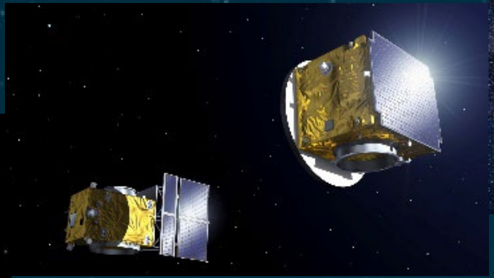
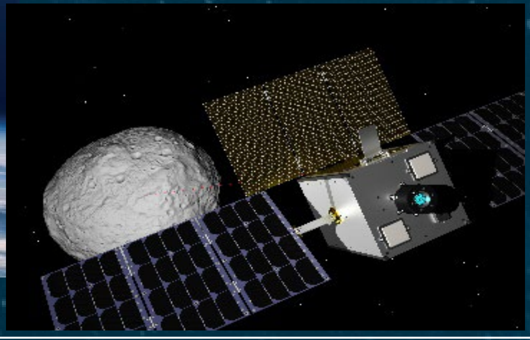



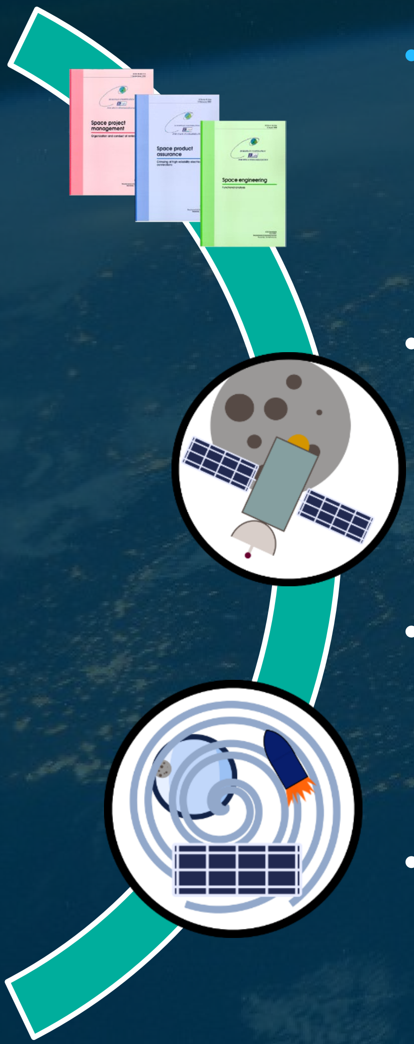

Radiation Hardness Assurance for space applications

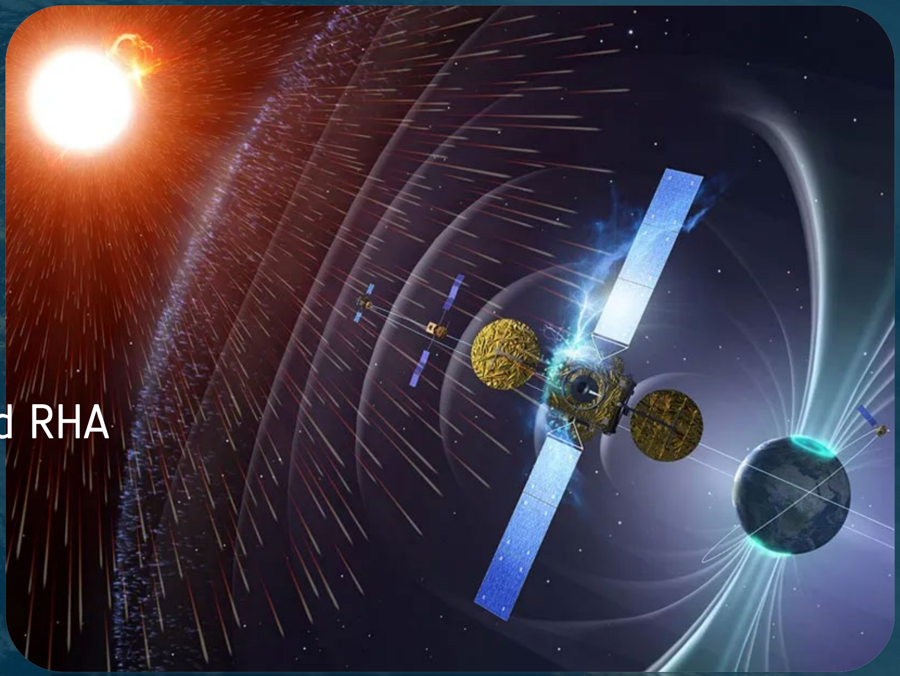




Cristina Plettner, ESA

Table of content



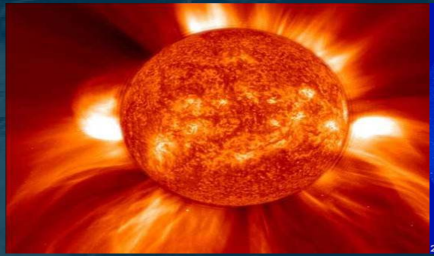


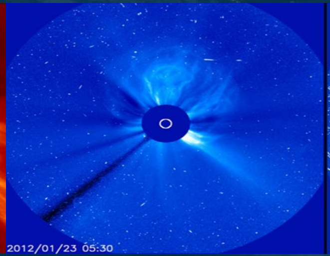
What is Radiation Hardness Assurance?

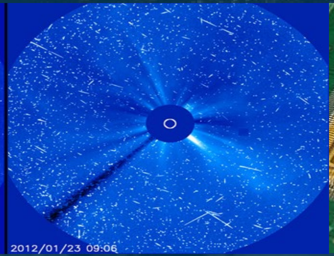
All activities undertaken to ensure that the **electronics** and **materials** of a space system perform to their **design specifications during exposure** to the space radiation environment.

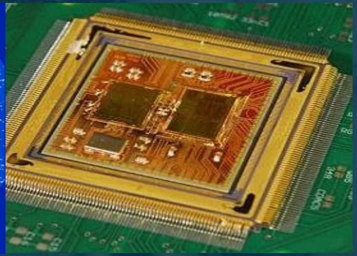
RHA envelops:

- space environment definition
- mission/system/subsystems requirements
- part selection & testing, spacecraft layout, spacecraft radiation shielding
- *radiation tolerant design*







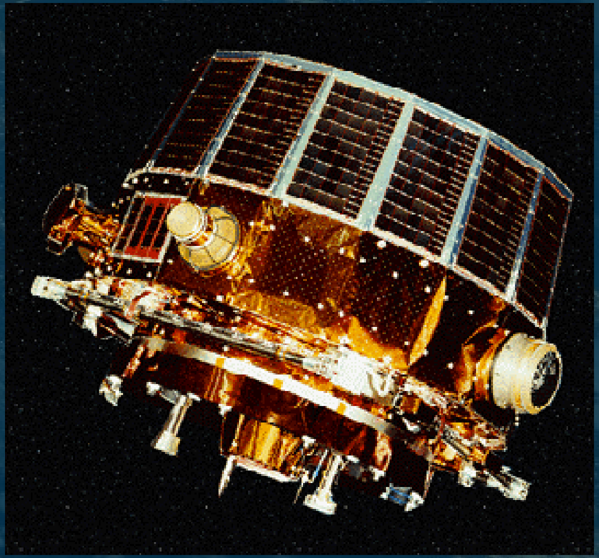


Radiation in Space

The effects on mission performance can be very detrimental:

- Reduced availability of a system, potentially below mission requirements
- Error in, or destruction of, critical components in equipments - resulting in module and subsystem failure
- Worst-case:- It can result, if not mitigated, in total mission loss

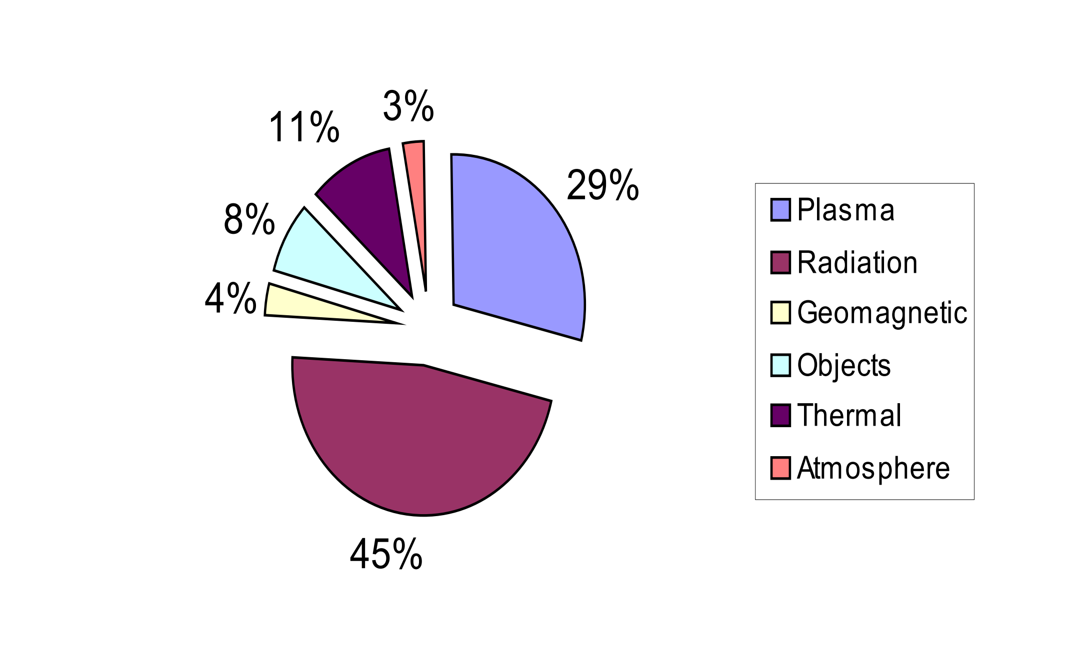
EQUATOR-S mission Launched: 02-December-1997
Failure of primary processor unit: 17 December 1998
Failure of redundant processor unit: 05 January 2017
Failure attributed to a destructive Single Event Effect (SEL) in unit memory devices.
Result of radiation impact: Total mission loss.

