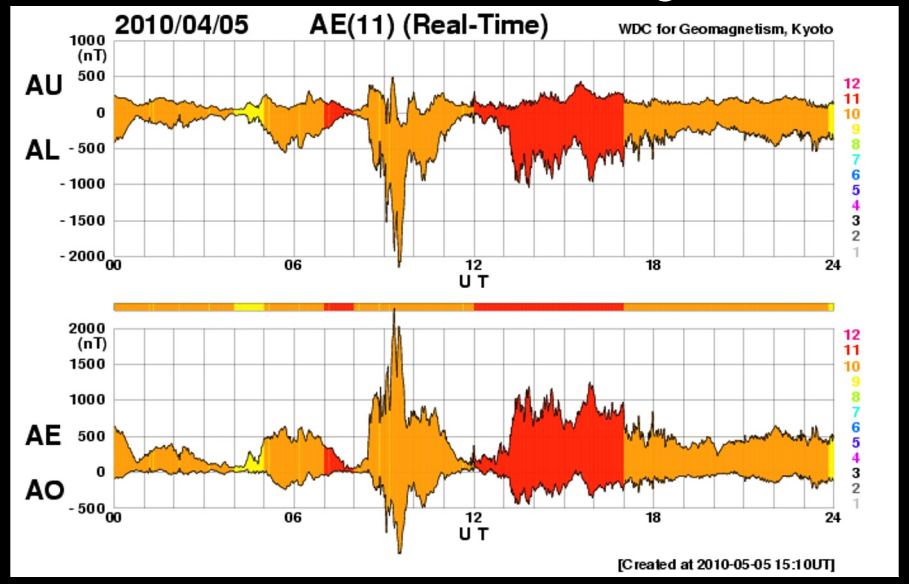
Galaxy 15 failed approx 9:48 UT, located around 01 MLT

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

AU/AL/AE: indices for substorm activity

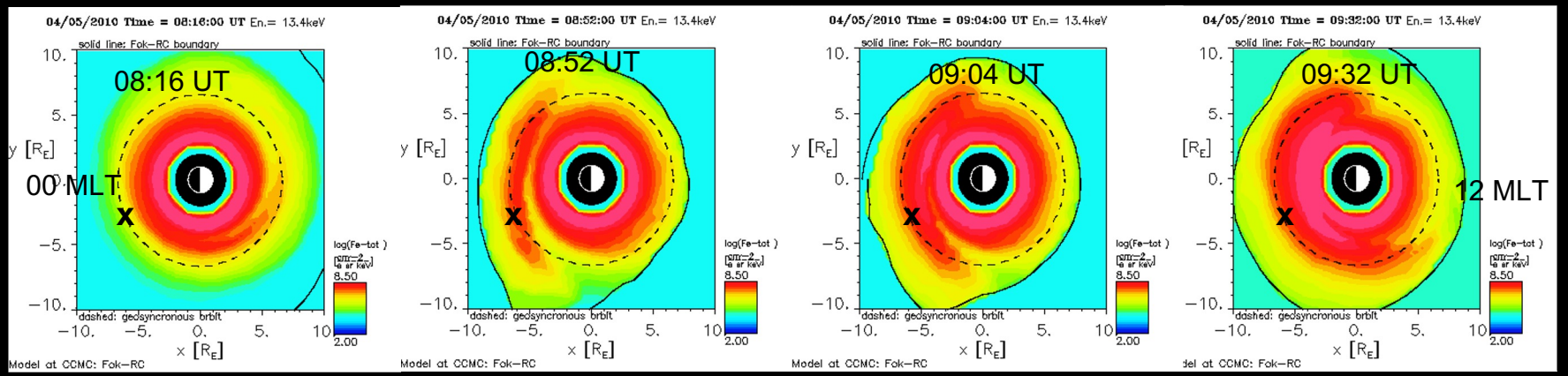
super substorm (AL: -2200 nT)!

