EPFL

Introduction to the Design of Space Mechanisms

Theme 2:

Environmental constrains

Part 1

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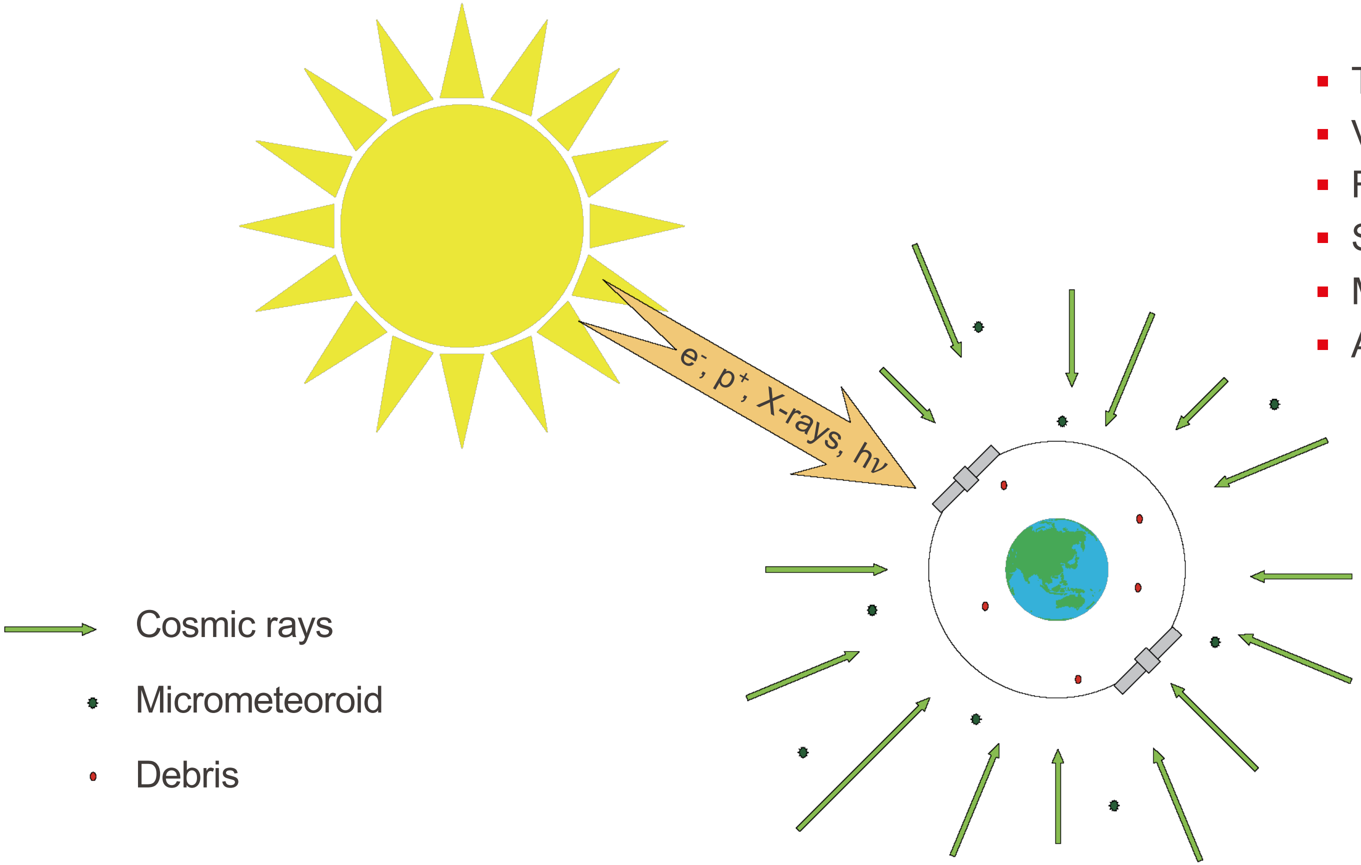
Space Environment Constraints

Main environmental constraints:

- **Vacuum, Temperature**
  - Outgassing
    - Material evaporation
    - Recondensation (degradation of optics)
    - Outgassing of non-tight cavities (blind threaded holes …)
    - Desorption effects: e.g. deformation of composite structures because of the evaporation of the absorbed water
    - Chemical effects on the materials (ATOX, aging, corrosion)
  - Tribology Effects
    - Change of the friction coefficient
    - Cold welding
    - Evaporation of lubricants
  - Thermal Effects
    - Heat exchanges through **radiation and conduction**
  - Mechanical Effects
    - Pressure and deformation of closed vessels, pipes, tanks, …
    - Depressurization and re-pressurization: gas flow, movement of dust particles …
  - Electrical Effects
    - Modification of insulation properties
    - Corona discharge
- **Radiations, Atomic Oxygen …**
- **Vibrations and Shocks**

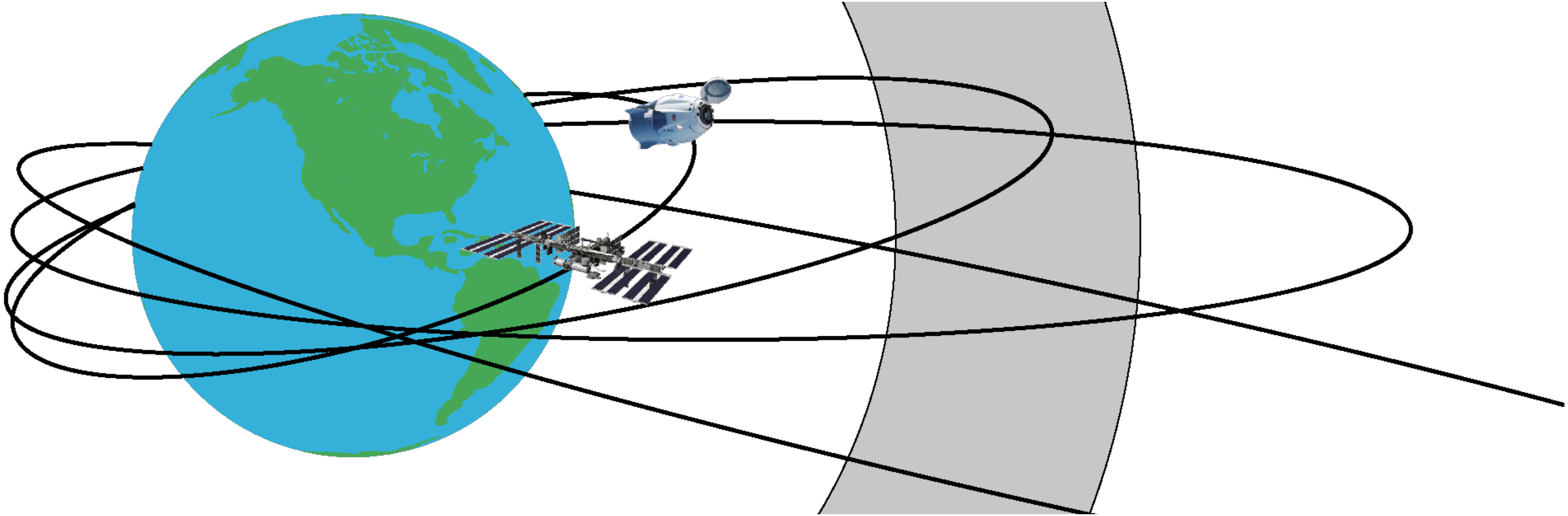
Space Environment Constraints



- Temperatures
- Vacuum
- Radiations
- Space Debris
- Micrometeoroids
- Atomic Oxygen

Space Environment Constraints

LEO	MEO	GEO
Atomic Oxygen	Van Allen Radiation	Solar Flare Protons
Meteoroids, Debris	Meteoroids, Debris	Spacecraft Charging
Ultraviolet	Ultraviolet	Ultraviolet
Thermal Cycling	Thermal Cycling	Thermal Cycling
Vacuum	Vacuum	Vacuum



Vacuum

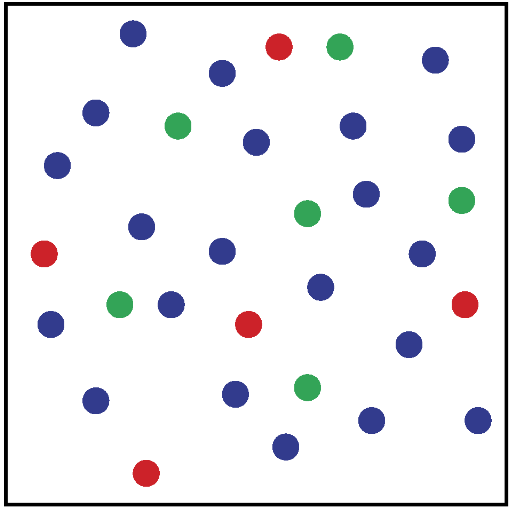
- Interstellar medium in a galaxy such as the Milky Way:
  (ref.: V. Baglin, Vacuum Systems Lecture 1, CERN 2019)
  - Composed of molecules, ions atoms, cosmic rays and dust
  - Atoms density:
    - 50×10^6 H/m^3 at 100 K (~10^{-11} hPa)
    - 10^6 H/m^3 at 10’000 K (~10^{-11} hPa)

Source: NASA, ESA, Hubble

- Low Earth Orbit (LEO) at 500km:
  - Highly ionized gas (O, N, H)
  - Atoms density:
    - 3.2×10^{11} H/m^3 (~10^{-6} hPa) - *ECSS-E-ST-10-04C-Rev.1 low solar activity [1.1]*
- Moon
  - Outgassing, dust, …
    - Release of gases such as radon and helium resulting from radioactive decay
  - Atoms density:
    - Pressure ~10^{-8} hPa (lunar night, very approximative)

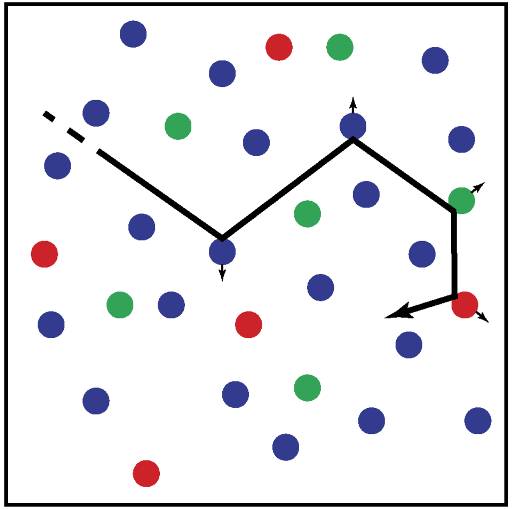
Vacuum

- A large number of molecules:
  - Very small when compared to intermolecular distance
  - Rectilinear movement between collision
  - Elastic collisions: against other molecules or against walls



Vacuum

- **Mean Free Path λ.**
  - It is distance that a molecule travel between two successive impacts with other molecules.