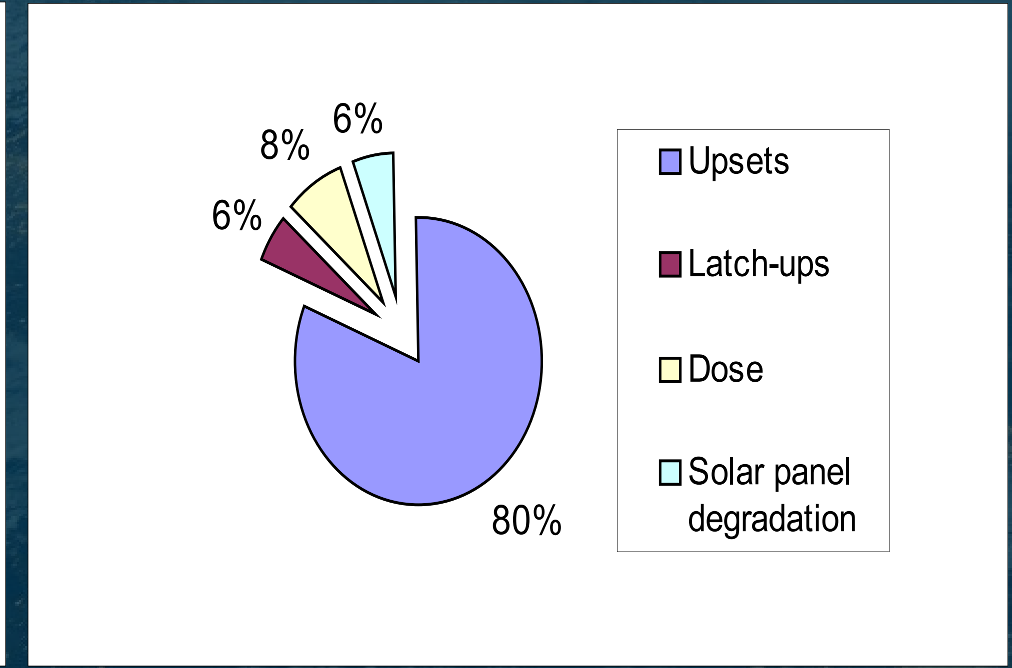


Spacecraft failures due to the Space Environment

esa

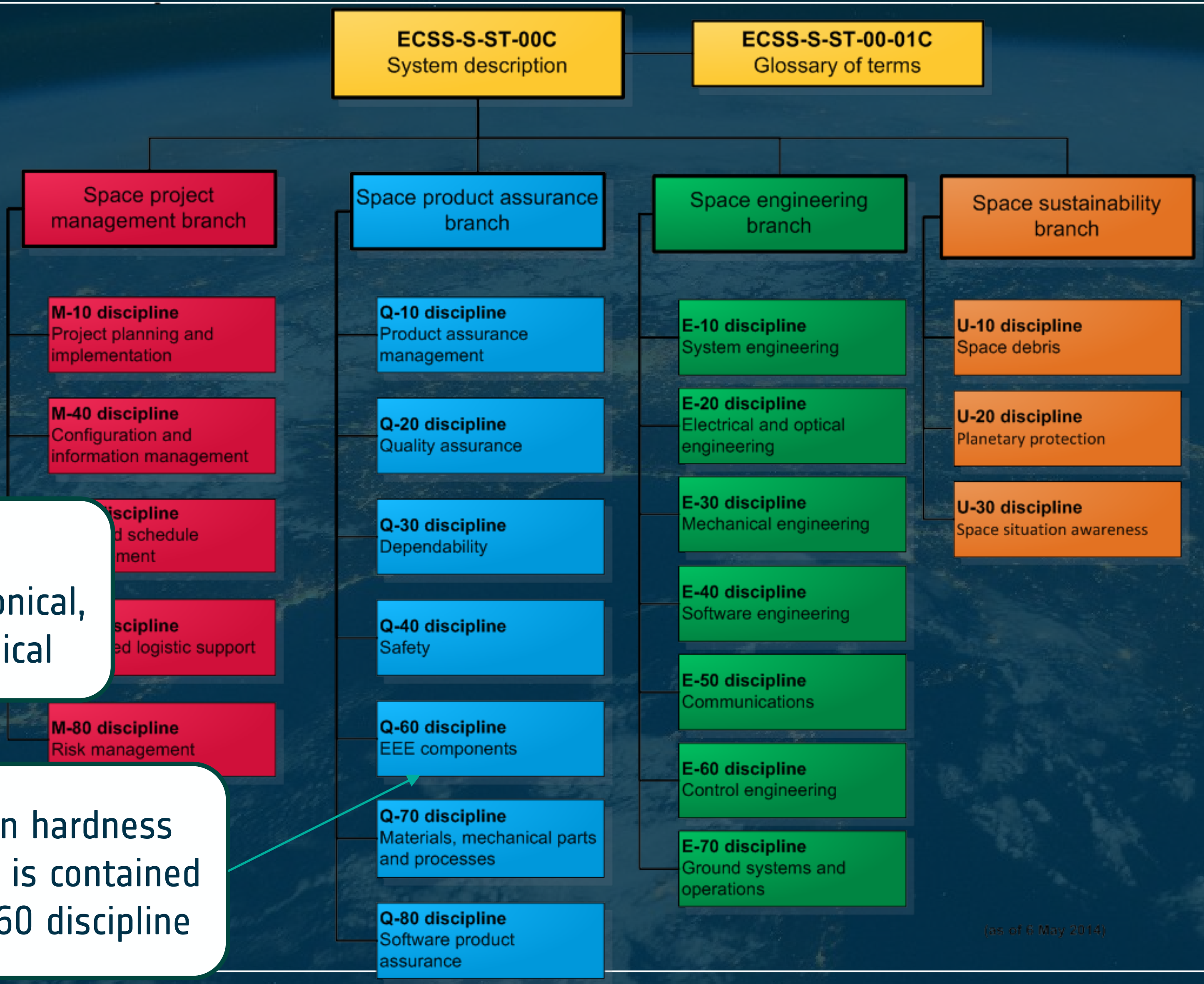
Distribution of spacecraft anomalies caused by space environment (not all anomalies) – All types of spacecraft, Earth Orbiting and Interplanetary.





« Spacecraft system failures and anomalies attributed to the natural space environment », NASA reference publication 1390, August 1996.

RHA belongs to the ECSS Space Product Assurance



ECSS- European Collaboration for Space Standardisation

Grand total of 25 000 Requirements
Digital in DOORS
System is tailorable

EEE- parts:
Electrical, Electronical, Electromechanical

Radiation hardness assurance is contained in the Q-60 discipline

For each spacecraft contract, ESA make a set of requirements applicable

Hardness Assurance Standards for Space

- ECSS, Space product assurance, Radiation Hardness Assurance
  - ECSS-Q-ST-60 EEE parts
  - ECSS-Q-ST-60-15C, Issue 1, October 2012 (in revision now) RHA
  - ECSS-Q-HB-60-02A – Techniques for radiation effects mitigation in ASICS and FPGAs hand
  - ECSS-E-ST-10-04C – Space Environment
  - ECSS-E-ST-10-12C – Methods for calculating radiation received, it's effects & design margi
  - ECSS-E-HB-10-12A – Handbook for the above


ECSS-Q-ST-60-15C
1 October 2012

EUROPEAN COOPERATION
ECSS
FOR SPACE STANDARDIZATION

Space product assurance

Radiation hardness assurance - EEE components

- Component Radiation Testing Specifications ESCC (European Space Components Coordina
  - ESCC 22900 – Total Dose Irradiation Test Method
  - ESCC 25100 – Single Event Effects Test Method and Guidelines

- Other standards
- NASA Avionics Radiation Hardness Assurance guidelines
  - NESC-RP-19-01489, July 2021
- NASA Radiation Hardness Assurance Standard
  - Draft under review
- Military Handbook, Ionizing Dose and Neutron Hardness Assurance

Guidelines for microcircuits and semiconductor devices MIL-HDBK-814, February 1994

Radiation Hardness Assurance (RHA) process

MISSION/SYSTEM REQUIREMENTS

RADIATION ENVIRONMENT DEFINITION

RADIATION LEVELS WITHIN THE SPACECRAFT

PARTS AND MATERIALS RADIATION SENSITIVITY

SYSTEM AND CIRCUIT DESIGN

ANALYSIS OF THE CIRCUITS, COMPONENTS, SUBSYSTEMS AND SYSTEM RESPONSE TO THE RADIATION ENVIRONMENT

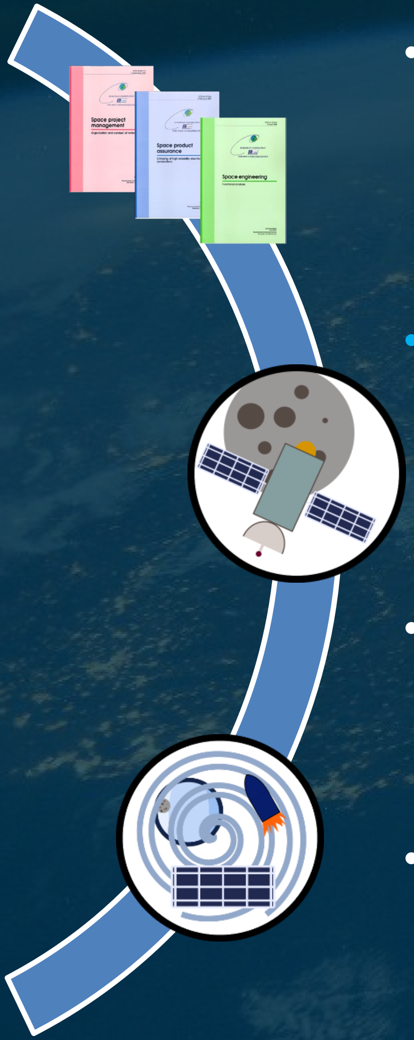
RADIATION ANALYSIS
RADIATION CONTROL BOARDS

