Space Environment

AERO0025

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SPAT0048-4 (Q1)
Earth's atmospheric and space environment

AERO0037 (Q1)
Space optical instrumentation

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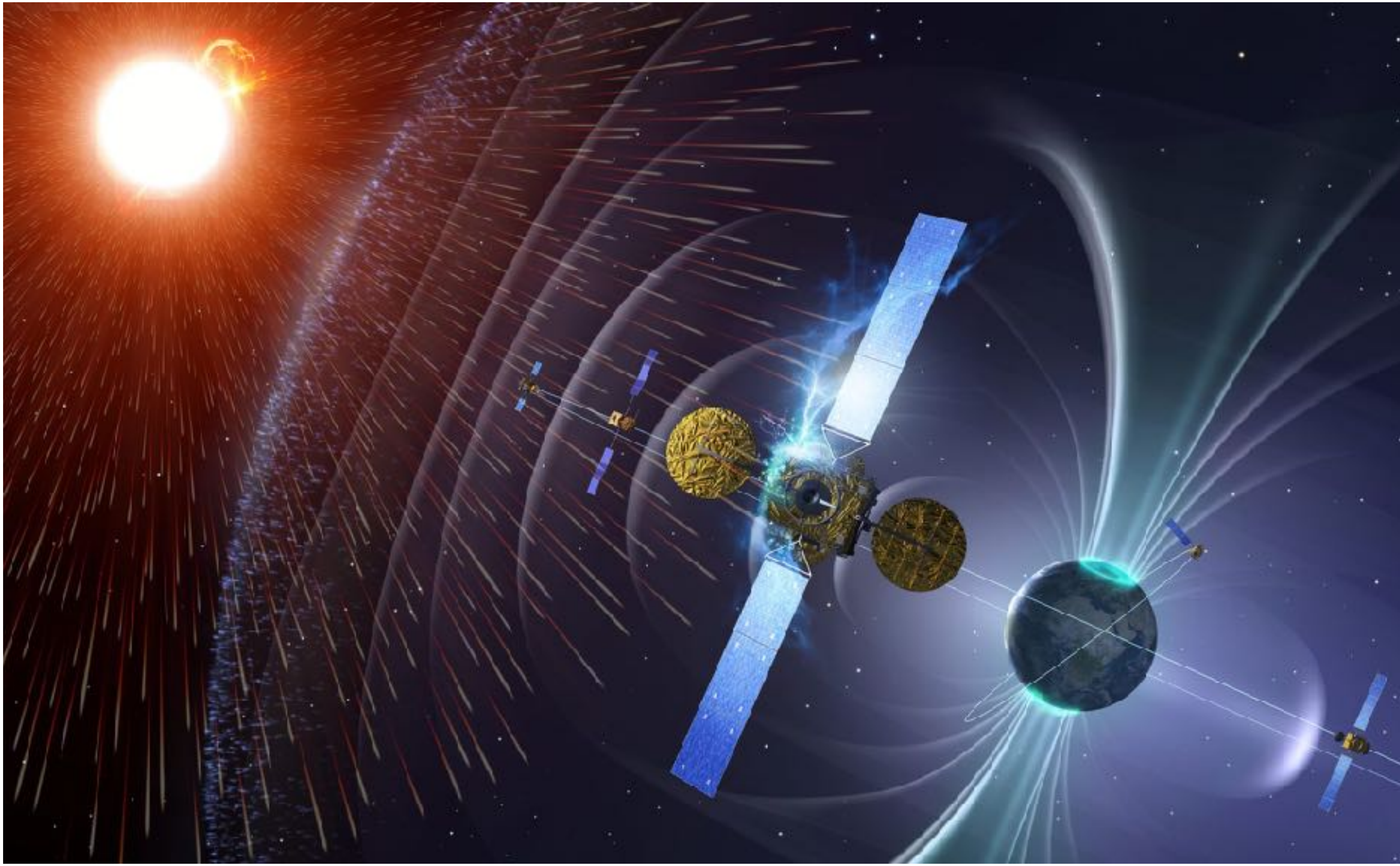
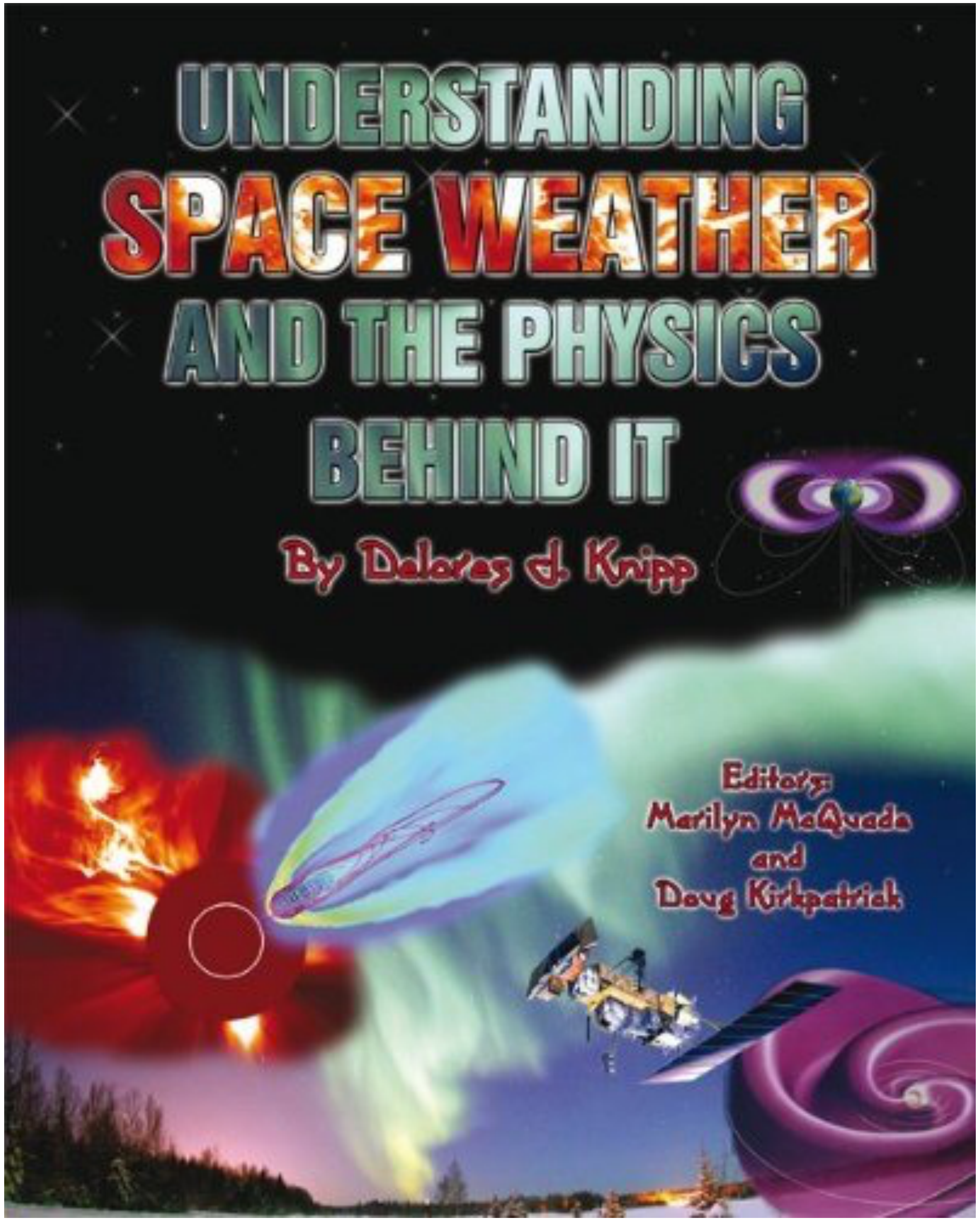
These interactions are studied in the frame of **Space Weather**