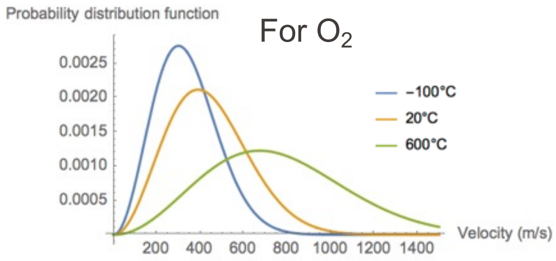
$$\lambda = \frac{k \cdot T}{\sqrt{2}\pi \cdot P \cdot \delta^2}$$

Where:

δ: Molecular diameter [m]
k: Boltzmann constant = $1.381 \cdot 10^{-23}$ [$J \cdot K^{-1}$]
T: Temperature [K]
P: Pressure [Pa]

Average velocity (Maxwell-Boltzmann distribution):

$$\bar{c} = \sqrt{\frac{8 \cdot R \cdot T}{\pi \cdot M}}$$



Where:

R: Gas constant = 8.31 [$J \cdot mole^{-1} \cdot K^{-1}$]
M: Molecular mass [g·mole]

EE580 Space Mechanisms – Vacuum

http://tiny.cc/EE580vac

Note:

With N_2 molecular diameter = 0.38 nm

Vacuum – Some order of magnitudes

- Mean free path: $\lambda = \frac{k \cdot T}{\sqrt{2}\pi \cdot p \cdot \delta^2}$
- Average velocity: $\bar{c} = \sqrt{\frac{8 \cdot R \cdot T}{\pi \cdot M}}$
- Particle(*) density: $\rho_p = N_A \frac{273.15K}{T} \frac{p}{1\,atm} \frac{1}{22.4 litres}$ *(ideal gas)*
- Impacts / surface unit: $n_c = \frac{1}{3}\rho_p \cdot \bar{c}$

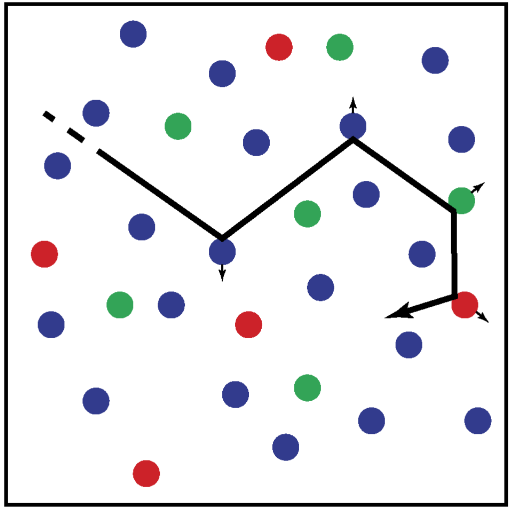
(*) *particles = molecules or atoms*

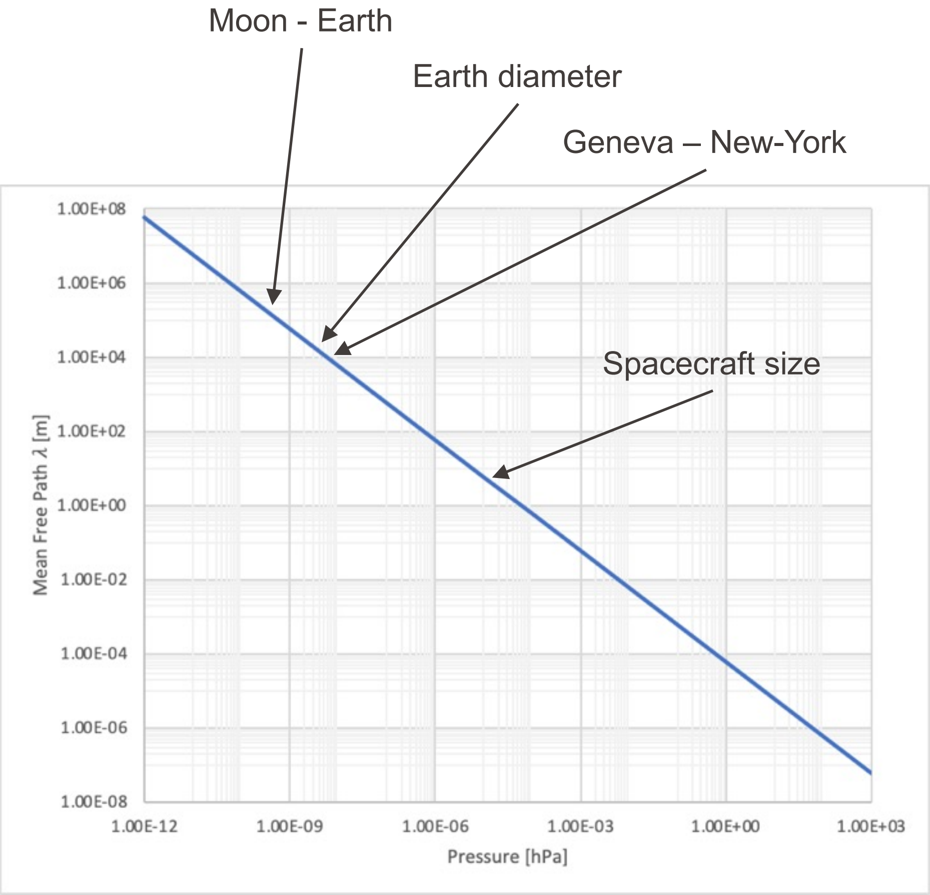
Molecule	δ [nm]	M [g/mole]	p [hPa]	T [°C]	λ [m]	c_{avg} [m/s]	ρ_p [cm^{-3}]	n_c [1/s/cm^2]
N_2	0.38	28	1013.25	20	$62.2\cdot10^{-9}$	471	$2.5\cdot10^{19}$	$3.9\cdot10^{23}$
			1013.25	1000	$270\cdot10^{-9}$	981	$5.8\cdot10^{18}$	$1.9\cdot10^{23}$
			10^{-6}	20	63.1	471	$2.5\cdot10^{10}$	$3.9\cdot10^{14}$
			10^{-6}	1000	274	981	$5.7\cdot10^{9}$	$1.9\cdot10^{14}$
H_2	0.27	2	1013.25	20	$123\cdot10^{-9}$	1761	$2.5\cdot10^{19}$	$15\cdot10^{23}$
			1013.25	1000	$535\cdot10^{-9}$	3670	$5.8\cdot10^{18}$	$7.1\cdot10^{23}$
			10^{-6}	20	125	1761	$2.5\cdot10^{10}$	$15\cdot10^{14}$
			10^{-6}	1000	542	3670	$5.7\cdot10^{9}$	$7.0\cdot10^{14}$

Pressure Conversion: **1000 mbar** = 1 bar = 1 atm = 10^5 Pa = **1000 hPa** = 760 mm Hg = 760 Torr

Vacuum

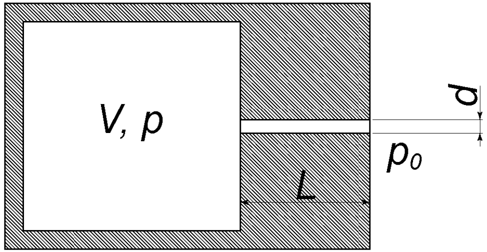
- Mean Free Path.
  - It is distance that a molecule travel between two successive impacts with other molecules.





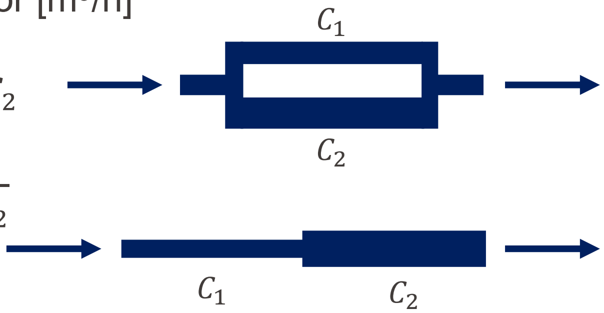
Mean free path of nitrogen molecules at 273.15K

Vacuum – Outgassing of a cavity



Q: molecular flux [Pa·m³/s]

- Conductance (C): $Q = C \cdot (p - p_0)$ [l/s] or [m³/h]
- Adding conductances in parallel: $C = C_1 + C_2$
- Adding conductances in series: $\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2}$



(Approximations)

- In high vacuum:
  - ➢ Molecular flow
  - ➢ Mean free path >> *d* (***d* = reference geometric dimension**)
- Conductance in molecular flow: $C = \frac{\pi \cdot \bar{c} \cdot d^3}{12 \cdot L}$

$\bar{c}$: average velocity (Maxwell-Boltzmann)

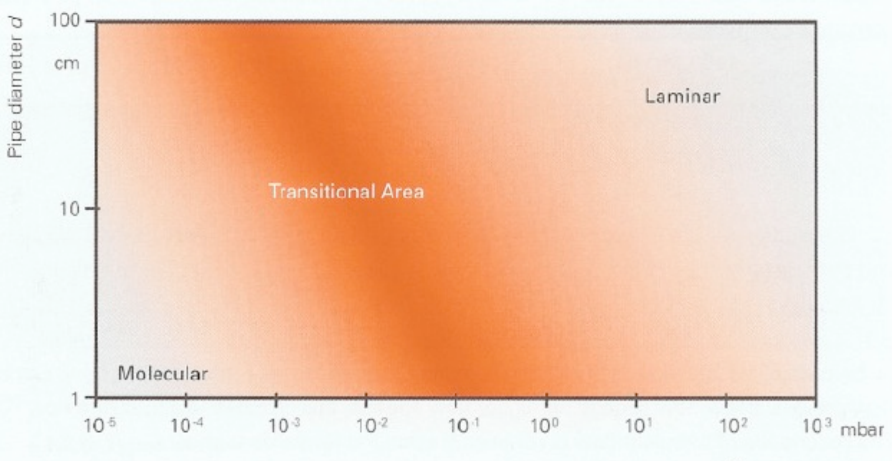
Outgassing of cavities

- Classification of gaseous flows:
  - Viscous flow (continuous): $K_n < 0.01$
  - Transitional flow: $0.01 < K_n < 0.5$
  - Molecular flow: $K_n > 0.5$

Knudsen number: $K_n = \frac{\lambda}{d}$

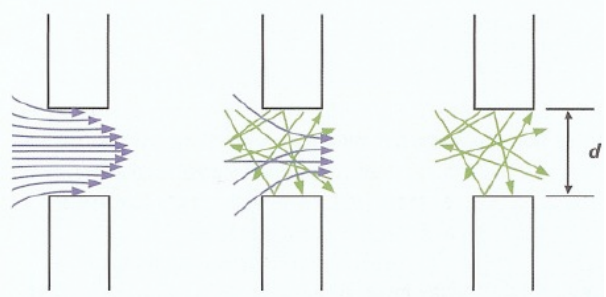
  - Laminar flow $Re < 2300$
  - Turbulent flow $Re > 4000$

Reynolds number: $Re = \frac{\rho}{\eta} \cdot v \cdot d$

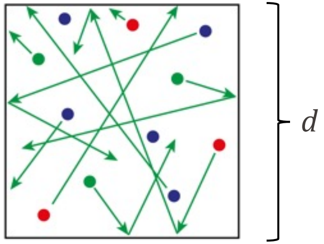


Source: Pfeiffer – The Vacuum Technology Book Volume II

ρ: specific mass of the gas [kg/m^3]
η: dynamic viscosity [Pa·s]
v: velocity of the gas flow [m/s]
d: diameter of the pipe [m]
λ: mean free path [m]