STANDARDISATION

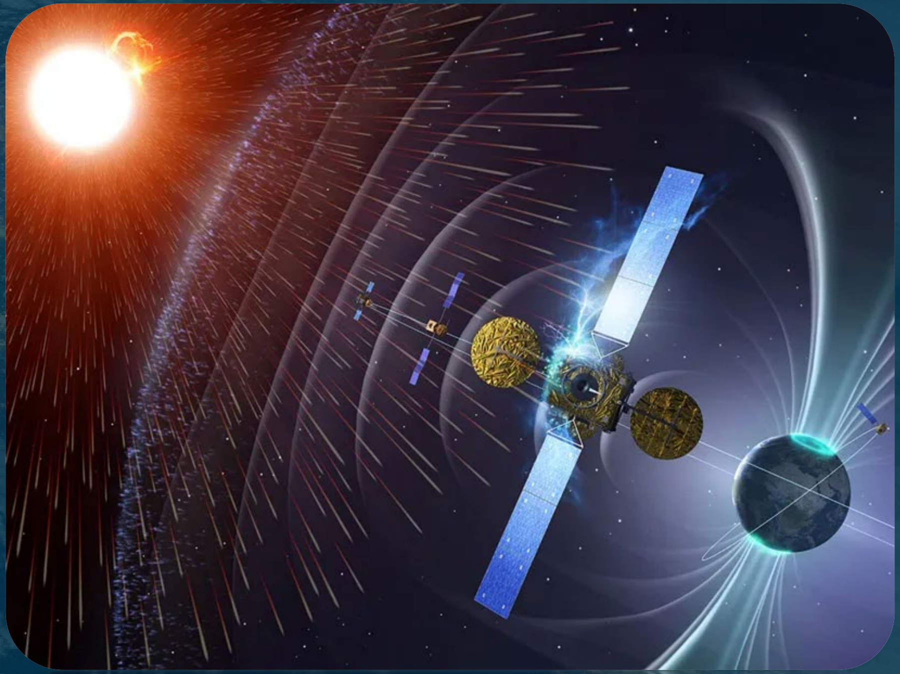
Radiation Hardness Assurance
- ECSS-Q-ST-60-15

Radiation Environment
- ECSS-E-ST-10-04

EEE Parts
- ECSS-Q-ST-60



- Radiation Hardness Assurance
    - Motivation (spacecraft failures)
    - Space Standardisation system
    - Radiation Hardness Assurance standards
- Radiation Environment
    - Trapped Particles
    - Solar Flare Particles
    - Galactic Cosmic Rays (GCR)
- Radiation Effects on Components and RHA
    - Total Ionising Dose (TID)
    - Single Event Effects (SEE)
- Conclusions



Space Environment and effects

One of the main differences between the terrestrial environment and the space environment is:

The abundance of high energy particles in space

High energy particles originate from a number of sources.

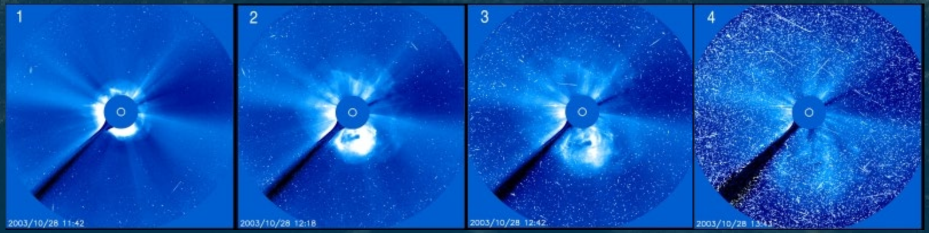
Space radiation can be dangerous for humans in space.

Space radiation environment can also be dangerous for **materials** and **EEE components** used in spacecraft.

SOHO 2003

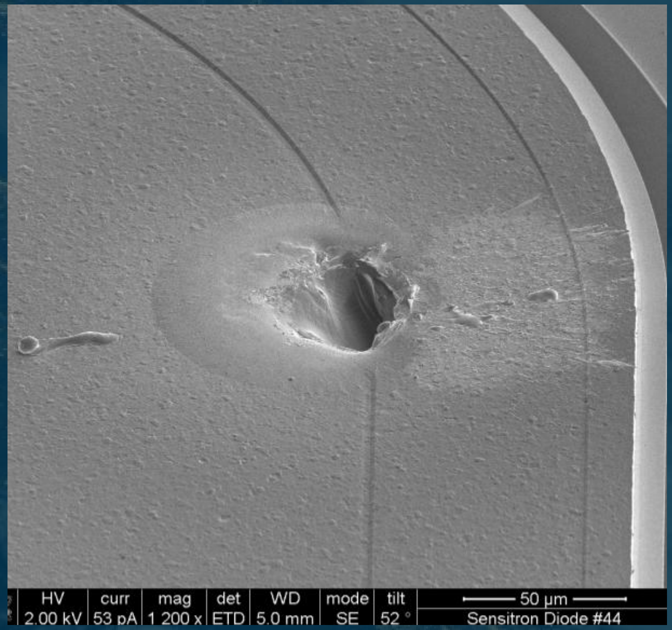
Effect of a solar Coronal Mass Ejection resulting in a high energy proton event.

Protons impinging on the imaging sensor of the instrument are observed as bright pixels or streaks

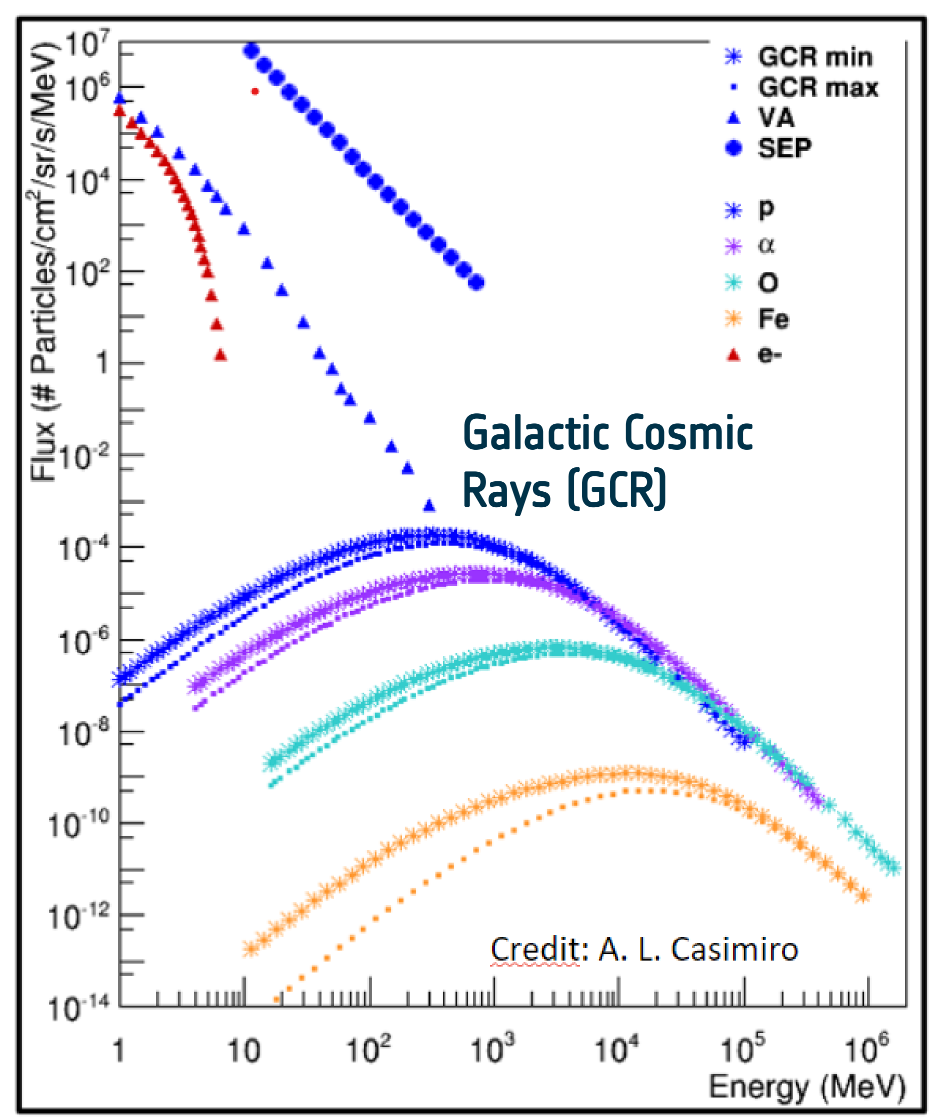


High energy impact on a Schottky diode

J. S. George et al., "Single Event Burnout Observed in Schottky Diodes", 2013 IEEE Nuclear and Space Radiation Effects Conference (NSREC) Radiation Effects Data Workshop



Radiation Environment: Van Allen belts, solar particles, galactic cosmic rays



Van Allen (Earth) Radiation Belts

Protons and electrons AP-8 and AE-8 models

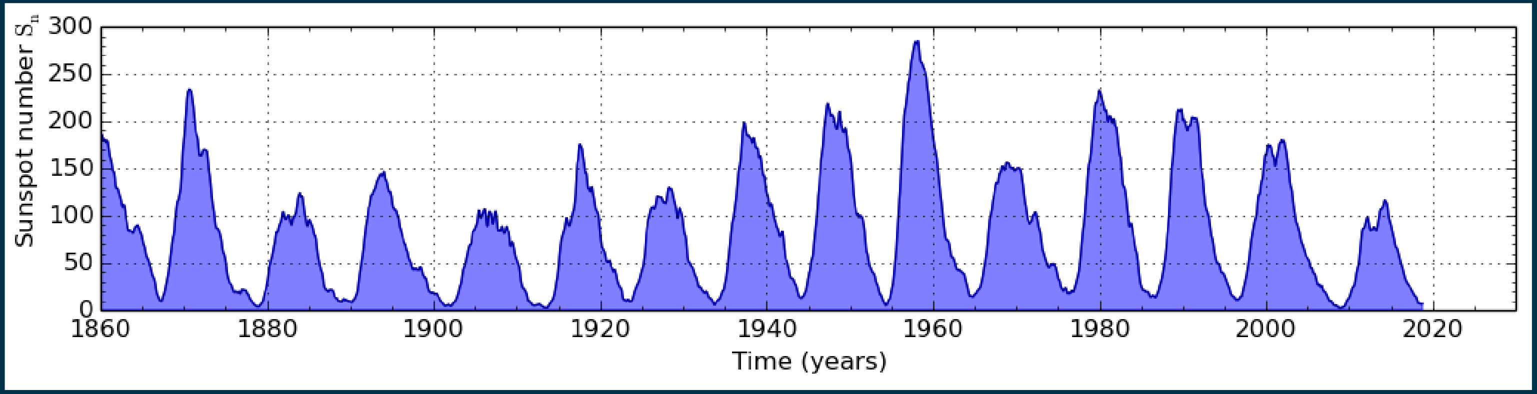
Solar Energetic Particles (SEP)

Integrated 14 day SEP event of December 2006

Galactic Cosmic Rays (GCR)