Particles, Photons, Fields



ESA-P. Carril

Reference book



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No longer edited, no electronic version
pdf 'available' on eCampus

Understanding Space Weather and the Physics Behind It

1 2 3 4 5 6 7 8 9 0 QVR QVR 13 12 11

ISBN-13: 978-0-07-340890-3
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Near-Earth Is a Place...with Susceptible Hardware and Humans

13

UNIT 3. IMPACTS AND EFFECTS OF SPACE WEATHER AND SPACE ENVIRONMENT

With Contributions by George Davenport, R. Chris Olsen, W. Kent Tobiska, Steve Johnson, Eugene Normand, AF Research Laboratory, and NOAA Space Weather Prediction Center

You should already know about...

- Energy delivered by fields, particles, and photons (Chap. 2)
- Maxwell's Equations (Chap. 4)
- Plasma motions (Chap. 6)
- Magnetospheric current systems (Chaps. 7 and 11)
- Plasma populations of the magnetosphere (Chaps. 7 and 11)
- Geomagnetic field variations (Chaps. 7 and 11)
- Thermospheric variations (Chaps. 8 and 12)
- Drivers of space weather disturbances (Chaps. 9–12)

In this chapter you will learn about...

- How geomagnetic field variations affect space- and ground-based technologies
- Ground-induced currents and their effects
- Radiation terminology and units
- Single-event effects
- How space weather affects orbiting astronauts
- Effects of energetic plasmas
- Satellite drag
- The meteor and space debris environment
- Space weather economic and societal effects

Impacts and Effects of Space Weather and Space Environment

SPAT0048-4 (Q1)
Earth's atmospheric and space environment

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Space optical instrumentation

TOC

PDF version of presentation may be downloaded from eCampus

Recorded lesson available on *Vimeo*

Exam: TBD with G. Kerschen

13.1.1 Particle Radiation Environment

Definitions

Space **Radiation**

Transfer of energy from one entity to another without a local medium

i.e. the medium is not involved in the transfer of energy

entity

(high energy) particle, photon of human / planetary / magnetic / solar / stellar / cosmic origin

effects

penetrate materials

- biological degradation (on humans/ life forms)
- solar cell degradation
- detector malfunction or degradation
- optical system degradation
- memory system alteration
- control system malfunction or failure ...