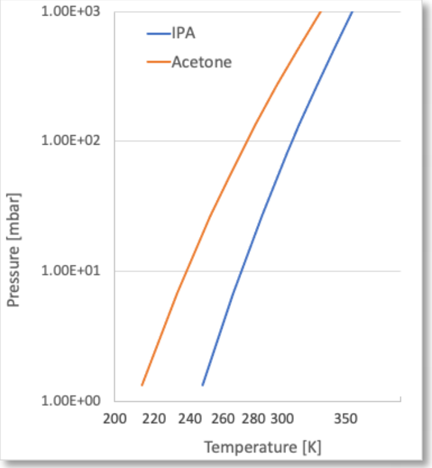


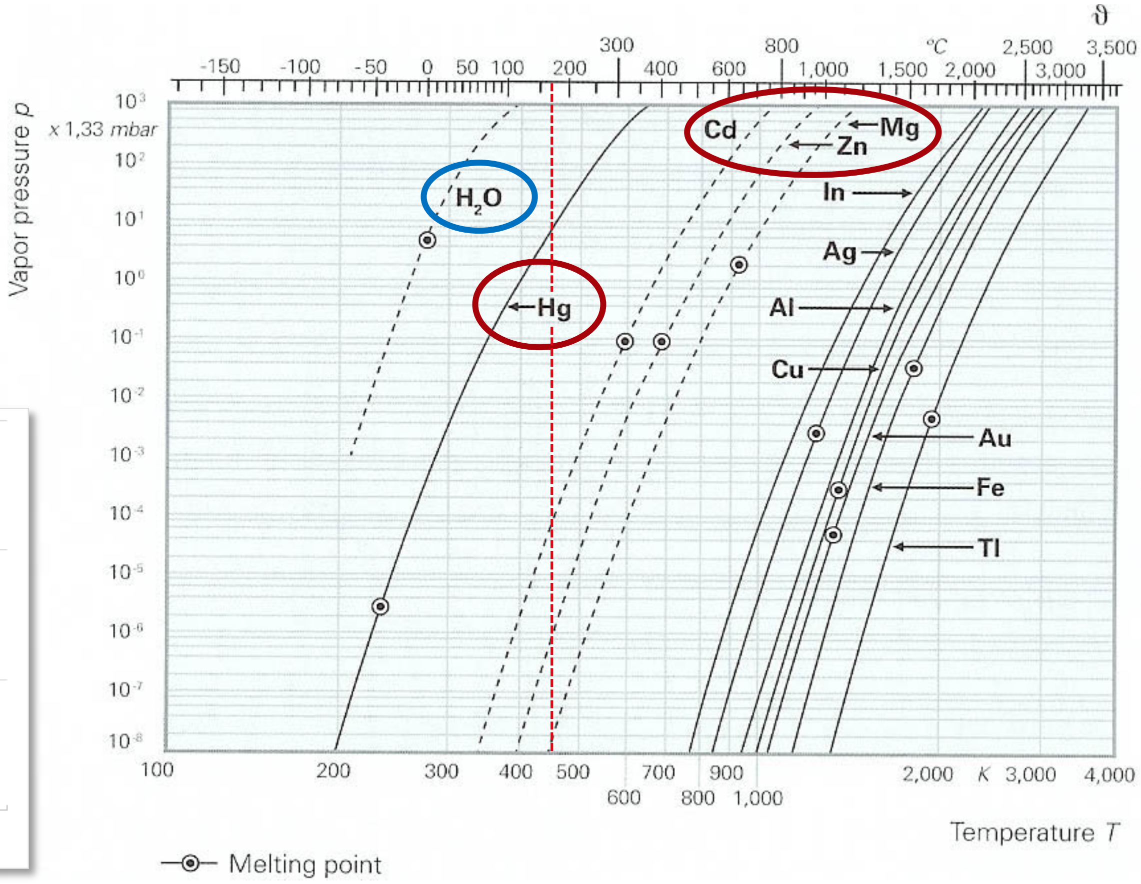
Molecular flow



- Mean free path λ is of the order or larger than the typical dimensions d of the vacuum vessel
- Typically around < 10^{-5} hPa for a vacuum chamber
- Molecular collisions with the wall of the vacuum envelope become preponderant
- Intermolecular interactions cease to have any effect on the gas displacement
- No more heat exchange by convection => radiation (and conduction) only

Vapor Pressure





Source: Pfeiffer - The Vacuum Technology Book Volume II

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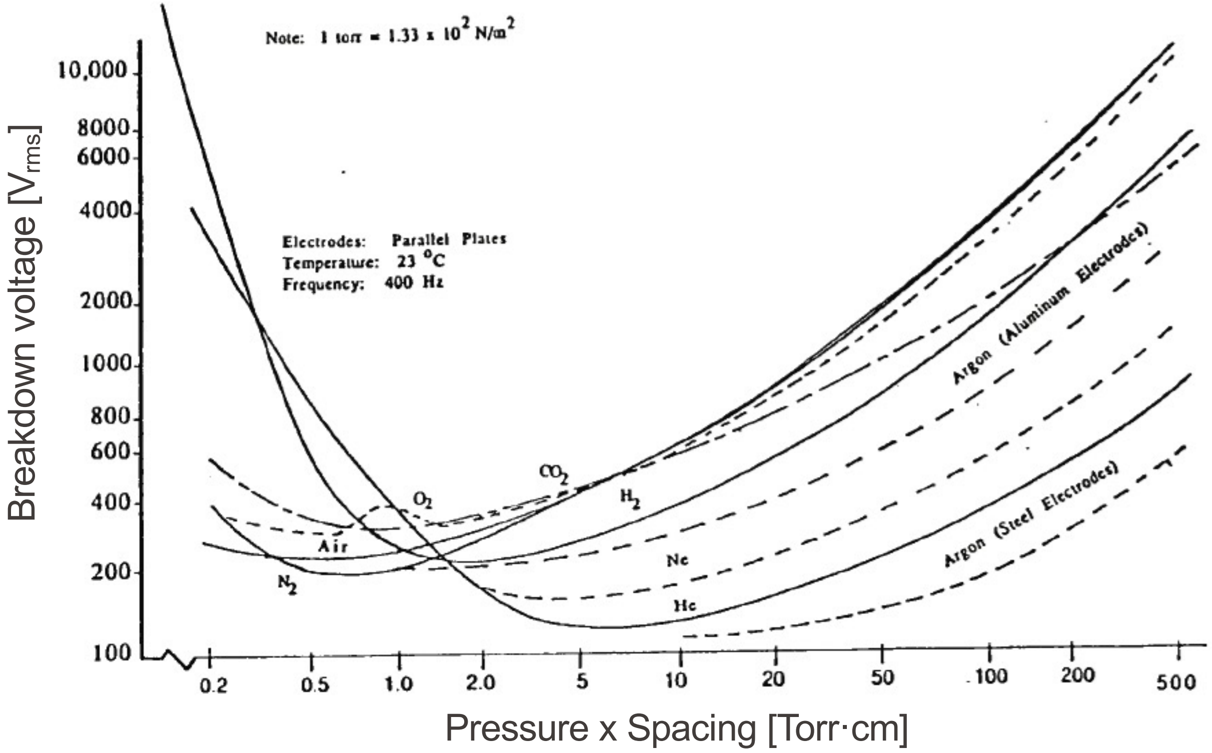
Paschen Law – Breakdown Voltage



Source: Dunbar, W.G., High Voltage Design Guide: Aircraft, AFWAL–TR–82–2057, January 1983, pp. 31 / ECSS-E-HB-20-05A "Space engineering - High voltage engineering and design handbook"

Careful with uninsulated electrical lines

Pressure Conversion: **1000 hPa = 1000 mbar** = 1 bar = 1 atm = 10^5 Pa = 760 mm Hg = 760 Torr

References

- Reading for the vacuum technology:
  - Paolo Chiggiato “**Outgassing properties of vacuum materials for particle accelerators**”, Proceedings of the 2017 CERN-Accelerator-School course on Vacuum for Particle Accelerators, Glumslöv **[2.1a]**

French only document (dedicated to technical staff)

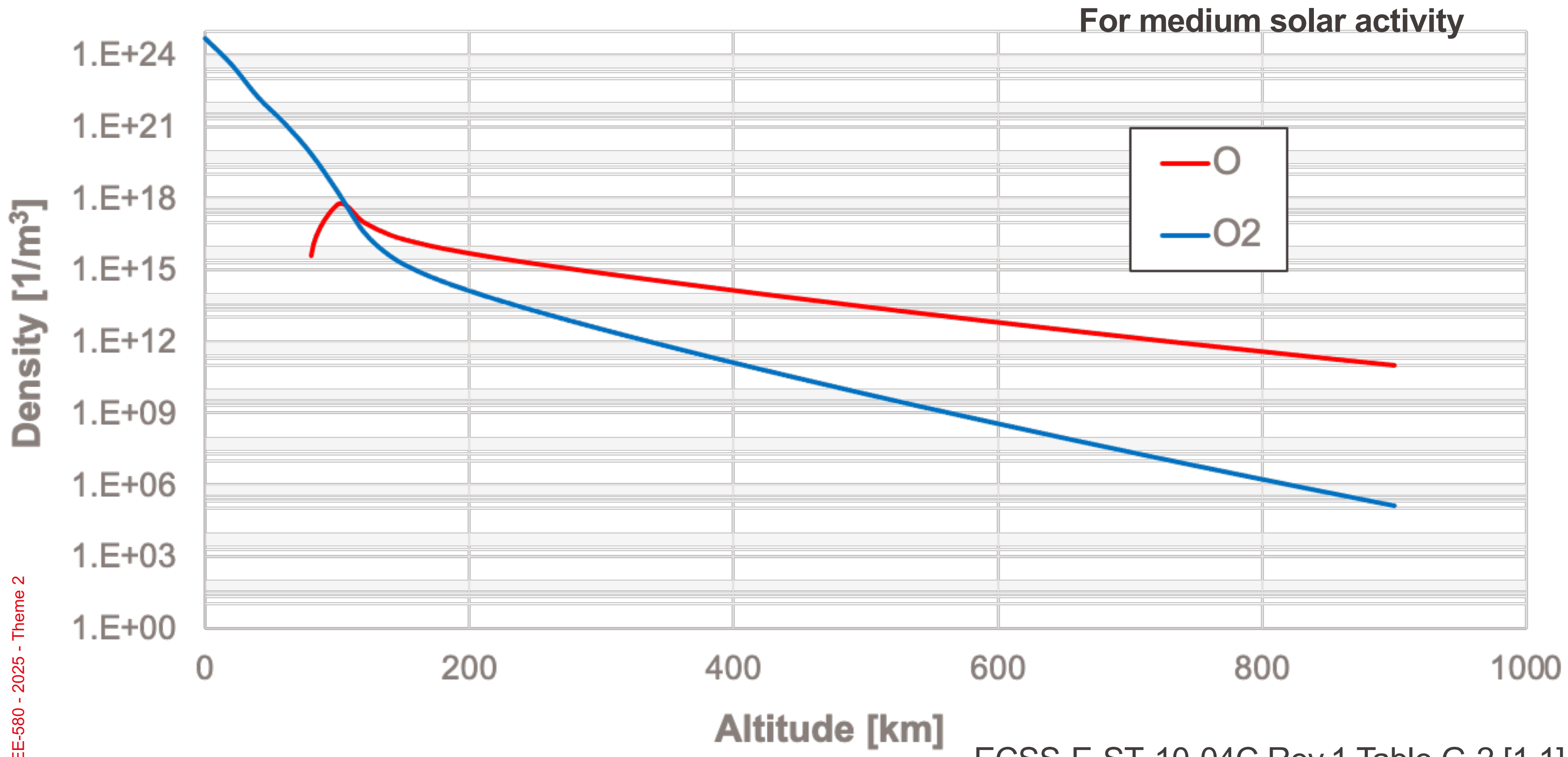
  - *Paolo Chiggiato “**Dégazage des solides en ultravide : quelques notions de base pour les techniciens du CERN**”, CERN ATS/Note/2012/048 TECH (dated 2012-06-01)* **[2.1b]**