ISO 15390 min (30/01/2009) max (30/01/2014)

Solar activity

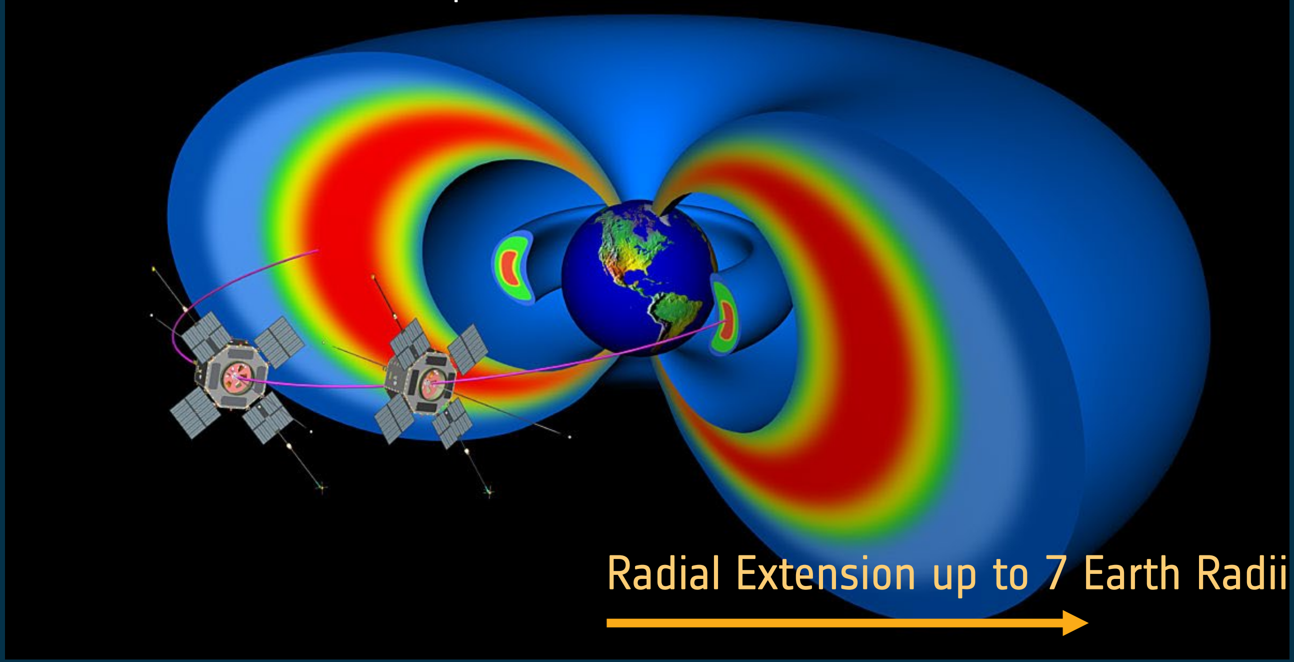


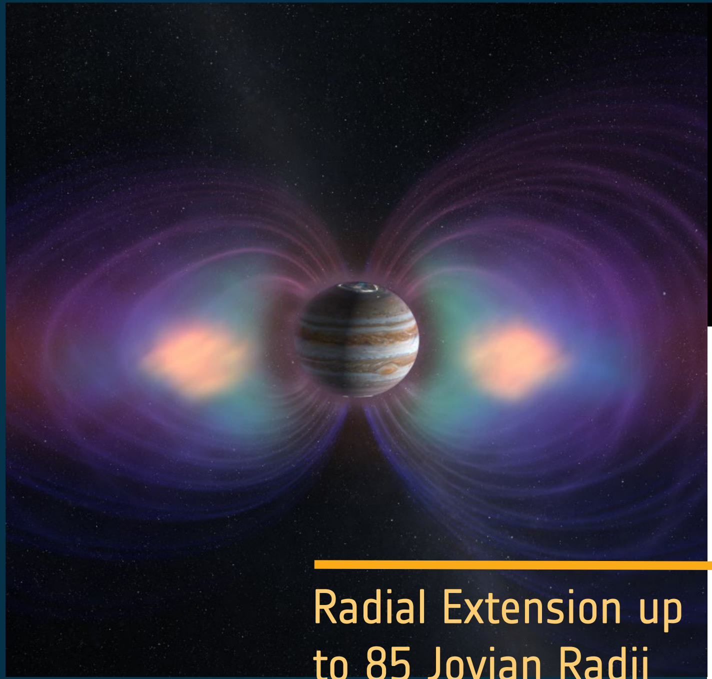
Trapped Radiation Belts: Earth vs Jupiter

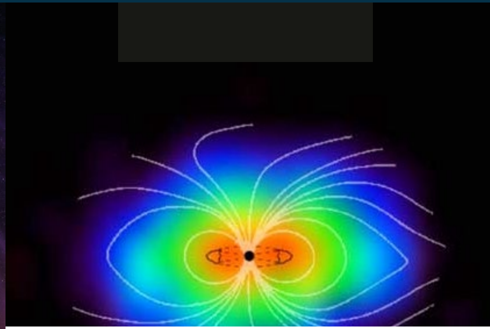
Inner belt: energetic protons up to ~400 MeV energy range

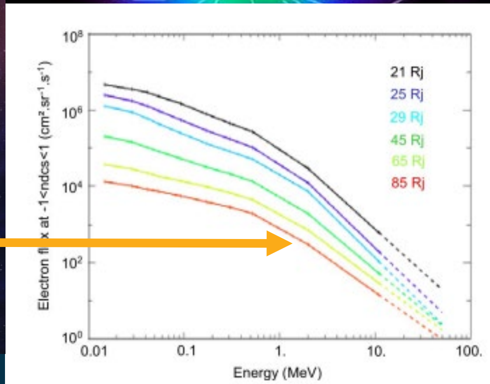
Inner edge is encountered as the South Atlantic Anomaly (SAA)

Dominates the Space Station and LEO









Outer Belt: energetic electrons up to 7 MeV

Dominates the geostationary orbit environment (mostly telecom) and Navigation (Galileo, GPS) orbits

Jovian Electron Belt: energetic electrons up to 50 MeV

Energetic protons extend from 1 MeV to 1 GeV

IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 58, NO. 3, JUNE 2011

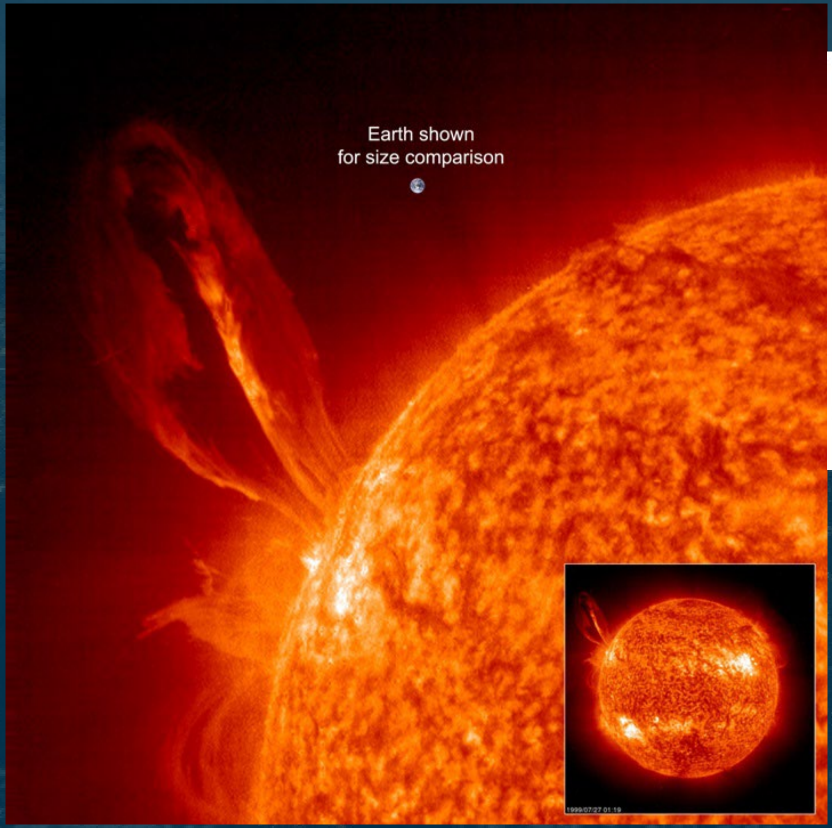
Solar flares

- Solar flares represent emission of a broad spectrum of particles releasing very high energy

- The electrons, protons and heavy ions ejected reach Earth in a couple of days. Radiation fluxes can be high for several days during solar flares
- Solar flare frequency depends on the Solar activity cycle approximately 11 years long
- Fluences are high enough to cause damage => importance of proper shielding

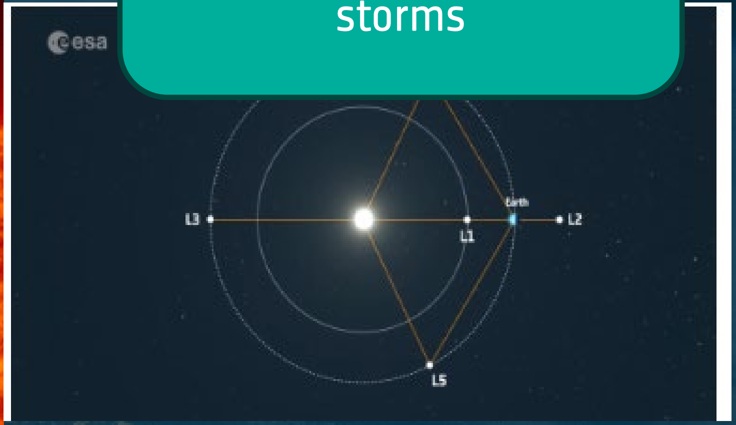
- Essentially unpredictable, however efforts dedicated to address the problem in various Space Weather initiatives

- Solar particles are shielded by the Earth's magnetic field, however, can penetrate to lower orbits at the polar caps