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

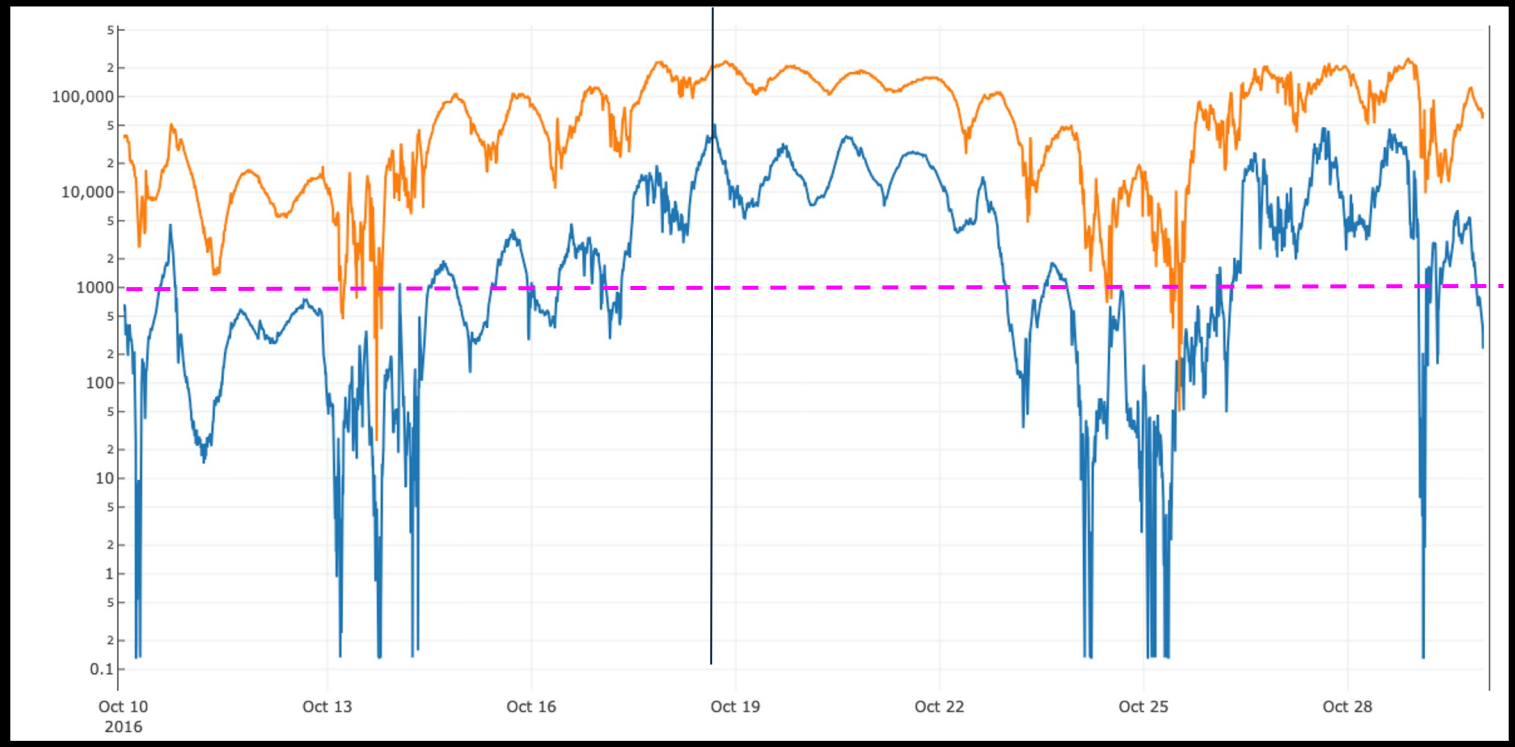
ISWA layout
https://iswa.ccmc.gsfc.nasa.gov/app/?layout=internal_charging_training