- Some of the coming slides are extracts from the following document:
  - The **ESA SME Initiative Training Courses (2004)**
    - Materials Properties & Associated Test Methods for Non-metallic Materials: M. Van Eesbeek, ESA/ESTEC/TOS-QM

Chemical and Mechanical Effects (Erosion)

- **Atomic Oxygen** (ATOX):
  - O, O^+ et O^{2+}
  - High reactivity of O, O^+ et O^{2+}
    - Very short life on ground
    - LEO atmosphere: about 96% oxygen
    - O_2 molecules broken by UV's

Atomic Oxygen and Oxygen



ECSS-E-ST-10-04C Rev.1 Table G-2 [1.1]

Atomic Oxygen

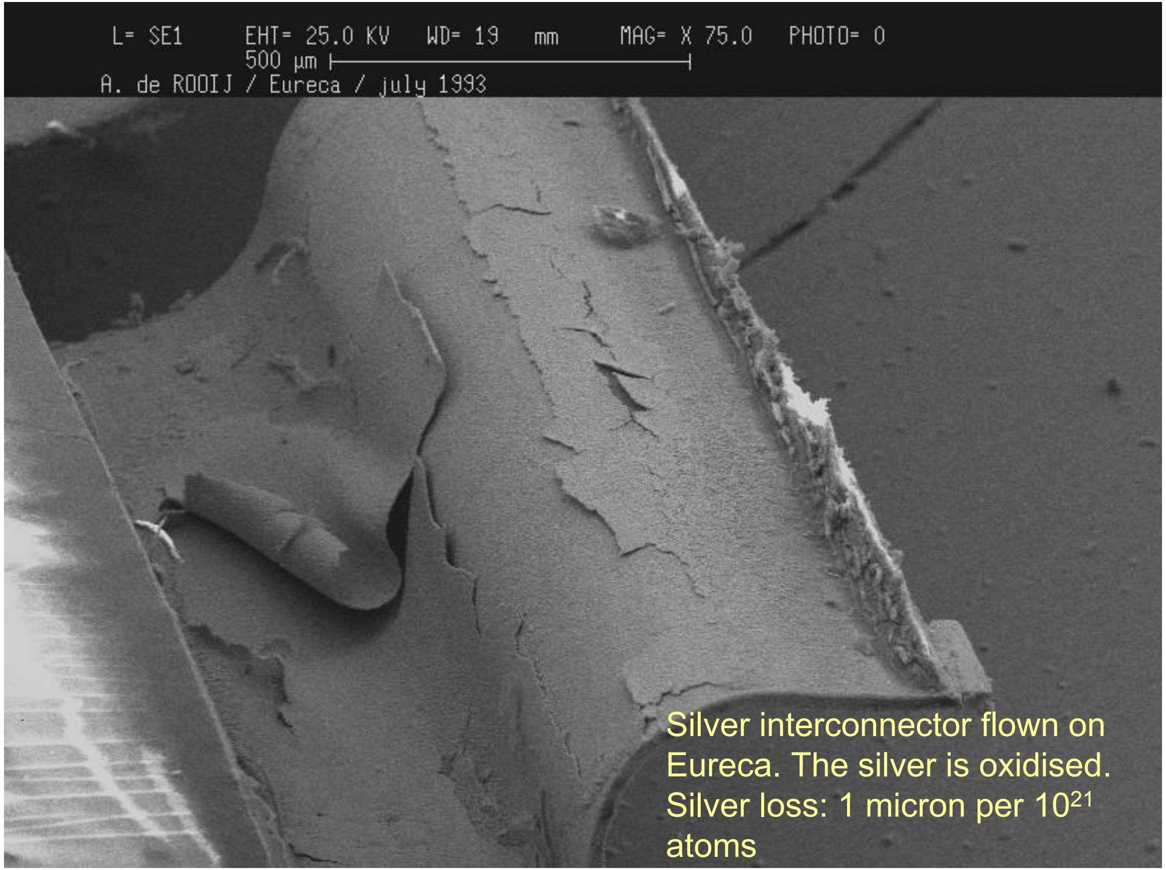
- Erosion by Atomic Oxygen (ATOX):
  - High reactivity of O, O^+ et O^{2+}
    - Erosion, in particular of several **organic materials**
      - KAPTON, MYLAR: high degradation
      - PTFE (TEFLON): quite good resistance
      - Epoxy: erosion
      - Glues: change of color, but low degradation of the gluing resistance
      - Paints: highly variable resistance
        discoloration by UV
    - **Metals**: Erosion and oxidation
      - Silver: highly degraded by oxidation
      - Copper et Copper-Beryllium: strongly oxidized (also on ground)
      - Steel, Aluminum, Titanium: good structural resistance

Atomic Oxygen

ESA EURECA

Source: NASA

Source: Guido Schwarz

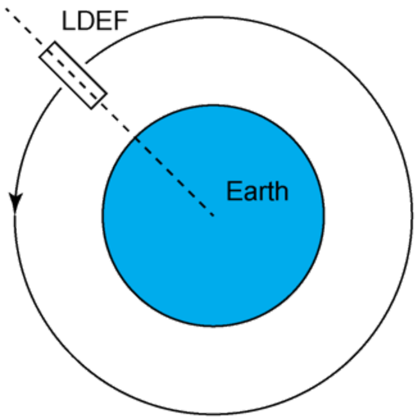


Silver interconnector flown on Eureca. The silver is oxidised. Silver loss: 1 micron per 10^{21} atoms

Source: ESA/A. de Rooij (2010)

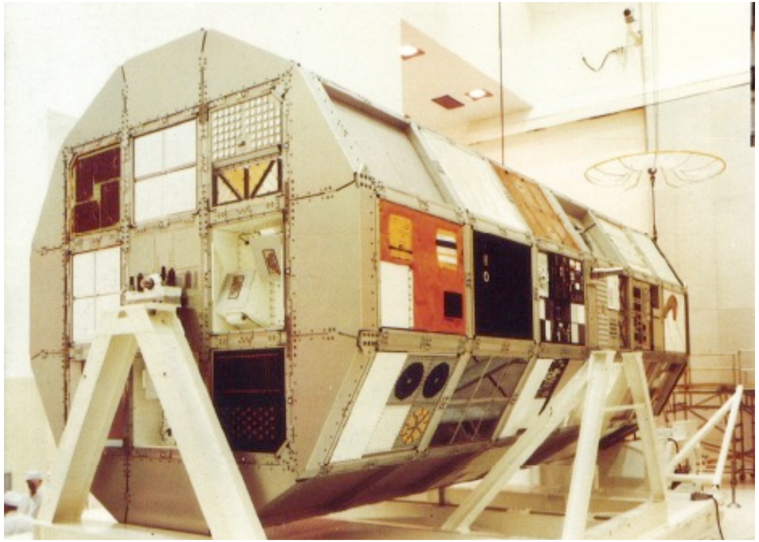
Study on the impact of space environment

- NASA LDEF (Long Duration Exposure Facility)
  - Technology spacecraft
    - Ø 4.3 x 9 m
    - 11 metric tons
    - 57 experiences, of which 11 French ones (FRECOPA)
  - Launch: April 1984
  - Retrieval: January 1990
  - Circular orbit (inclination 28.5°):
    - 476 km BOL (Beginning Of Life)
    - 330 km EOL (End Of Life)
    - Orientation stabilized by gravity gradient (long axis always towards Earth)



Source: NASA

Study on the impact of space environment



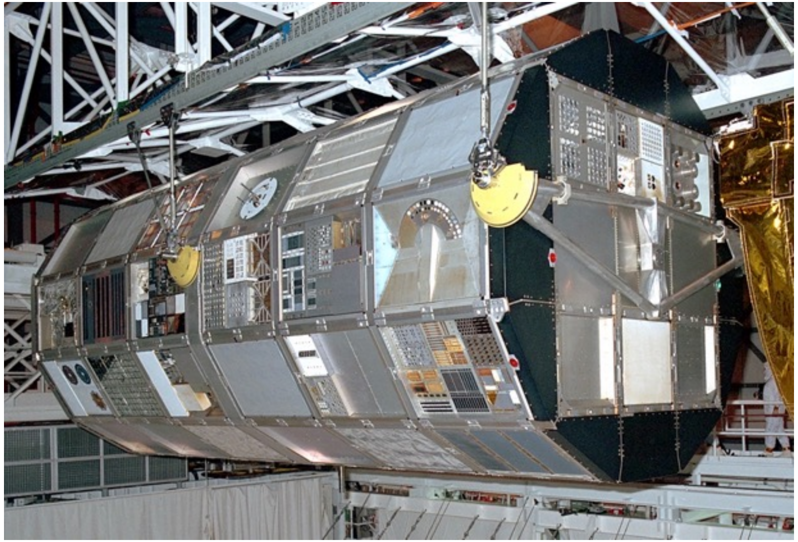
Source: NASA

Before flight

1984

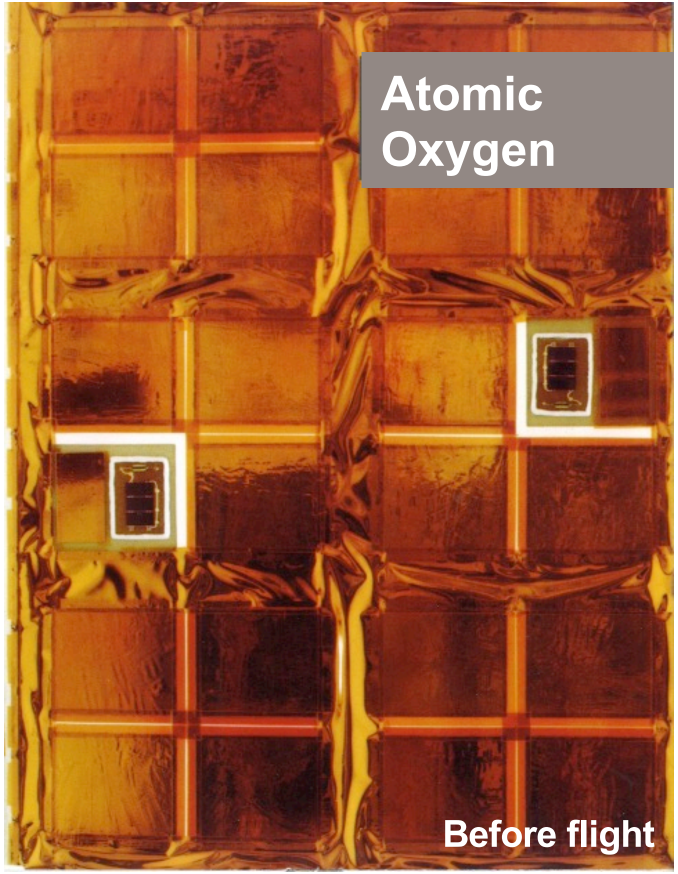
1990

After flight



Source: NASA

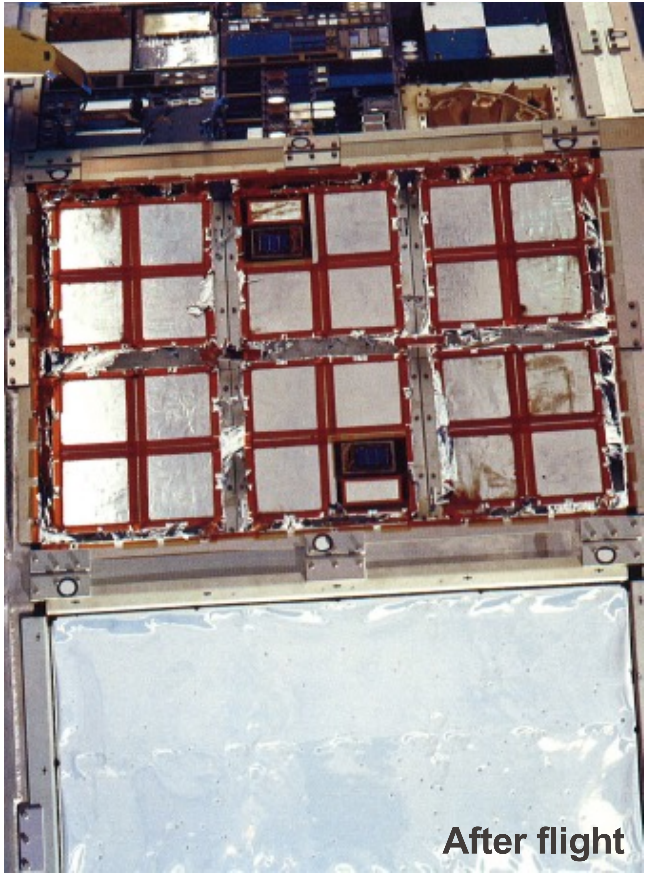
Chemical effects



Source: NASA

Aluminized Kapton
(125µm, Al, 200µm):