GCR or SEP

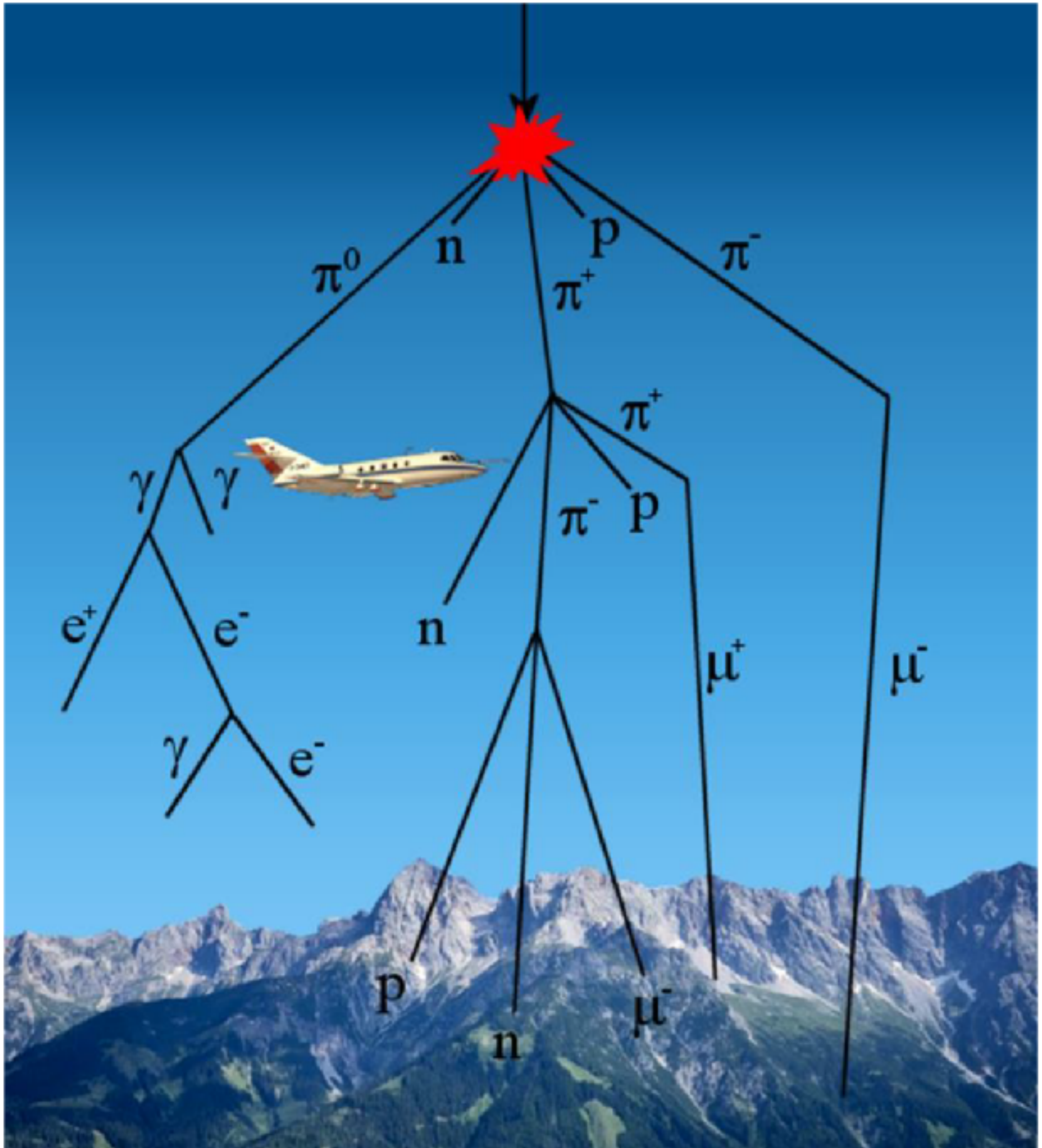


Table 13-1. Radiation Terminology. Here we list radiation types associated with the space environment and space weather effects.

Energy Carrier	Radiation Terminology
High-energy photons – (Energy > 4 eV) UV-EUV	Ionizing radiation
Very high-energy photons, X rays, and γ rays	Ionizing X-ray and gamma radiation
Neutral particles—mostly neutrons	High-energy neutrons
Electrons and positrons	Beta (β) radiation
Energetic protons	Z = 1
Energetic helium atoms, stripped of electrons	Z = 2, alpha (α) radiation
Energetic heavier atoms, many electrons missing*	High charge and energy (HZE)
By-products from nuclear reactions	Nuclear radiation or radioactivity

* The most biologically damaging component of space radiation.

Definitions

Ionizing Radiation

X + radiation -> X^+ + e^-

removes one or more electrons from an atom or molecule

Energy > "ionisation threshold"

Atome molécule	Ionisation P.I. (ev)	Longueur d'onde (Å)
He	24.6	504
H_2	15.6	795
N_2	15.6	795
N	14.54	852
CO	14.0	885
CO_2	13.8	899
O	13.6	911
H	13.6	911
O_2	12.05	1029
NO	9.25	1340

if radiation = photon

UV range
(may be blocked by a thin sheet of paper)

Energy may be much larger (particles)
few tens of keV => biologically significant

neutrons do not need to be so energetic

High energy particles penetrate deep into materials, ionising the constituent material (multiple ionisations)