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

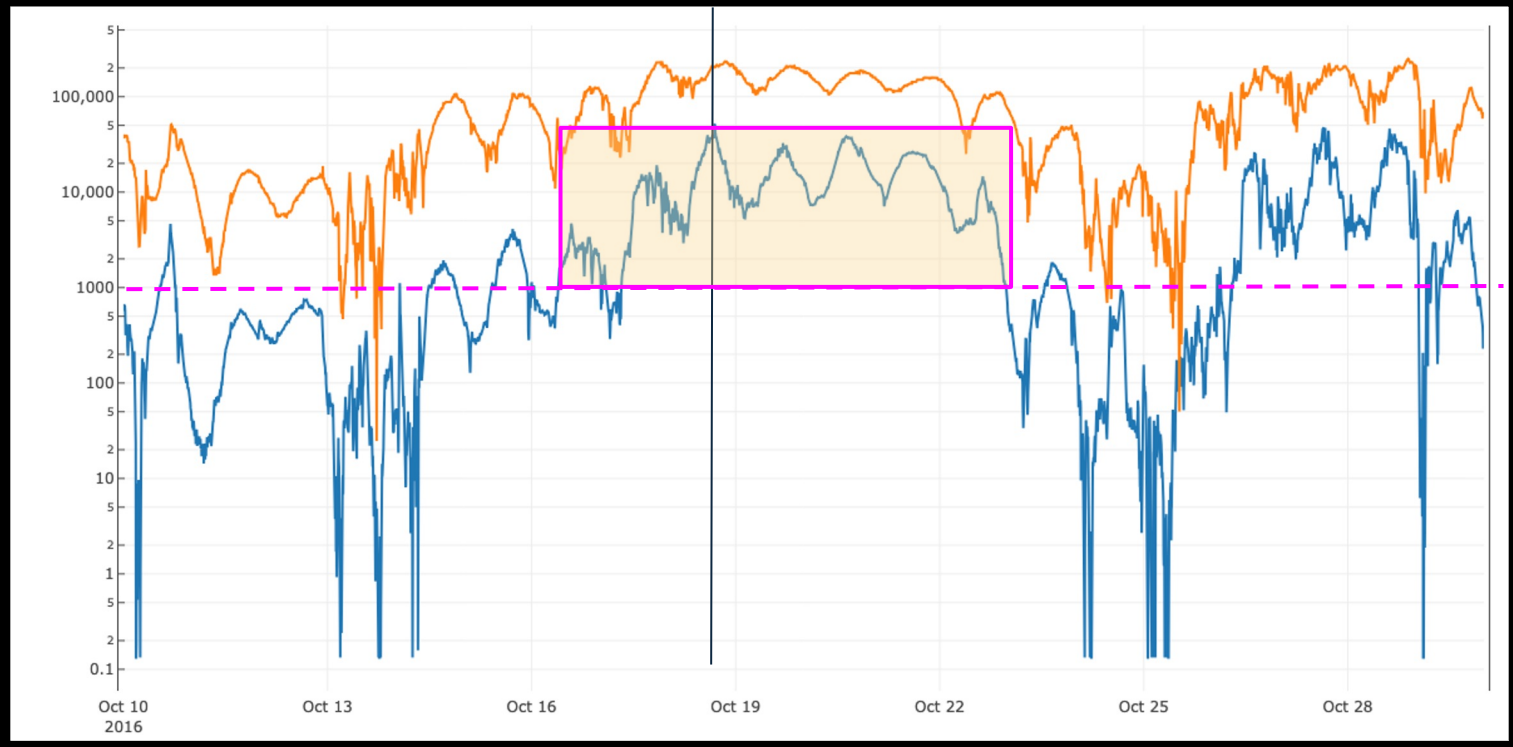
Q: A spacecraft experiencing these conditions on 2016-10-18T16:00Z might experience anomalies due to what spacecraft impact?