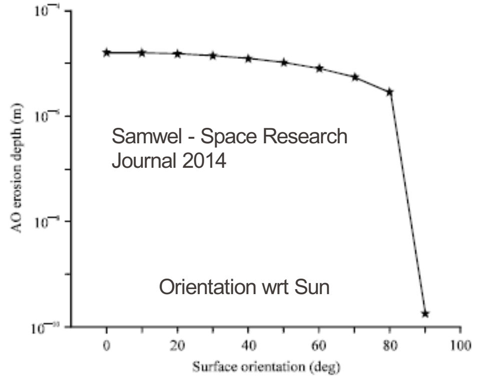
- Totally eroded Kapton
- Only Al layer, very brittle

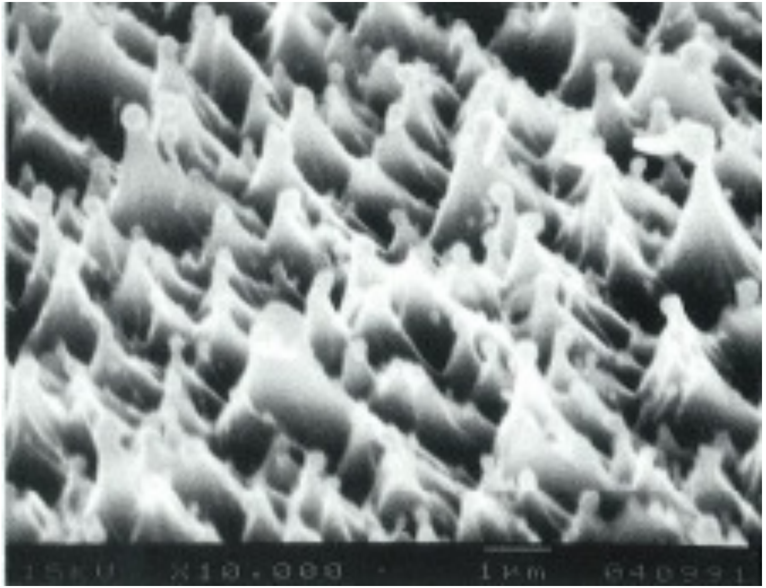


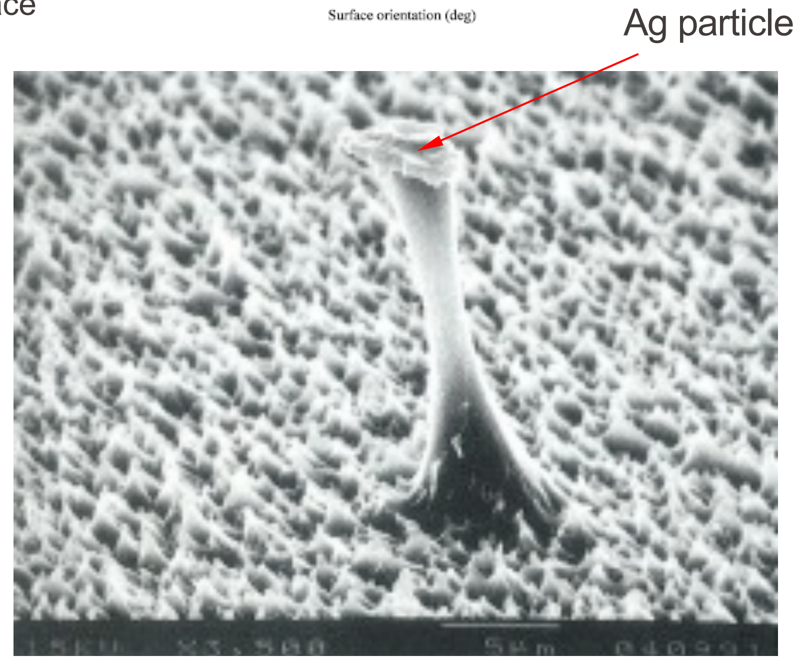
Source: NASA

Chemical effects

LDEF satellite: Silver coated PTFE exposed to ATOX







Other retrievable space experiments

- European Retrievable Carrier (EURECA) – ESA
  - 4.5-tonne satellite with 15 experiments
  - 515 km BOL (Beginning Of Life)
  - ~300 km EOL (End Of Life)
  - Launch (STS-46): July 1992
  - Retrieval (STS-57): July 1993
- Mir Environmental Effects Payload (MEEP) – NASA
  - Installed on MIR station docking module
    - Launch (STS-76): March 1996
    - Retrieval (STS-86): October 1997
- Materials International Space Station Experiment (MISSE) – NASA/DoD
  - Mounted externally on the International Space Station
  - Series of experiments. First launch in 2001.
- Euro Material Ageing (EMA) – ESA/CNES
  - Space Experiment Study on Ageing of MatErial (SESAME)
  - Bartolomeo platform (Airbus)
  - Attached to ISS European Columbus Module

Source: NASA

Source: NASA

Source: NASA

Thermal Effects

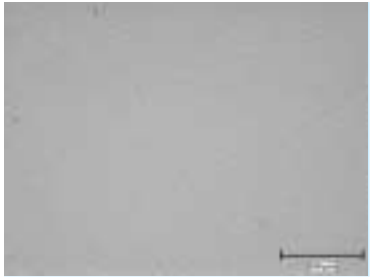
- Mechanical Effects
  - Thermal expansion (incl. differential thermal expansion)
  - Modification of the strength, embrittlement
  - Fracture, cracks
  - Creep
  - Lubrication power, viscosity of lubricants
  - …
- Electrical Effects
  - Evolution of the characteristics of the material
    - Resistance
    - Operating point of semiconductors
    - Aging of electronic components
    - …

Thermal Effect

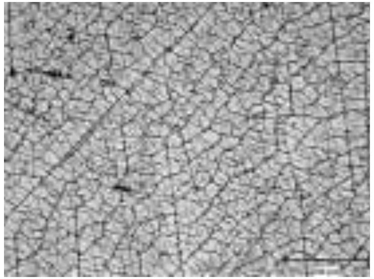
Source: ESA

Thermal Effect

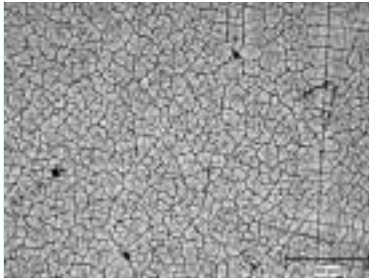
Vapor Deposited Aluminum (VDA)
On Fluorinated Ethylene Propylene (FEP)



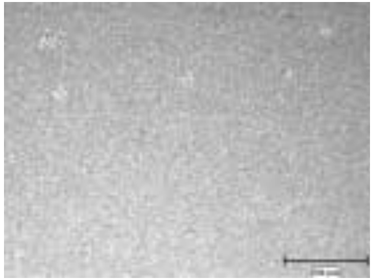
VDA layer at BOL



14 days aged at 200°C



44.9 days aged at 200°C

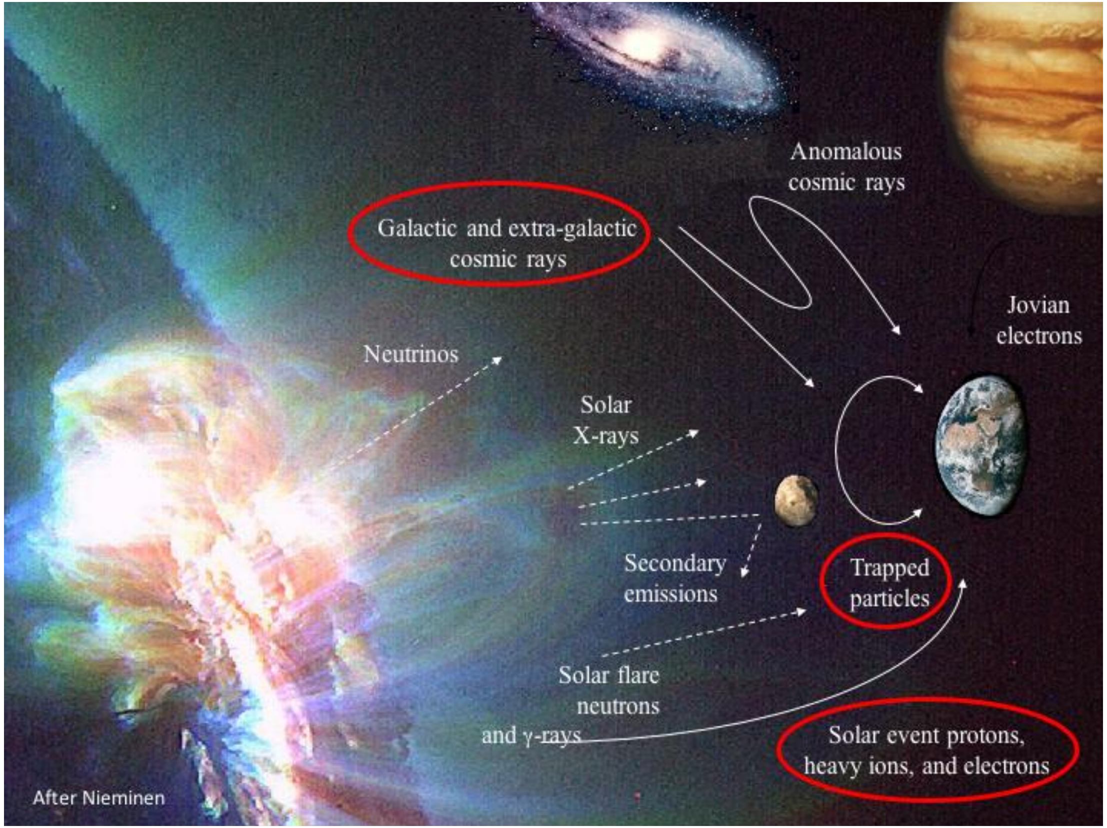


T.C. -100°C / +100°C

Source: ESA/M. Van Eesbeek

Radiations

- Source of radiation in space



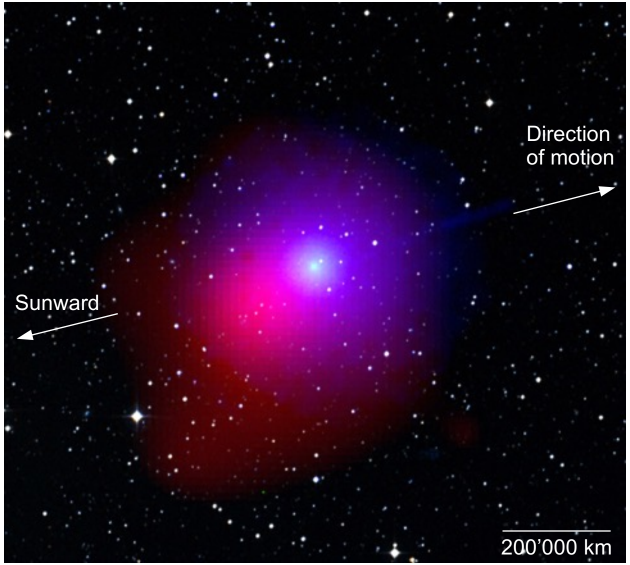
Source: C.Poivey, Radiation Effects in Space Electronics (ESA 2019),

What are the sources of highest energy radiations?