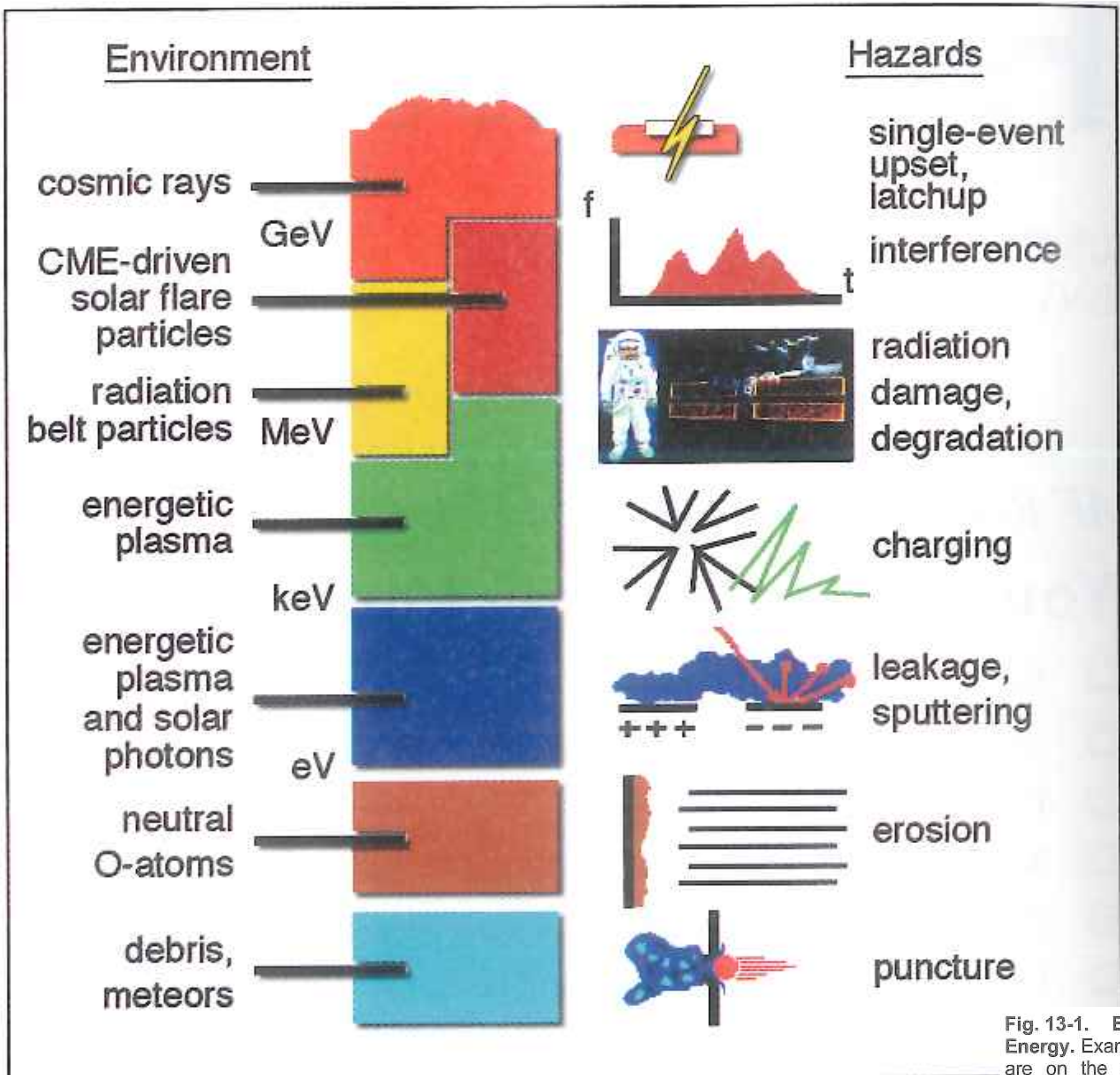