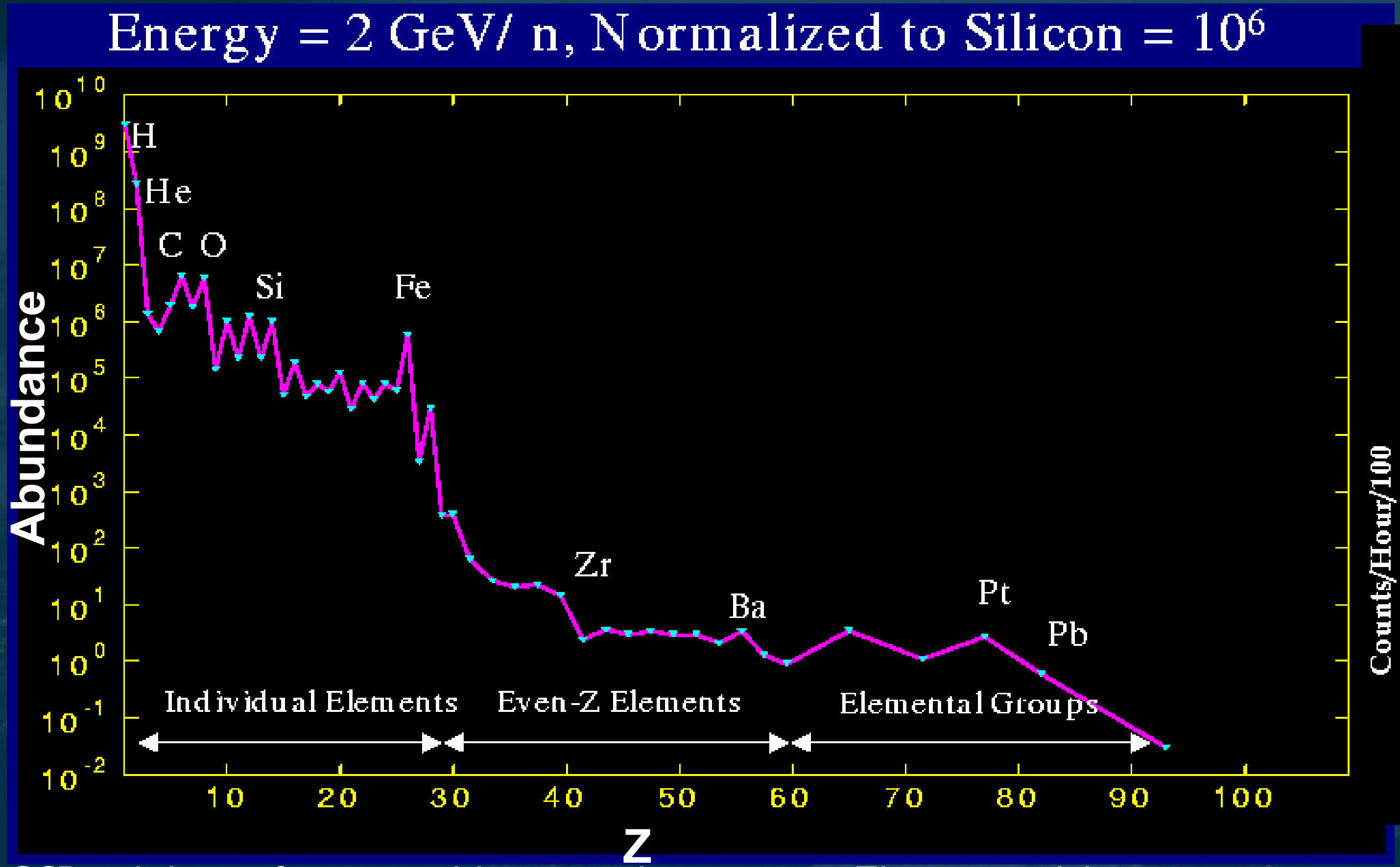


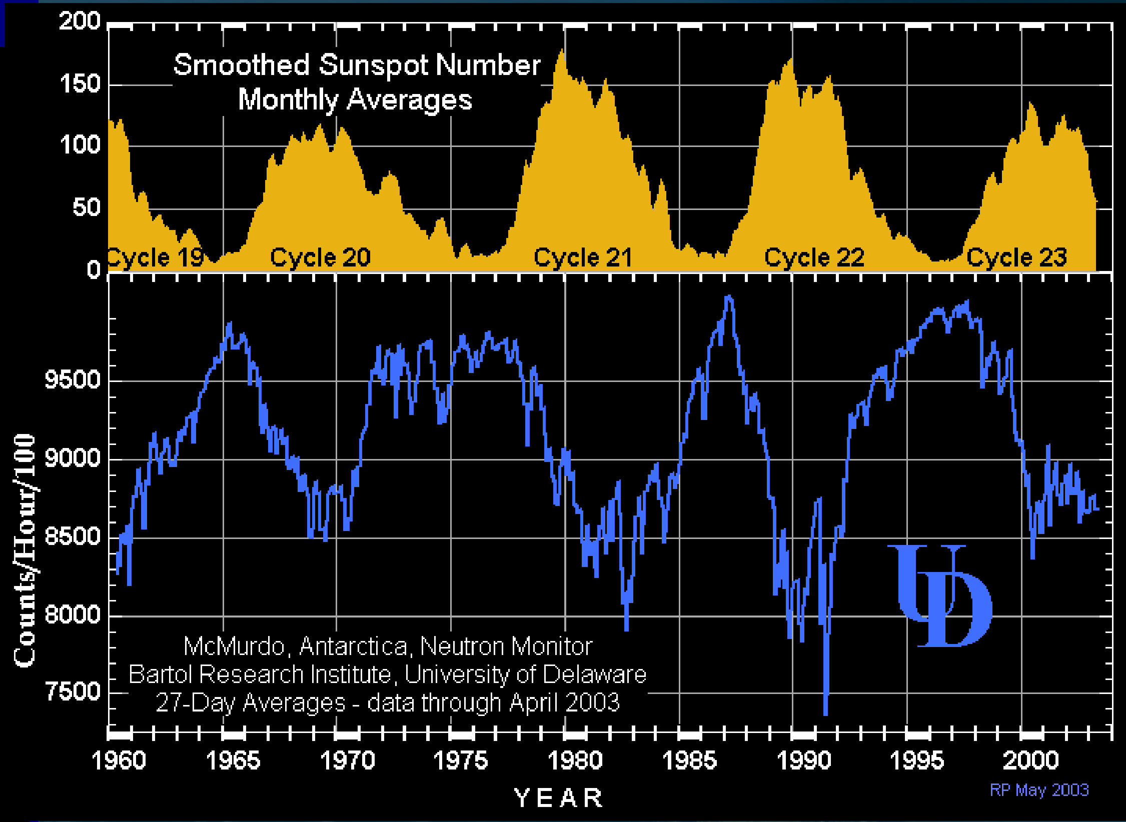
Large solar eruption captured by SOHO on the 27 July 1999. The eruption is larger than Earth

ESA future mission: Vigil
150 E6 km to the sun
Advance warning of solar storms



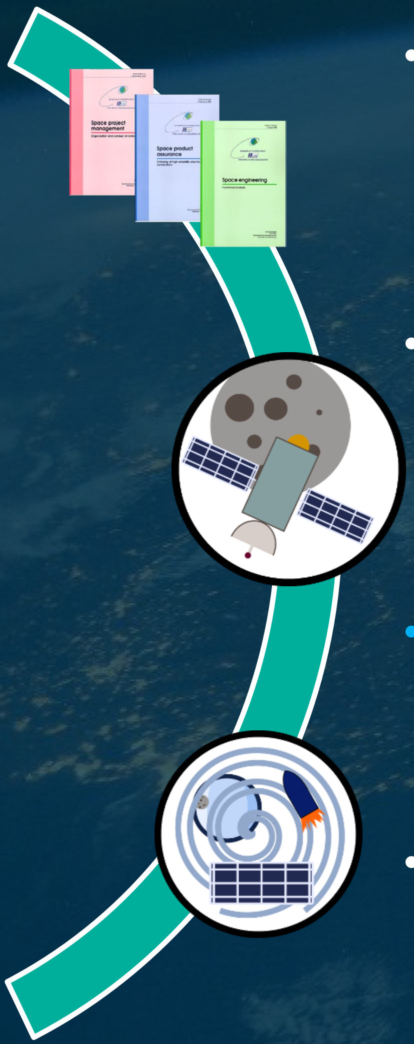
Galactic Cosmic Rays: GCR



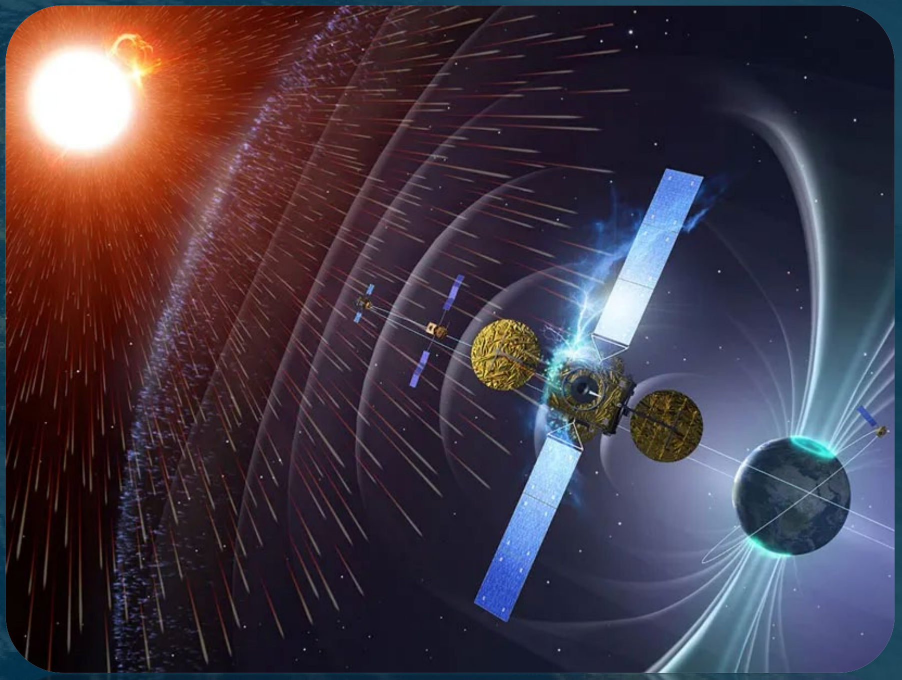


GCR originate from outside our solar system. These particles are highly energetic (E > TeV) and are thought to be generated in supernovae.