A. Solar radiations
B. Cosmic radiations
C. Earth trapped particles

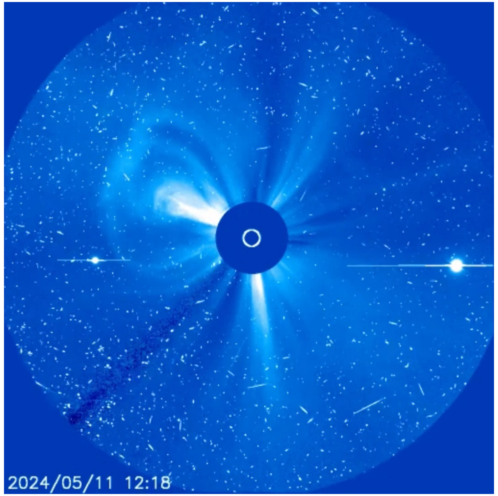
Solar Wind

- Picture: **Comet Lulin**
  - Photo taken by Swift spacecraft (NASA + Italy and UK, detection of gamma-ray bursts)
  - False color image
    - Red: X-ray emissions (ions-gazes interactions)
    - Blue and green: ultraviolet/optical emissions (OH molecules)
    - The cloud of water shed by the comet is excited by the solar wind, generating X-ray emissions.



Source: NASA/Swift/Univ. of Leicester/Bodewits et al.

Exercise 2.1: Solar Wind



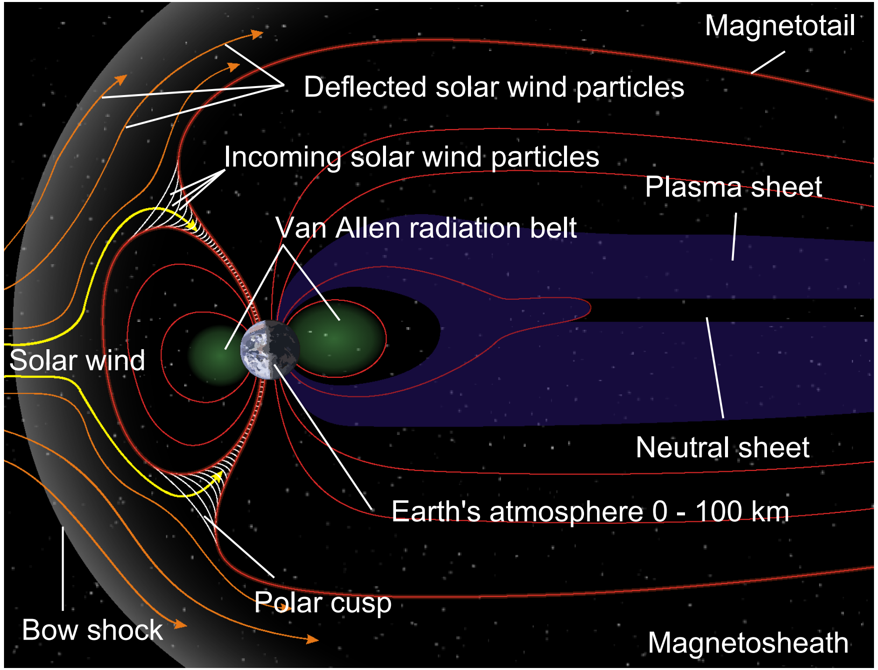
Source: NASA/ESA/SOHO

- Picture: ESA/NASA **SOHO** (Solar and Heliospheric Observatory), the effect of **solar Coronal Mass Ejection** resulting in a strong high energy proton event. Proton impinging on the imaging sensor of the instrument are observed as bright pixels or streaks.

  SOHO’s view of the 11 May 2024 solar storm

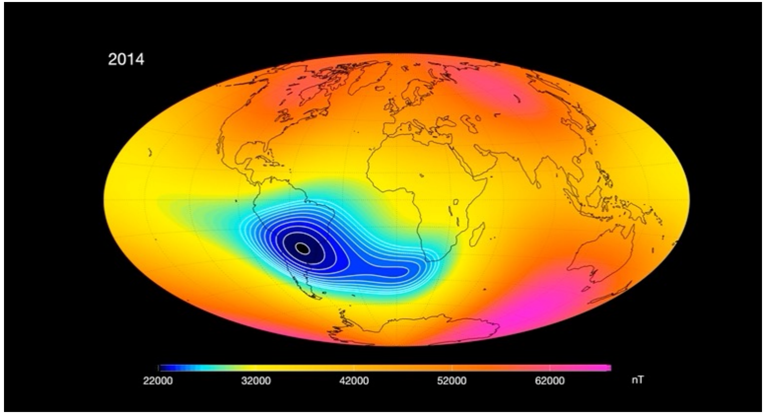
Ionizing Radiations: around the Earth

Structure of Earth Magnetosphere



Source: NASA

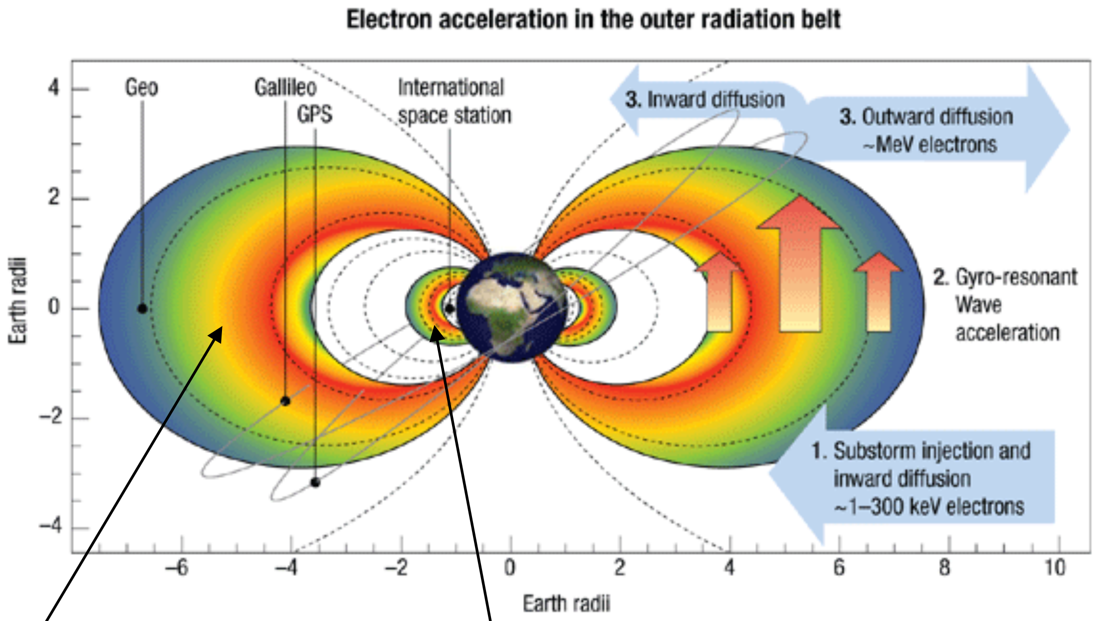
South Atlantic Anomaly (SAA)