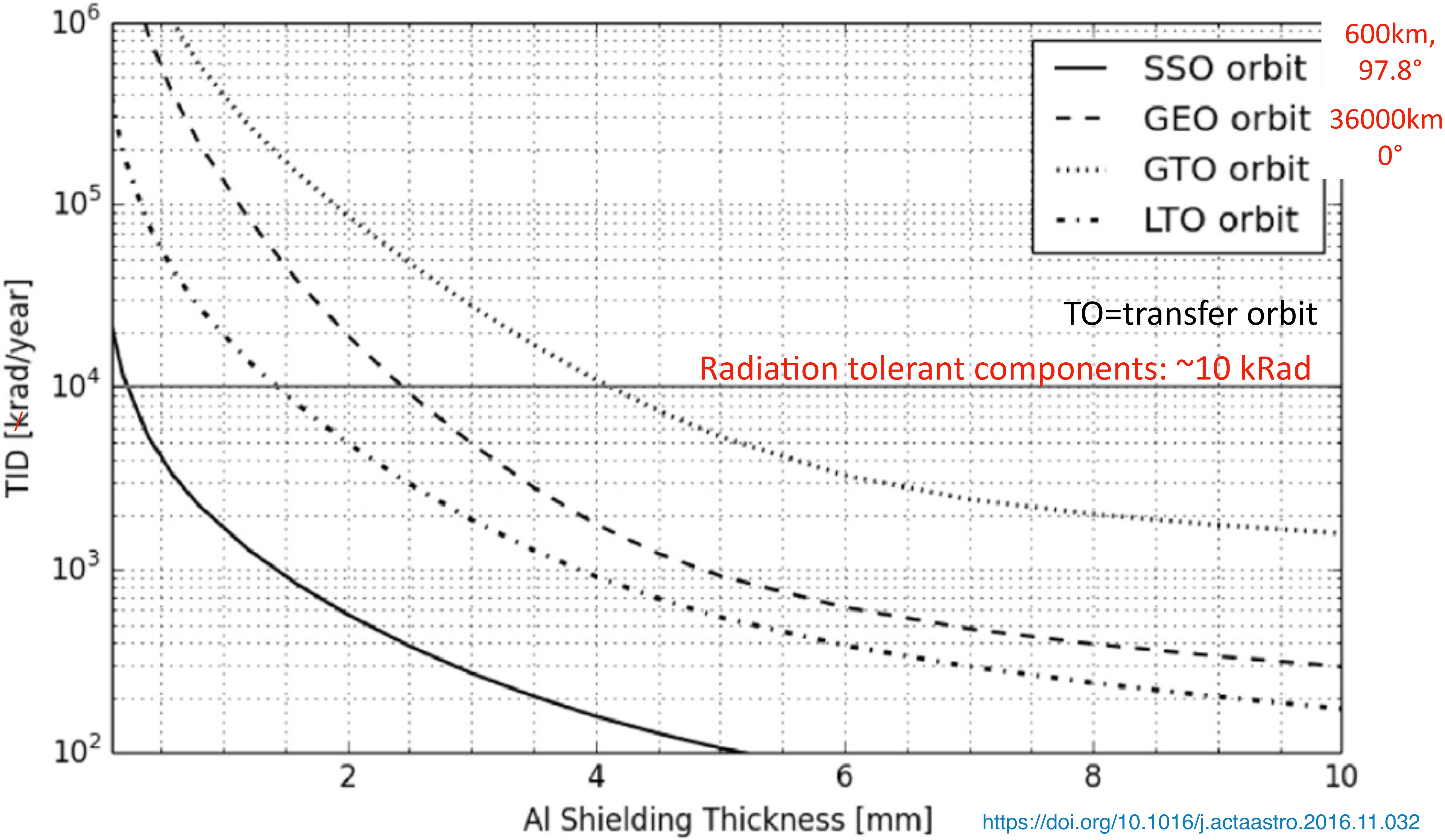