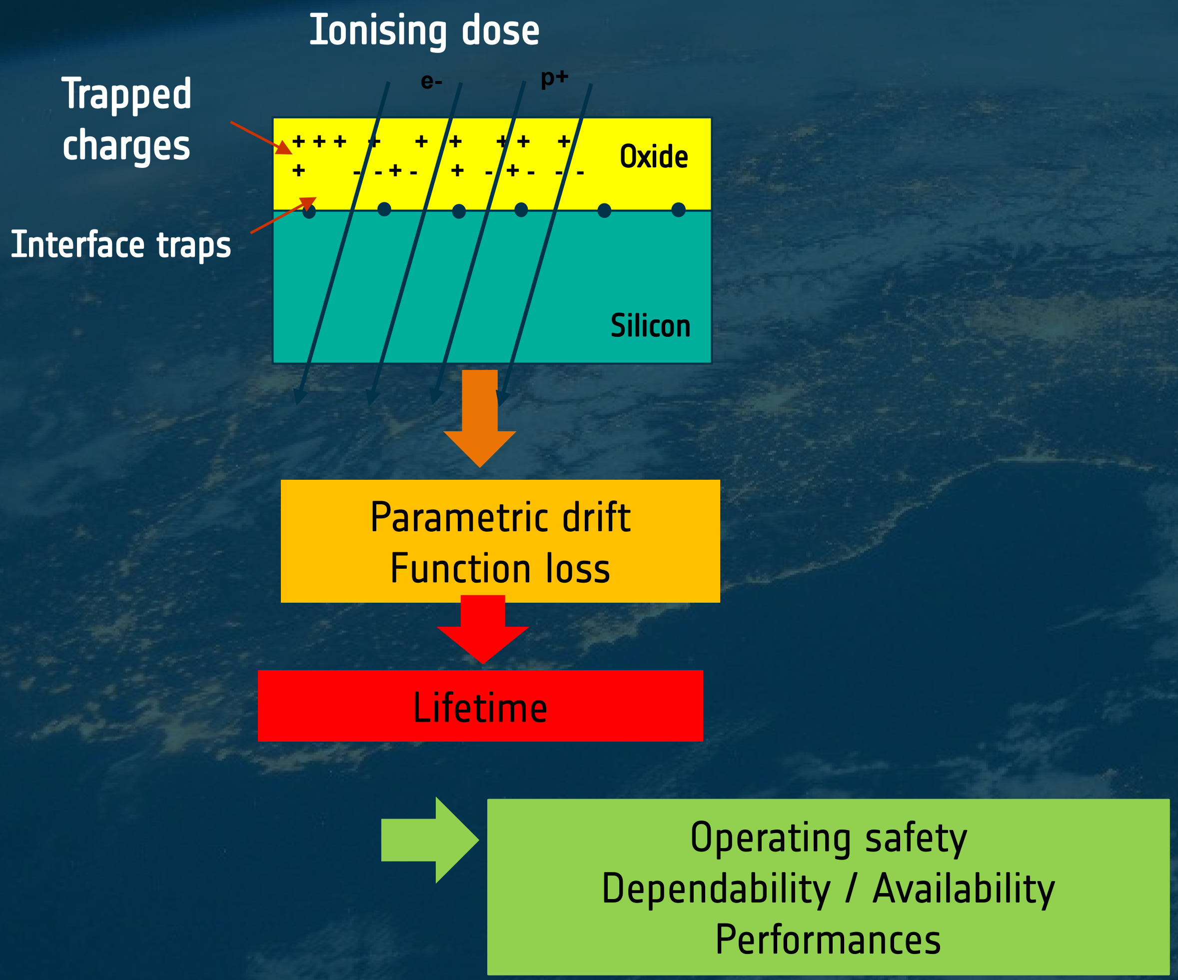
GCR are anticorrelated with the solar cycle.



- Radiation Hardness Assurance
  - Motivation (spacecraft failures)
  - Space Standardisation system
  - Radiation Hardness Assurance standards
- Radiation Environment
  - Trapped Particles
  - Solar Flare Particles
  - Galactic Cosmic Rays (GCR)
- **Radiation Effects on Components and RHA**
  - **Total Ionising Dose (TID)**
  - **Single Event Effects (SEE)**
- Conclusions



Total Ionising Dose: charged particles



Dose = the total energy accumulated in a given volume element of a specific material (usually Silicon)

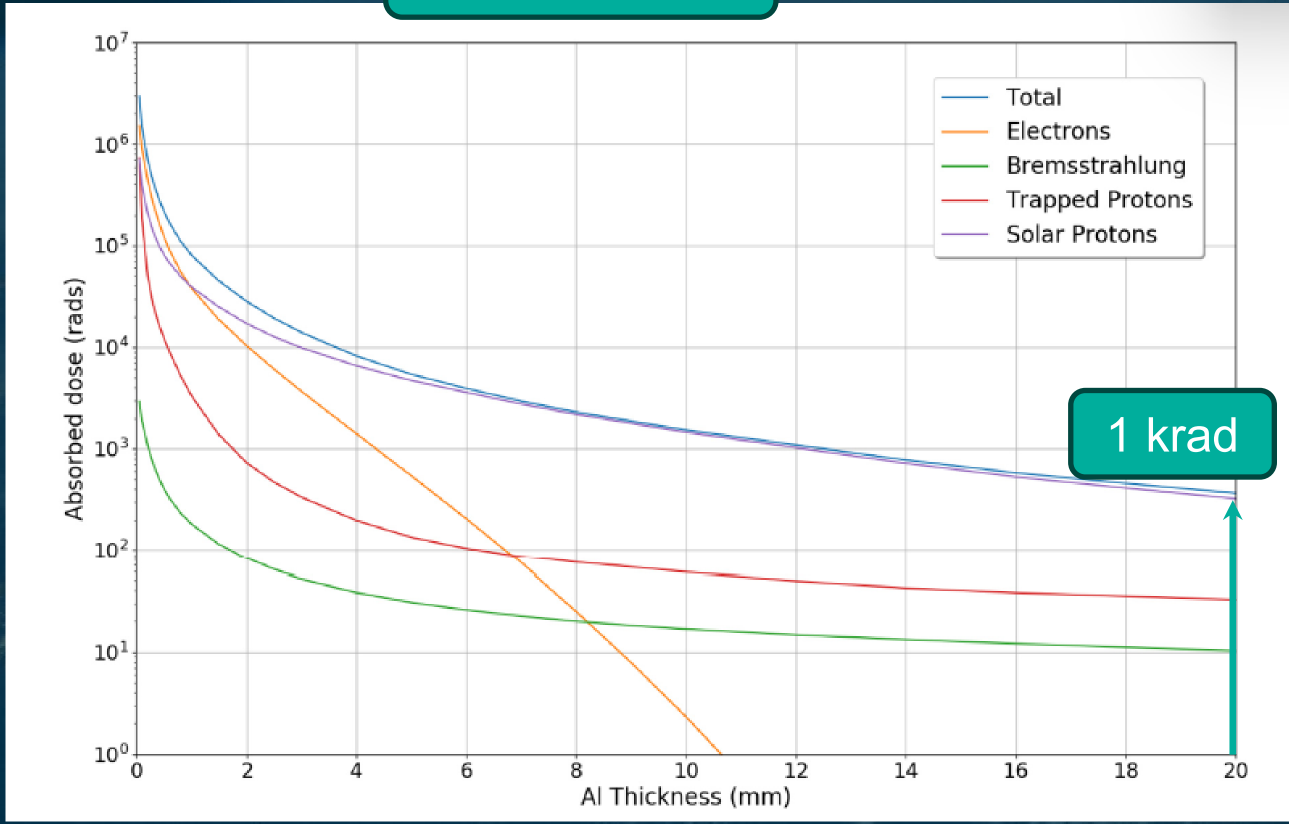
Unit = rad (rad is used in the Space Industry; the S.I. unit is the Gray (Gy), 100 rad = 1Gy, 1 Gy = 1 J kg^{-1})

Ionising radiation causes electron-hole pairs to form in semiconductor oxides

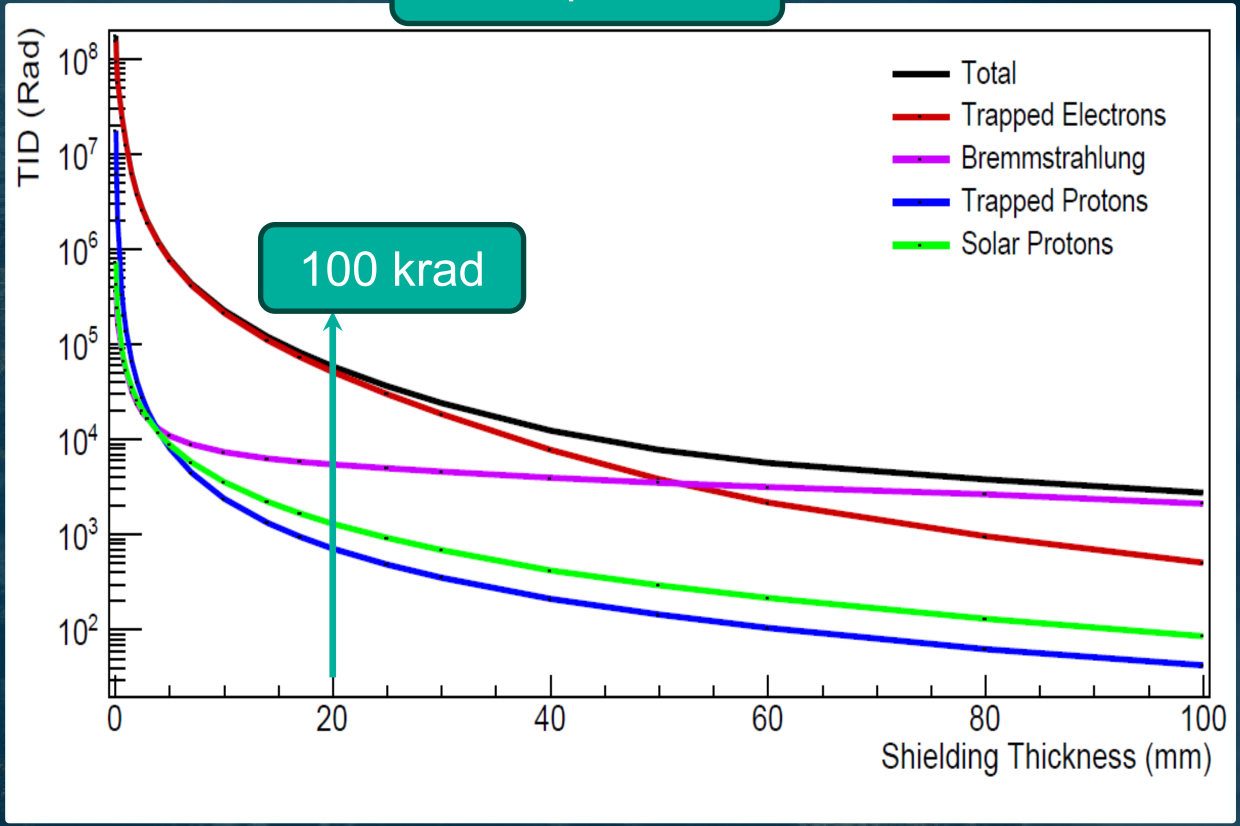
- These e-h pairs may recombine or get separated across layers
- Effectively changes the semiconductor doping
- Can decrease device gain and leakage current for example
- Happens when device is biased or unbiased (ON or OFF)
- Component degradation due to TID is very much dependant on the device biasing conditions
- In a CMOS device that is biased, electrons are swept out of the oxide and holes remain, leading to trapped charge or interface traps, which can
- significantly alter an electronic components performance