Source: Division of Geomagnetism, DTU Space

e^-, p^+, X-rays, hν

Ionizing Radiations: Van Allen Belts



Source: Richard Bertram Horne Nature Physics 3, 2007

Outer belt

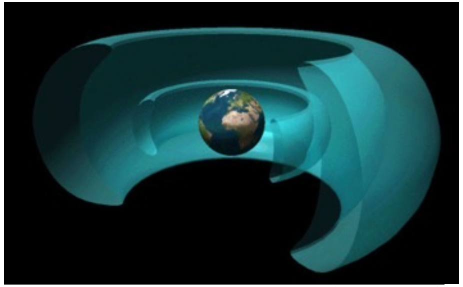
- *Electrons up to 7 MeV*

Inner belt

- *Protons up to ~400 MeV*

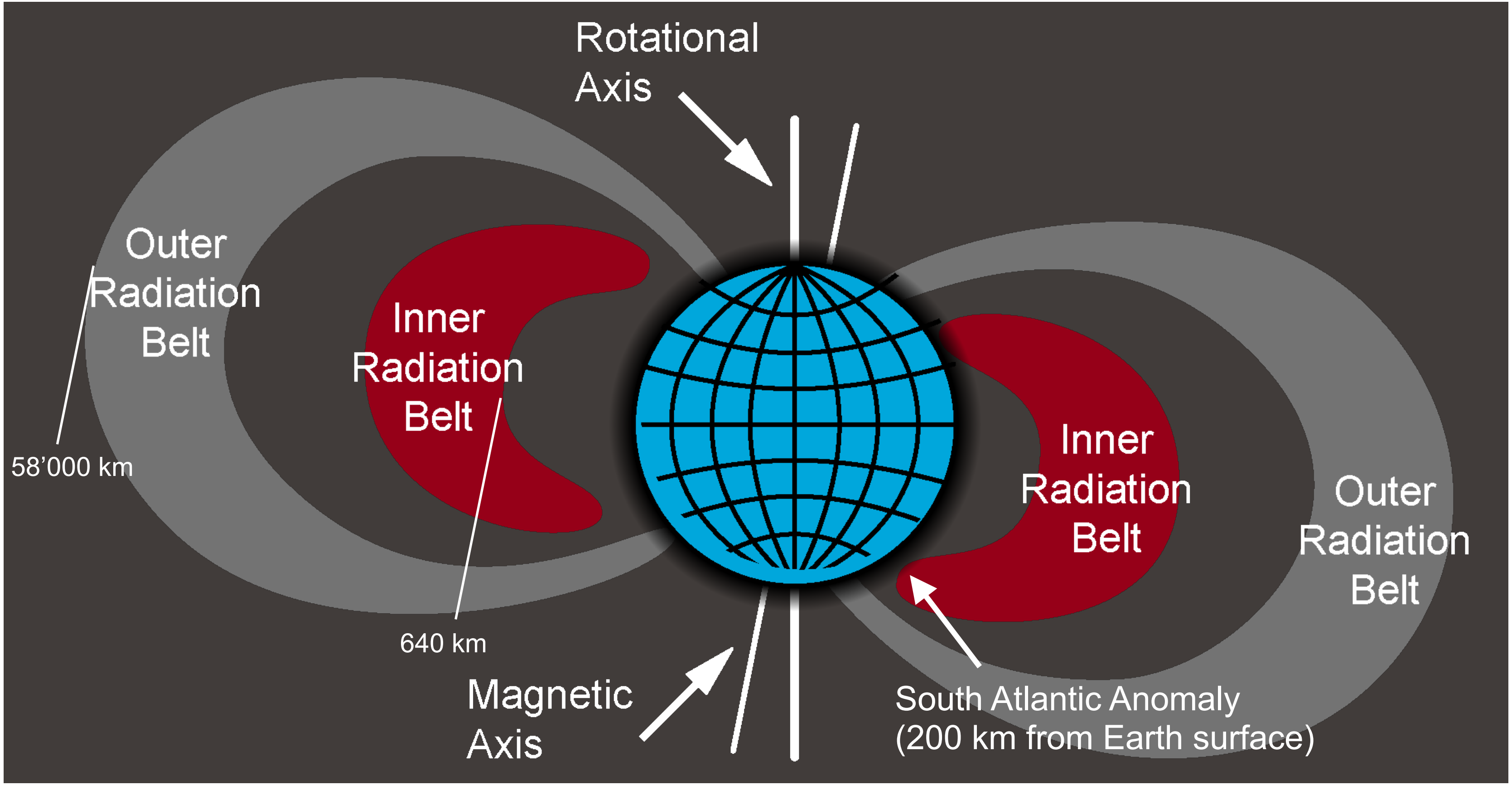
James Alfred Van Allen

Source: NASA



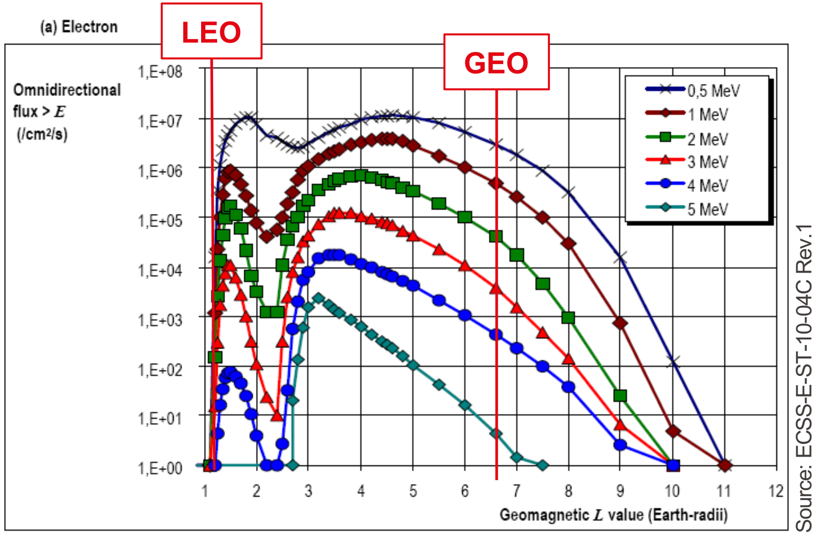
Source: NASA

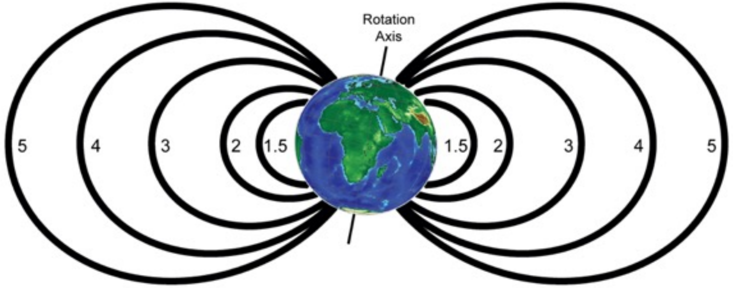
Ionizing Radiations: Van Allen Belts



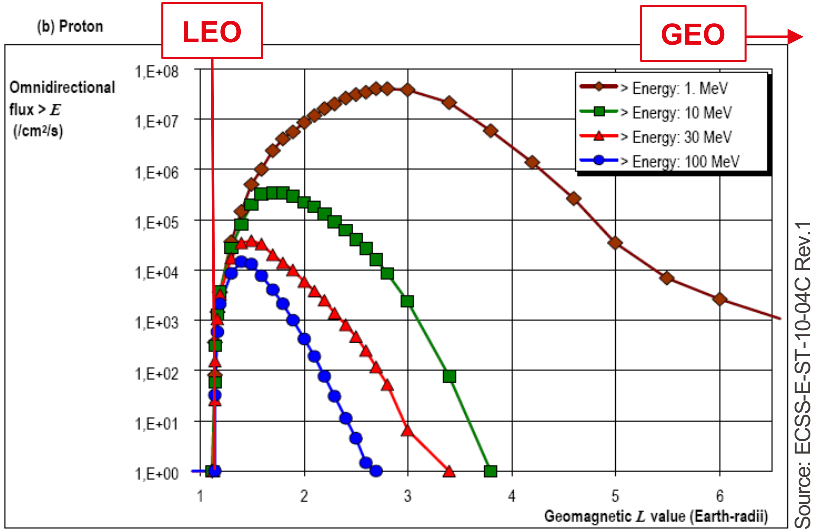
Source: https://commons.wikimedia.org/wiki/File:Van_Allen_radiation_belt.svg

Solar Wind: Electrons and Protons (models)





Source: https://en.wikipedia.org/wiki/File:L_shell_global_dipole.png



- Individual events:
  Exceptional solar activity (solar flares)
- Proton trapped in Earth orbit
  Worst case event:
  - $3 \cdot 10^{10}$ protons (>30MeV) / cm^2
    From ECSS-E-ST-10-04C Rev.1 [1.1]

EPFL

Solar Wind: Particles

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Particle Radiation

Orbit	Fluence [J.m^{-2}. Year^{-1}]			Absorbed Dose in 4 μm Al (Gy.year^{-1})		
	Electrons	Protons	Total	Electrons	Protons	Total
MIR;LEO;350; 51.6;C	4.6×10^{2}	11	4.7×10^{2}	6.4×10^{2}	1.5×10^{1}	6.6×10^{2}
ISS;LEO;426; 51.6;C	8.6×10^{2}	36	9.0×10^{2}	1.2×10^{3}	4.8×10^{1}	1.2×10^{3}
GEO;35790;0; C	9.8×10^{5}	3.8×10^{4}	1×10^{6}	5.4×10^{5}	8.3×10^{6}	8.8×10^{6}
GLON;19100; 64.9;C	8.3×10^{5}	2.6×10^{5}	1.1×10^{6}	3.8×10^{5}	2×10^{6}	2.4×10^{6}
HEO;500-39660;65;E	4.9×10^{5}	6.8×10^{4}	5.6×10^{5}	2.6×10^{5}	3.1×10^{5}	5.7×10^{5}
POL;LEO;600 ;97;C	2.3×10^{3}	1×10^{2}	2.4×10^{3}	2.5×10^{3}	3.0×10^{2}	2.8×10^{3}

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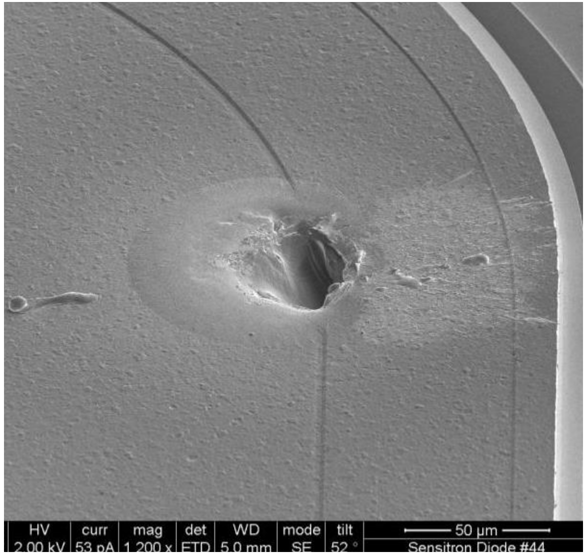
Source: M. Van Eesbeek, ESA/ESTEC/TOS-QM

Ionizing Radiations: material degradation

- Aging of materials:
  - Embrittlement
  - Modification of structure
  - Modification of material properties
  - Modification of thermo-optical properties
  - …
- Health effects
- Degradation of electronic components
- Electrostatic charges of insulators, surface charging



Picture: High-energy particle impact on Schottky diode

Source: J. George NSREC Radiation Effects Data Workshop 2013

Ionizing Radiations: material degradation

- Dose (cf. ECSS-E-ST-10-04C Rev.1 [1.1]):
  - A spacecraft is exposed to high flux of charged particles, in particular when crossing the Van Allen Belts.
    - Electrons (mainly trapped by the terrestrial magnetic field)
      - Energies of several 10^{th} of keV
      - High fluctuation of the electron density (factors from 1 to 100) depending on day/night, solar activity, ...
    - Solar Wind
      - Protons: 95%
      - Alpha-particles: 4%
      - Others (C, N, O, Ne, Mg, Si, Fe, …): 1%
      - Average velocity of the particles 468 km/s, frequent high-speed streams at 700 km/s, sometimes > 1000 km/s (high solar activity).
  - Specific characteristics for each missions
    - Exposition data are parts of the requirements for a mechanism (e.g.: the total ionizing dose - TID - for the mission shall be $5 \cdot 10^6$ rad)
    - Such an exposition is higher than the allowed dose for some materials, in particular for electronic components → Shielding is required

Ionizing Radiations: charged particles environment

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Charged Particles Environment

Radiation Source	Nature	Energy	Flux (part.cm^{-2}s^{-1})	Characteristics	Remarks
Galactic Cosmic Rays	Protons (~90%) α(He-nucleus) & Heavy Ions (10%)	10^{-2} GeV-10^{10} GeV	2-5		Least Significant for materials
Solar Wind	Protons (96%) α and O-ions Electrons	~ 1KeV ~ 1 KeV ~20-40 eV	p^+ 2.10^8 at 1A.U.	- Neutral plasma - Low energy restricts hazards to surface	No influence on circumterrestrial orbits at altitudes<6.6 R_E
Solar Cosmic Events (Flares)	Protons (95%) Heavy Ions	1-100 MeV (below 10 MeV spectrum ~$E^{-1..2}$, beyond ~E^{-5})	Precise prediction of solar activity cannot be made	- E and N particles varies by events - Omnidirectional isotropic	
Trapped Radiation 1.Inner Belts (1.2-3.2 R_E) 2.Outer Belts (3-7 R_E)	Protons and electrons Protons and electrons	E_{p+} < 30 MeV (90%) E_{e-} < 5MeV (90%) All E_{p+}<1MeV	p^+ 5.10^5 E>1 MeV e^- 2.10^7 E>.5MeV p^+ 10^9 E>10KeV e^- $5.2.10^7$ e^{-5xE} with E in MeV	- Omnidirectional Isotropic - Flux varies with magnetic latitude - Spectra are very variable with solar activity (GEO) - Fluxes not entirely symmetric in Longitude (SAA for protons)	- Most important for orbits at altitude <6.6 R_E - High E protons in inner belts only - Atomic displacements are possible at LEO in SAA
Aurora	Electrons and protons	e^- 2KeV<E<20 KeV p^+ 80<E<800 KeV	e^- 1010 during storms p^+ <107	- Observed between 65° and 70o N and S magnetic latitude at altitudes between 100 and 1000 km - Very much time dependent	

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Source: M. Van Eesbeek, ESA/ESTEC/TOS-QM

Solar Wind: Electromagnetic radiation

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High Energy Solar Flux

Type	Wavelength (nm)	Average Flux (W/m^2)	Worst Case Flux (W/m^2)
Near UV	180-400	118	177
UV	<180	2.3×10^{-2}	4.6×10^{-2}
FUV	100-150	7.5×10^{-3}	1.5×10^{-2}
EUV	10-100	2×10^{-3}	4×10^{-3}
X-rays	1-10	5×10^{-5}	1×10^{-4}
Flare X-rays	0.1-1	1×10^{-4}	1×10^{-3}