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

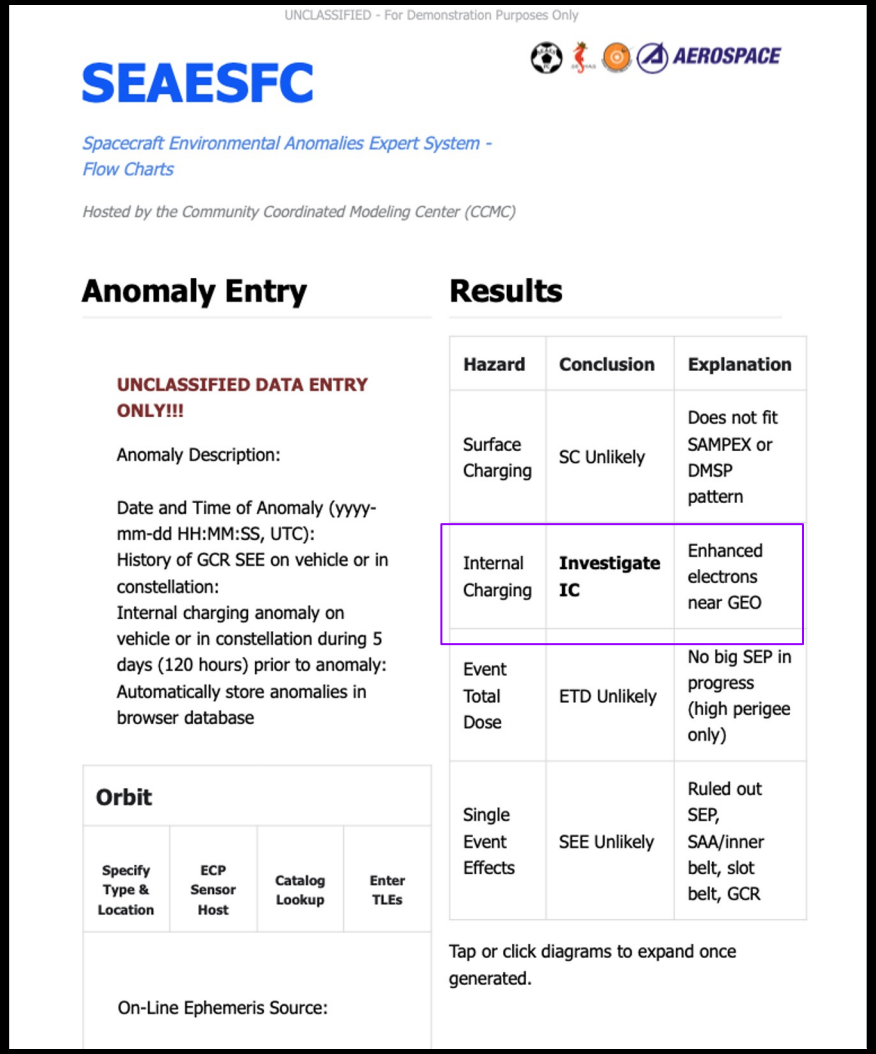


SWPC threshold: 1000 pfu

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

AEROSPACE

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

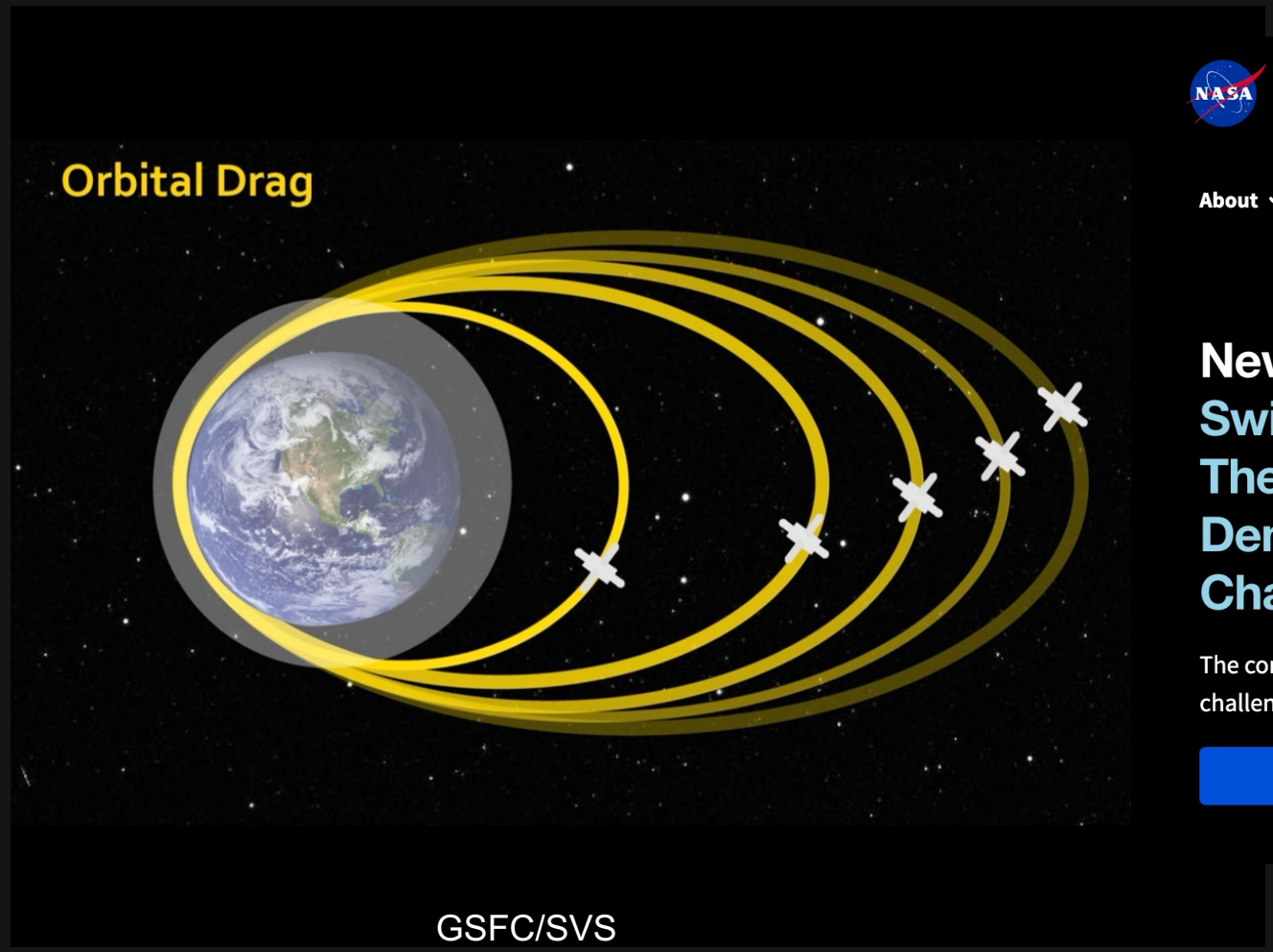
satellite: GOES 15

IC: Internal Charging

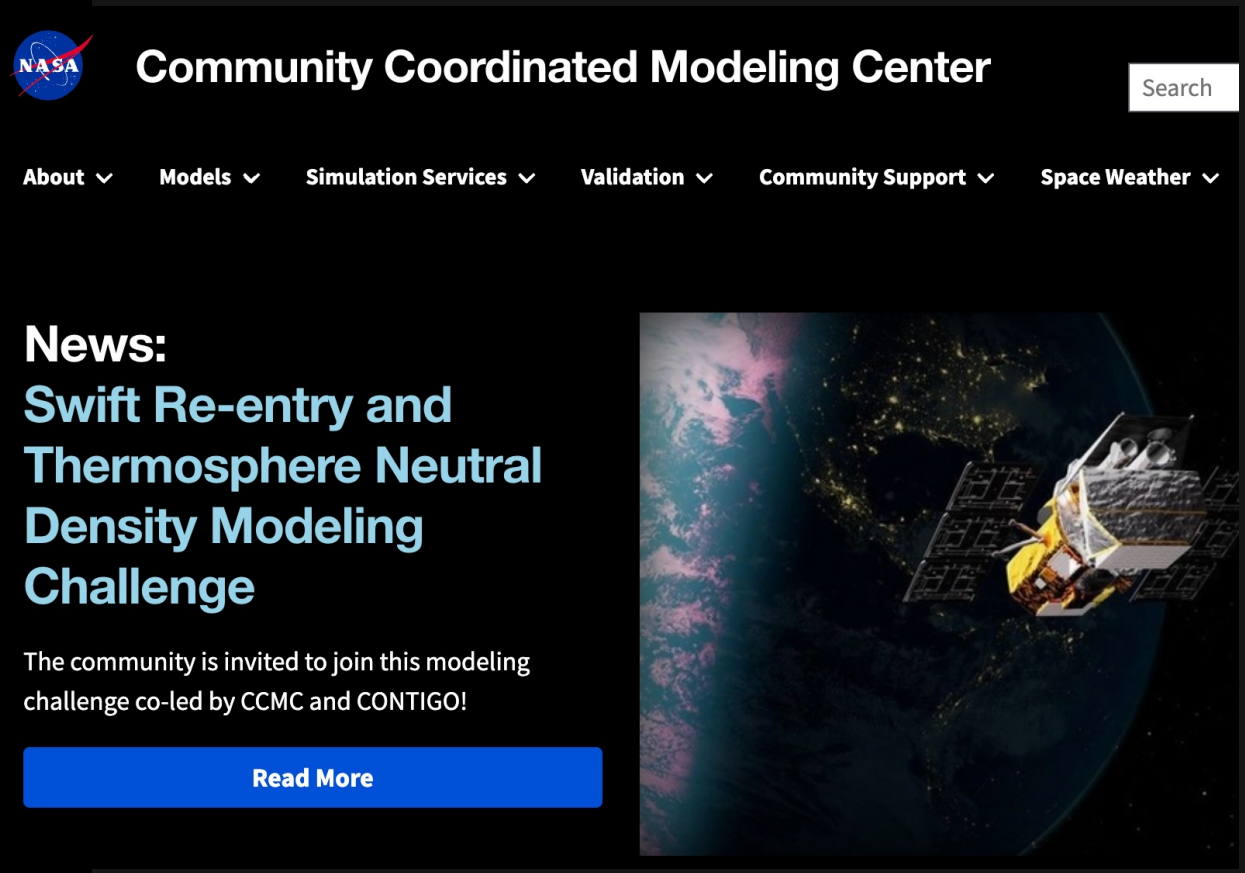
https://ccmc.gsfc.nasa.gov/seaesfc/

Backup slides