Total Ionising Dose: interplanetary vs Jupiter

Interplanetary

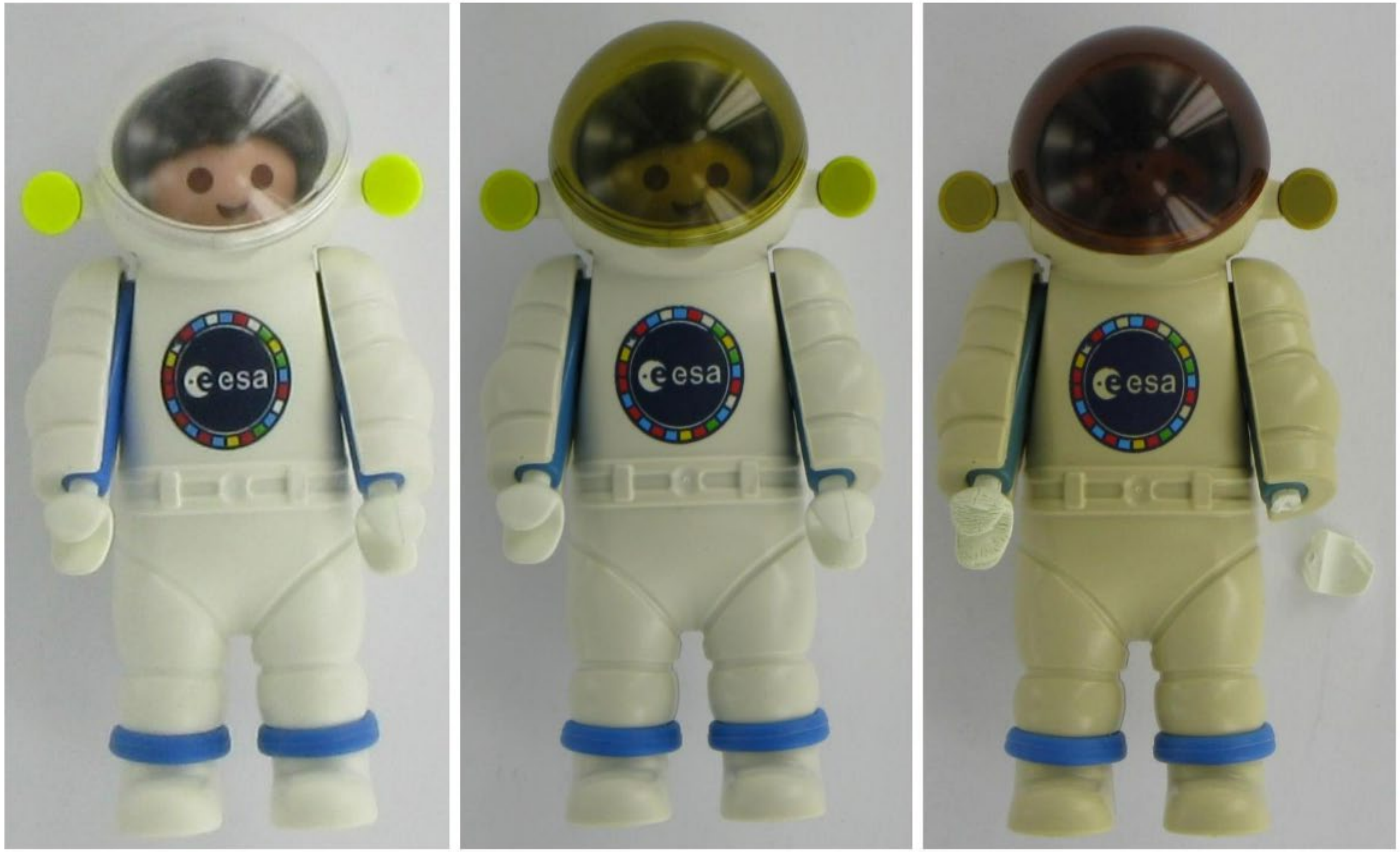


Jupiter



The TID requirements for the EEE parts can vary a lot, depending on the mission.

Effect of Ionising Radiation on Materials



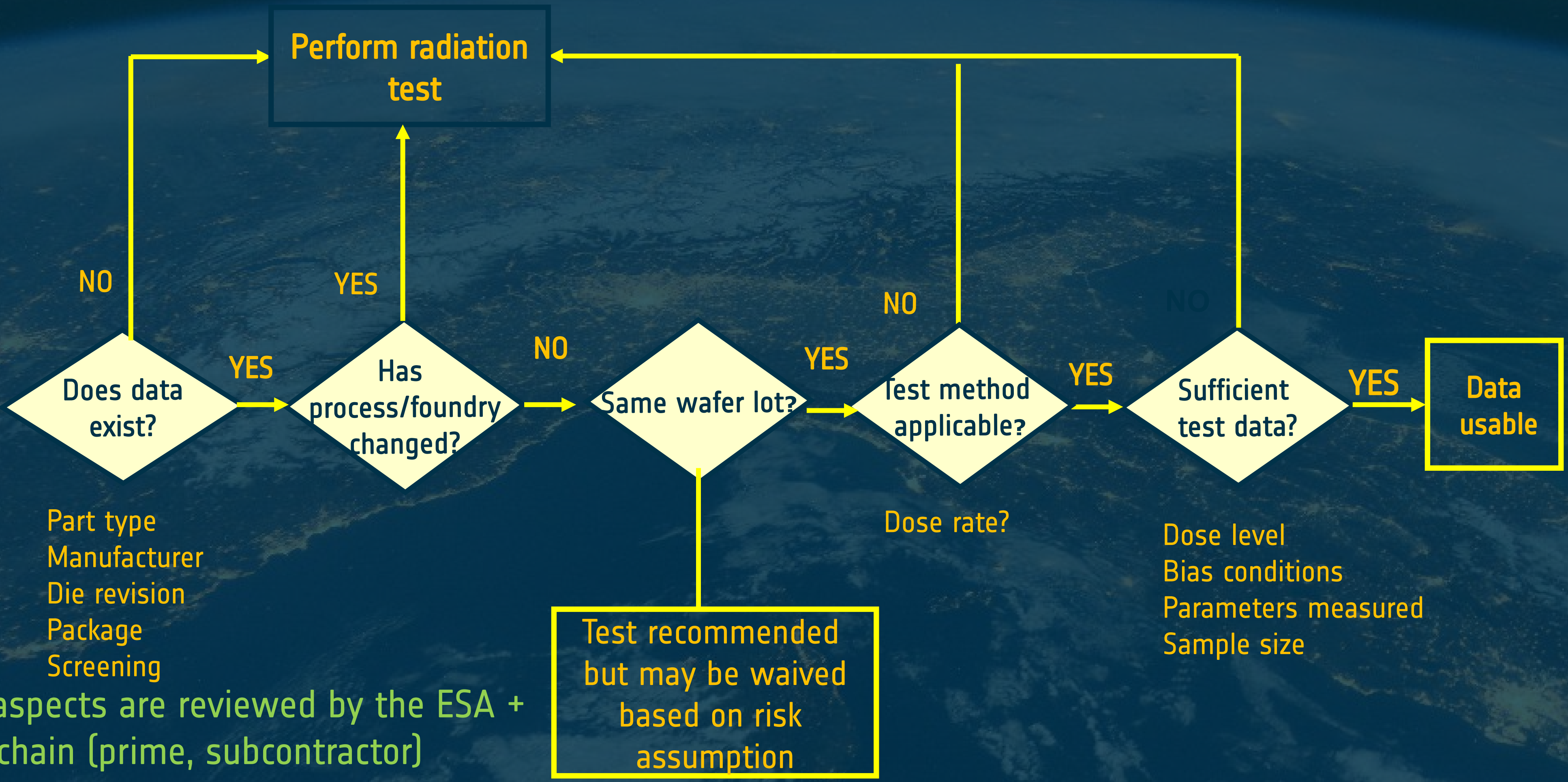
0 Gy | 270 kGy | 1.88 MGy

- Darkening effect
  - Lenses coating
- some materials become brittle
  - PTFE (from 1 Mrad)

Total ionising dose effects

Technology Category	Sub Category	Effects
MOS (metal oxide semiconductor)	NMOS PMOS CMOS CMOS/SOS/SOI	Threshold voltage shift Decreased in drive current Decrease in switching speed Increased leakage current
Bipolar Junction Transistor		H_{fe} degradation (current gain or amplification)
JFET		Enhanced source drain leakage current
Analog microelectronics		Change in offset voltage and offset current Change in bias current Gain degradation
Digital microelectronics		Enhanced leakage Logic failure
Charge Coupled Devicess		Increased dark current Effects on MOS transistor elements
Quartz resonant crystal		Frequency shifts

Verification of the TID sensitivity



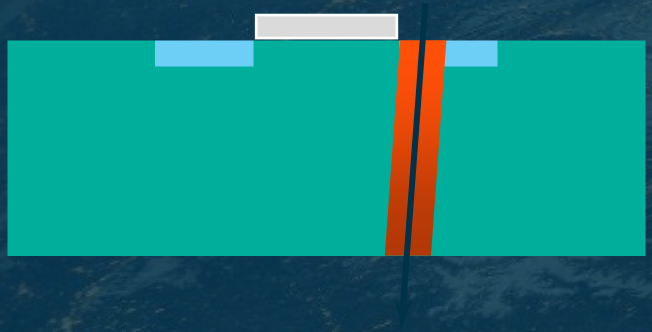
All these aspects are reviewed by the ESA + customer chain (prime, subcontractor) during the Equipment Radiation Control Board.