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Source: M. Van Eesbeek, ESA/ESTEC/TOS-QM

U.V. Radiations: an example, Mylar

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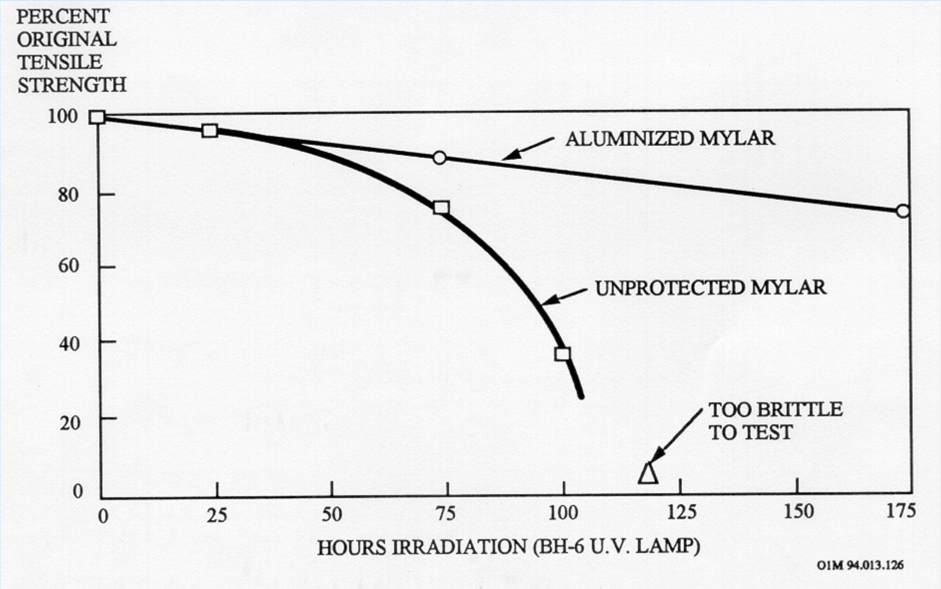
Effect of Radiation on Tensile strength of Mylar



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Source: M. Van Eesbeek, ESA/ESTEC/TOS-QM

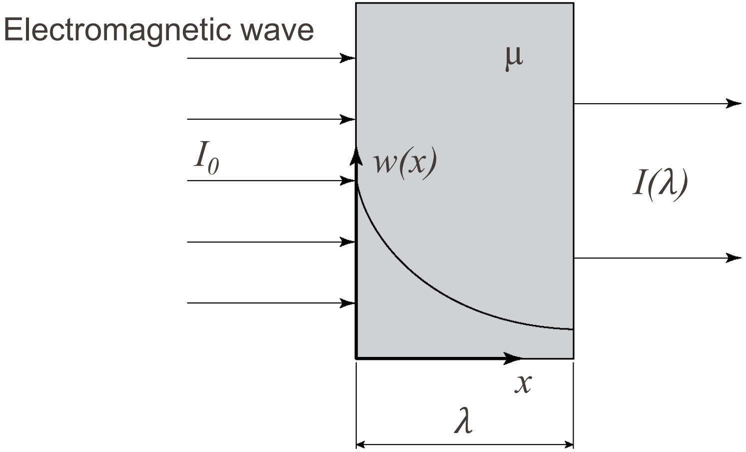
Ionizing Radiations: shielding (ECSS-E-ST-10-12C [2.2])

- For electromagnetic waves, the flux is reduced behind a metallic wall:

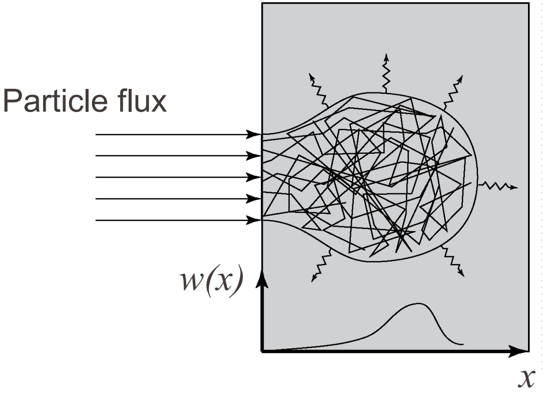
$$I(\lambda) = I_0 \cdot e^{-\mu \cdot \lambda}$$

Where

- μ: attenuation coefficient
  - Depends on the material
  - Depends on the energy (wavelength)



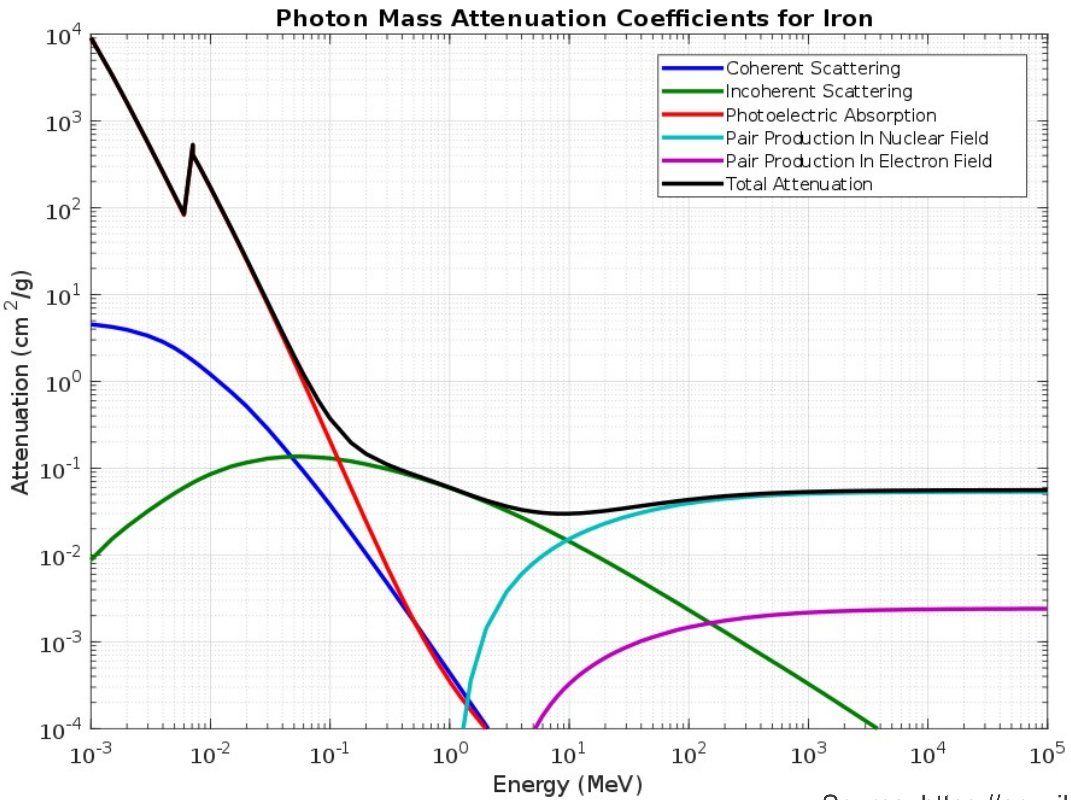
- For particles, absorption depends on other parameters
  - Type of particles
  - Charge
  - Energy (velocity of the incident particle)
  - Material (density, nuclear disintegration)



- The energy transferred to the human body depends on the radiation type, the organs and tissues and the geometry

Ionizing Radiations: Mass attenuation coefficient

- Various physical phenomena depending on the energy of the incident radiation



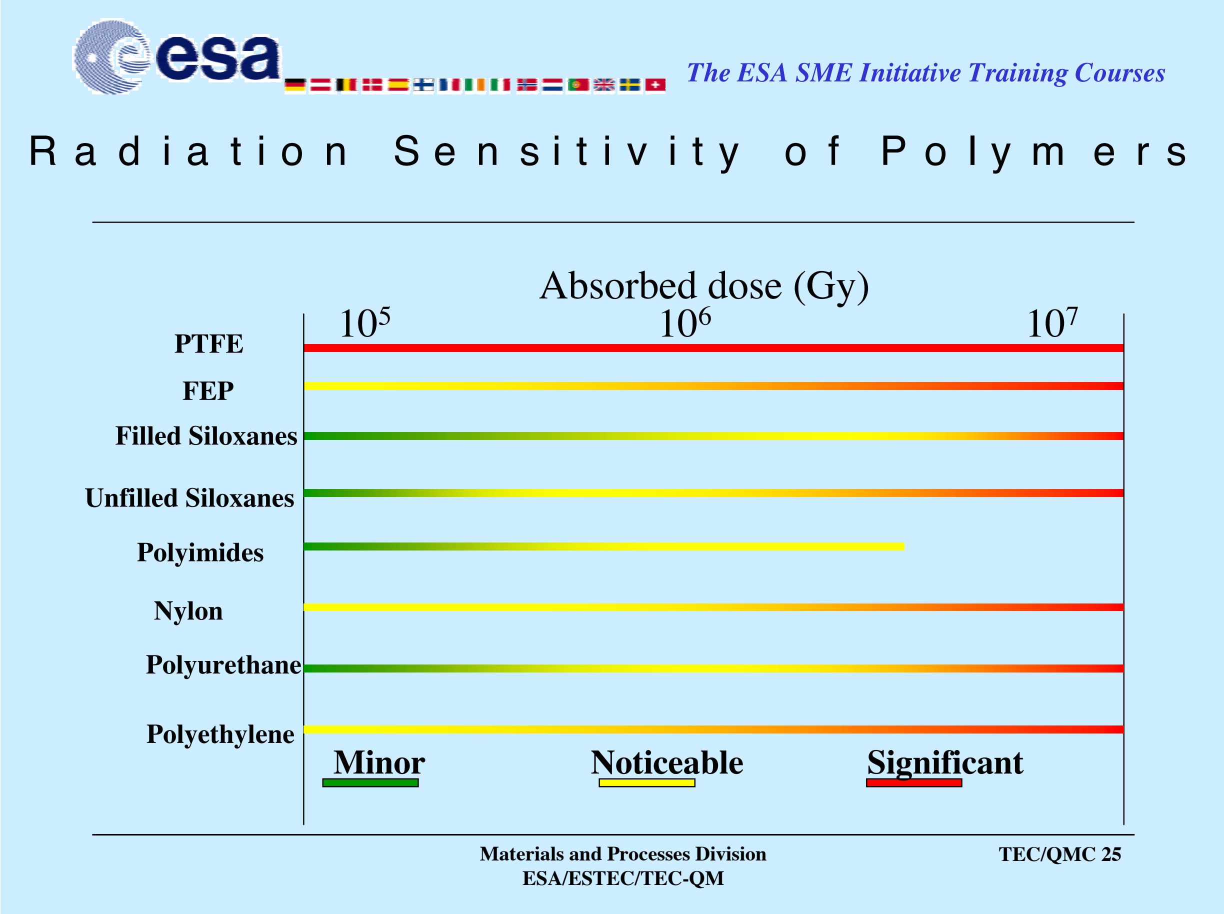
Mass attenuation coefficient: $\frac{\mu}{\rho_m}$

ρ_m mass density

x-rays,
gamma rays,
bremsstrahlung

Source: https://en.wikipedia.org/wiki/Mass_attenuation_coefficient

Ionizing Radiations: sensitivity of polymers



Source: M. Van Eesbeek, ESA/ESTEC/TOS-QM

Next week

- Theme 2 – Part 2: Environmental constrains, continued
- Theme 3: Systems Engineering, Project Management and Quality Assurance

- Exercise 2.1