Satellite Drag

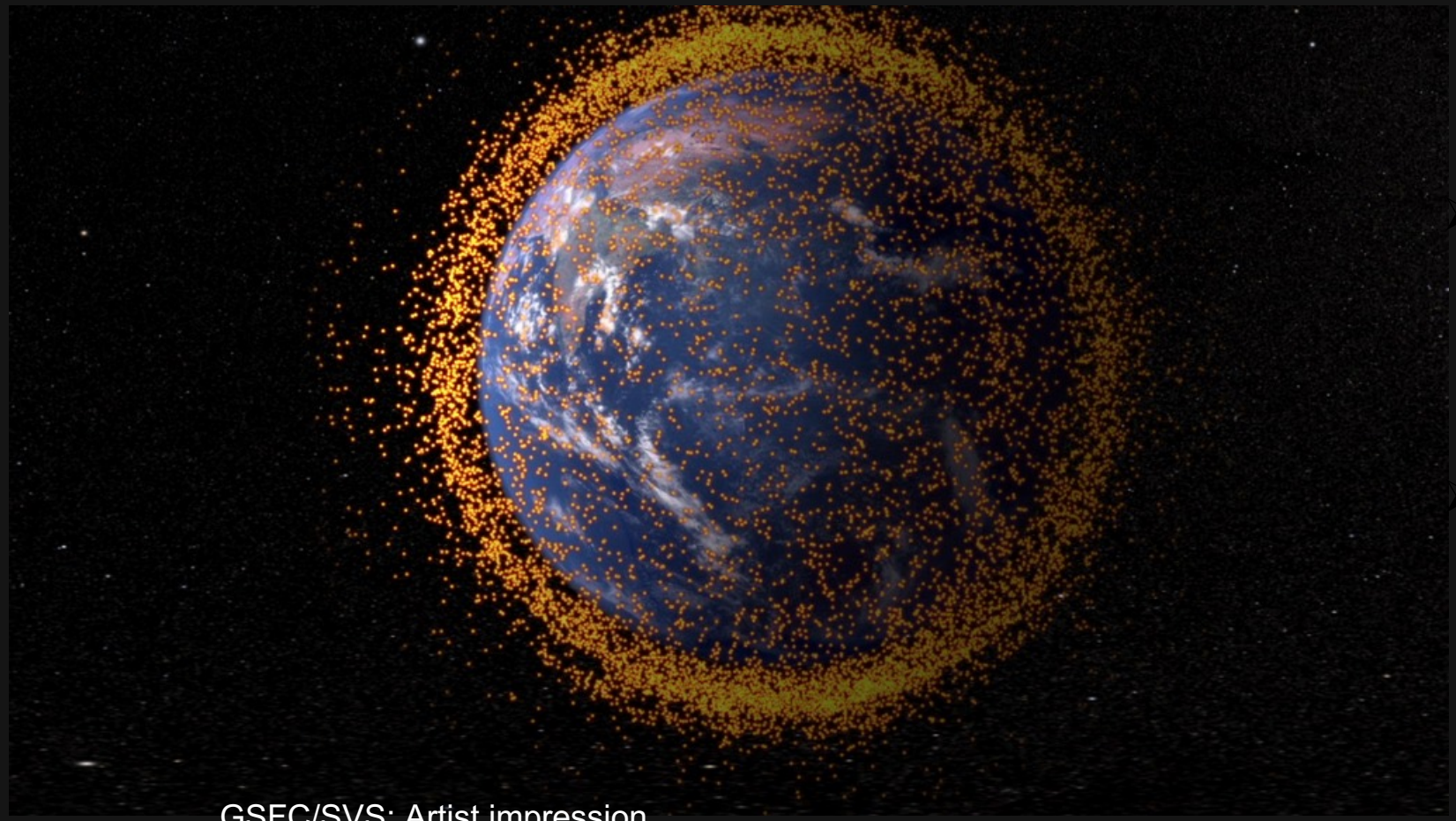


GSFC/SVS



CCMC + CONTIGO

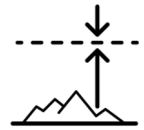
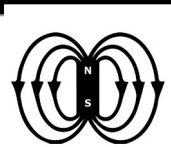
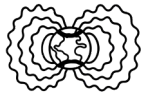
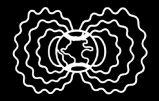
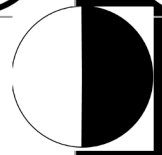
Satellite Drag on Space Debris



GSFC/SVS: Artist impression

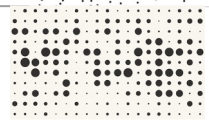