Single Event Effects (SEE)

esa

Heavy ion

Each ion produces an ionizing track

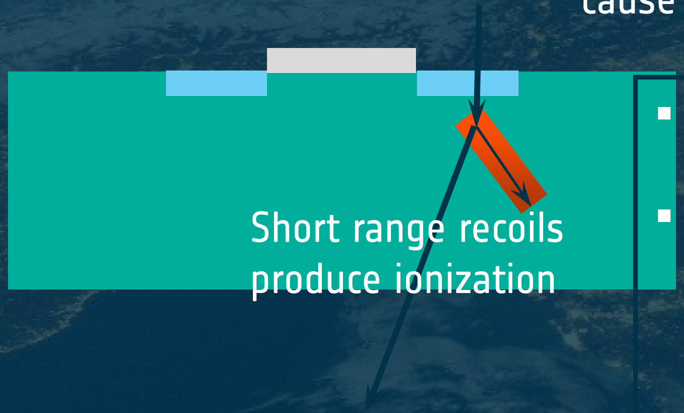


Direct energy deposition by the ion along the track

High energy proton, electron or neutron

Most protons pass through the device with little effect

A few protons (~10^{-5}) cause nuclear reactions



- Charged particles loose energy depositing charge by Coulombian interaction (ionization) along their track.
- Depending on the amount of charge deposited in a given volume a Single Event Effect can be generated in electronics. SEE can be even destructive.

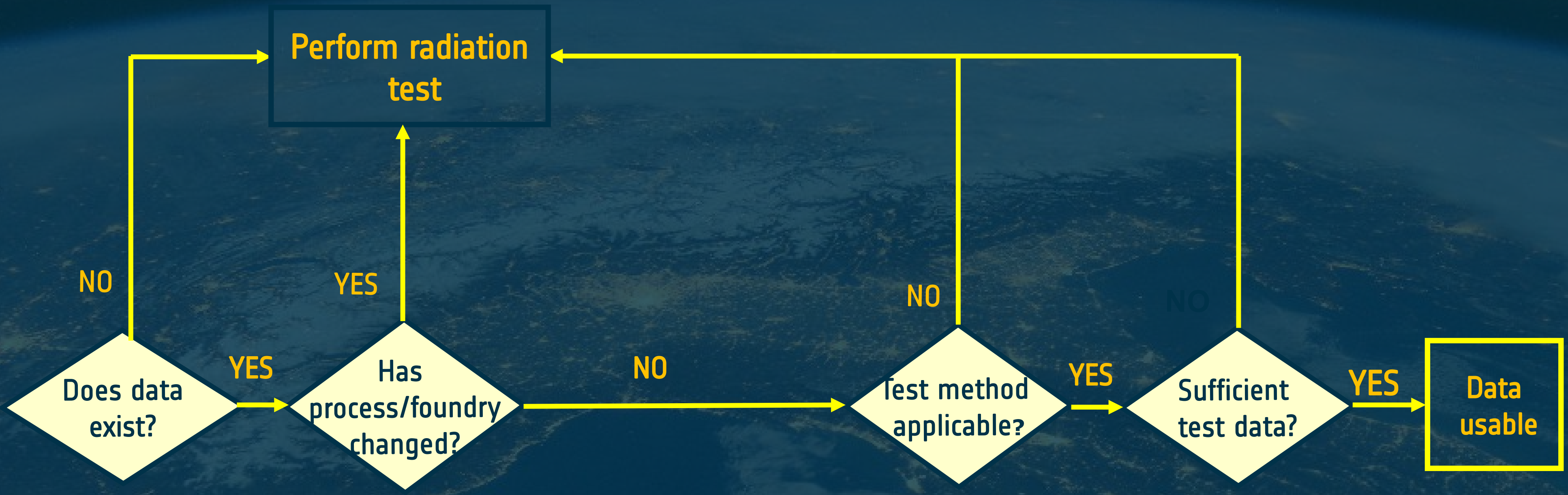
Energy mainly deposited by fragments of nuclei, from inelastic collision between a proton and a silicon nucleus. The fragments usually deposit in turn all their energy along their track or produce a cascade of particles

SEEs may also occur in terrestrial application in particular with the advent of new semiconductor ***technologies with smaller feature sizes.***

SEE sensitive parts and effects

Type of SEE	Effect	Type of devices sensitive
Single Event Transient (SET)*	Impulse response of a certain amplitude and duration	all
Single Event Upset (SEU)	Corruption of the information stored in a memory element	Memories, latches in logic devices
Multiple Cell Upset (MCU)	Several memory elements corrupted by a single ion or proton strike	Memories, latches in logic devices
Single Event functional Interrupt (SEFI)	Corruption of a data path leading to loss of normal operation	Complex devices with built-in state machine/control sections
Stuck bit / Intermittent Stuck bits (ISB)	Permanent or semi-permanent corruption of the information stored in a memory element	DRAM, SDRAM, DDR, DDR2, DDR3, DDR4
Single Event Latchup (SEL)	High current condition	CMOS, BiCMOS devices
Single Event Burnout (SEB)	Destructive burnout due to high current conditions	N channel power MOSFET, diodes
Single Event Gate/Dielectric Rupture (SEGR/SEDR)	Rupture of a (gate) dielectric due to high electrical field conditions	Power MOSFETs, Non volatile memories, linear devices,....

Verification of the SEE sensitivity



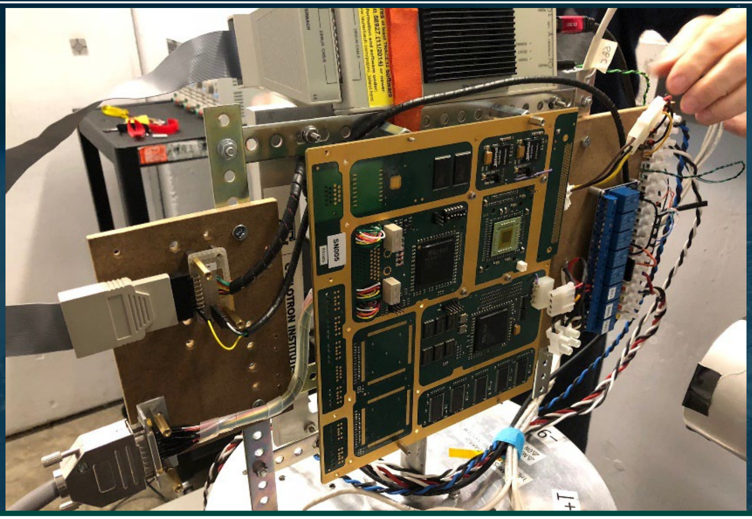
Part type
Manufacturer
Die revision

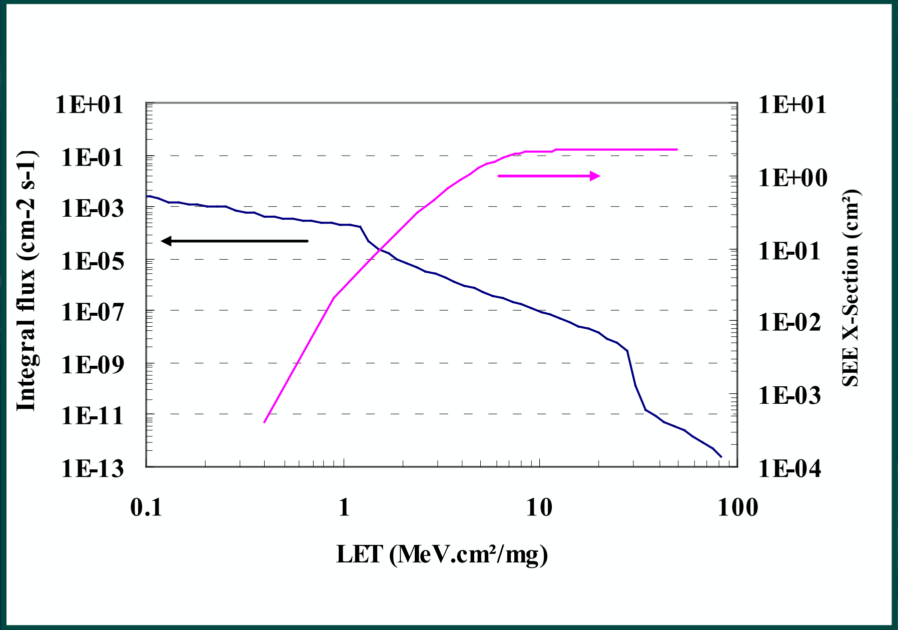
Flux
Type of particle
Energy/range
Temperature
Test sequence

Number of LET/energies
Test Fluence
Bias conditions
Events monitored /statistics
Sample size

All these aspects are reviewed by the ESA + customer chain (prime, subcontractor) during the Equipment Radiation Control Board.

Single Event Effects Test principle





- Facility is set to provide a given Liner Energy Transfer (corresponding to one ion at a given energy)
- Device under Test is bombarded with ions and tested in real time event are categorized by type and counted.
  - For each type of event, cross section is calculated

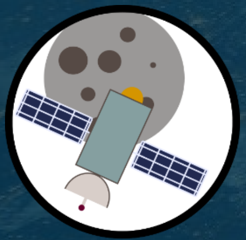
$$Cross\ section\ SEE(cm^2) = \frac{Number\ of\ events}{Ion\ fluence\ (\frac{ions}{cm^2})}$$

  - Event signature is characterized (SET, SEU, SEFI,SEL,...)
  - Possible recovery strategies are investigated
- Ions are changed to change the LET and build a cross section curve
- When the cross section curve is obtained, an event rate for a given orbit can be calculated.

Conclusion

(NASA technical Report TM 2018-220074)

- Radiation effects on electronics in space have a direct impact on the **reliability** and **availability** of a system and, therefore, on the success of a mission.
- Radiation Hardness Assurance (RHA) process shall be implemented to ensure that the electronics and materials of a space system perform to their design specifications after exposure to the space environment.
- RHA requires a considerable effort throughout the development of a space system from the early phases of a program development.
- The RHA approach on space systems is based on **risk management** and not on risk avoidance. It requires **radiation effect mitigation** and **tolerant electrical designs**.



Thank you for your attention!

Questions, Feedback, Collaboration ideas:
cristina.plettner@esa.int