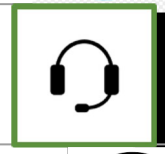
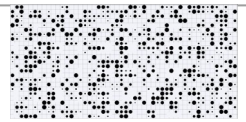
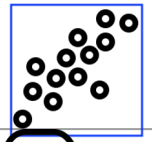
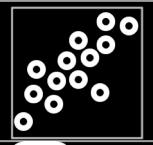
- Geomagnetic storms can result in drag – posing problems to operating satellites
- Can also help cleaning up some of the space debris

Icons

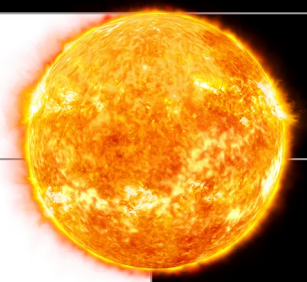
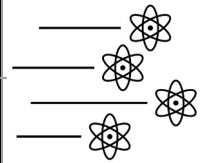
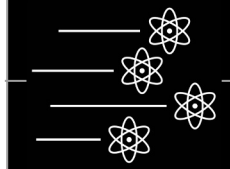
		Altitude			dipole
		Antenna			disturbed magnetic field auroral oval
		atmosphere polar cap			disturbed magnetosphere
		atmosphere			earth continents
		blue earth			Earth day/night
		cloud with wind no frame			earth latitude
		cloud with wind			EGSOL

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
		radiation			
		satellite			
		scale			

Satellite Frequency Bands in the Context of the Commonly Used Frequencies