Fig. 13-1. Elements of Space Environment Hazards Sorted by Energy. Example environments are in the left column, and hazards are on the right. *(After the European Space Agency, Space Environment and Effects Analysis Section)*

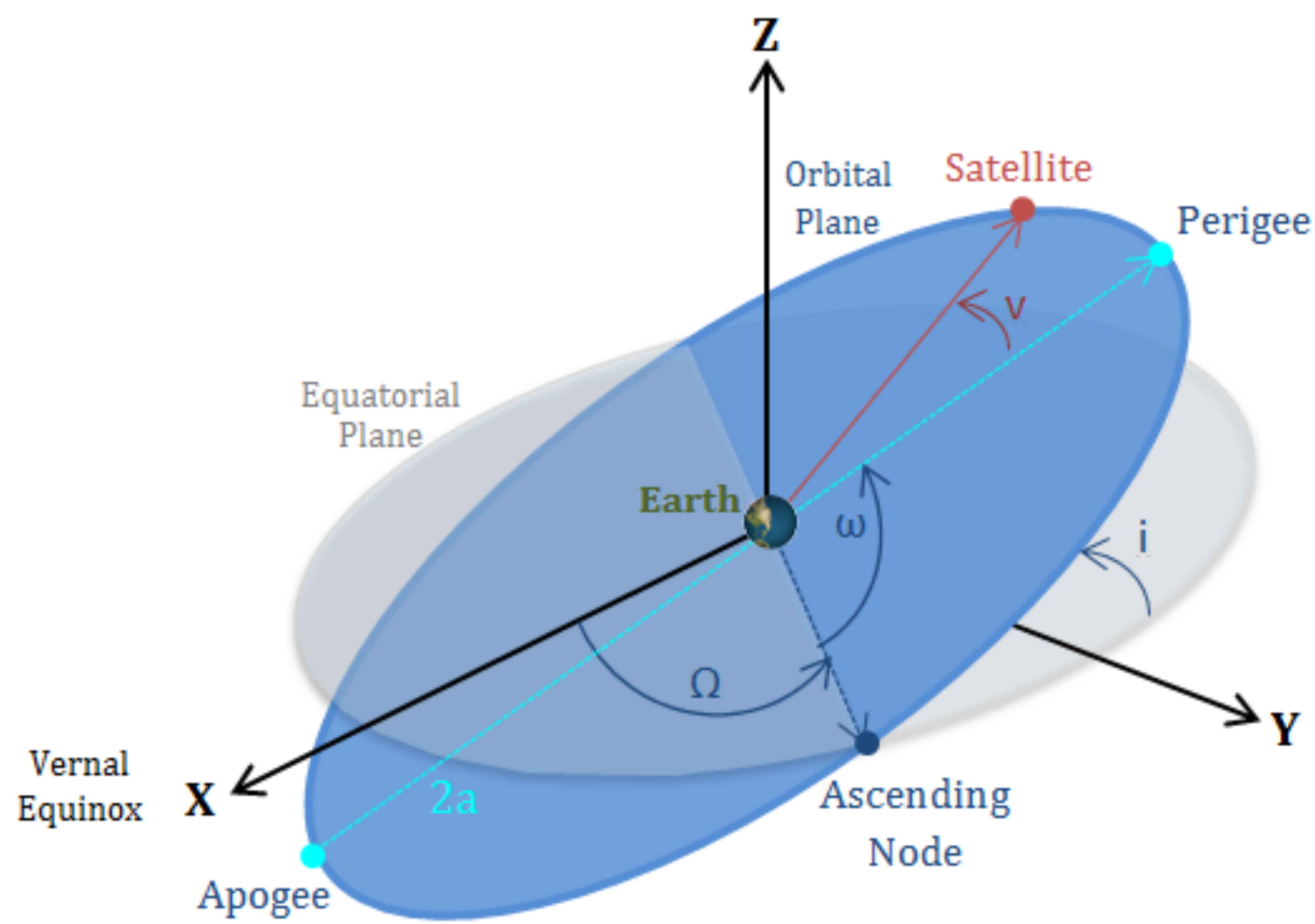
Keywords

- Cosmic rays
- CME
- Solar flare
- radiation belt
- plasma
- radiation
- solar photons
- neutral atoms
- Single Event Upset
- charging ...



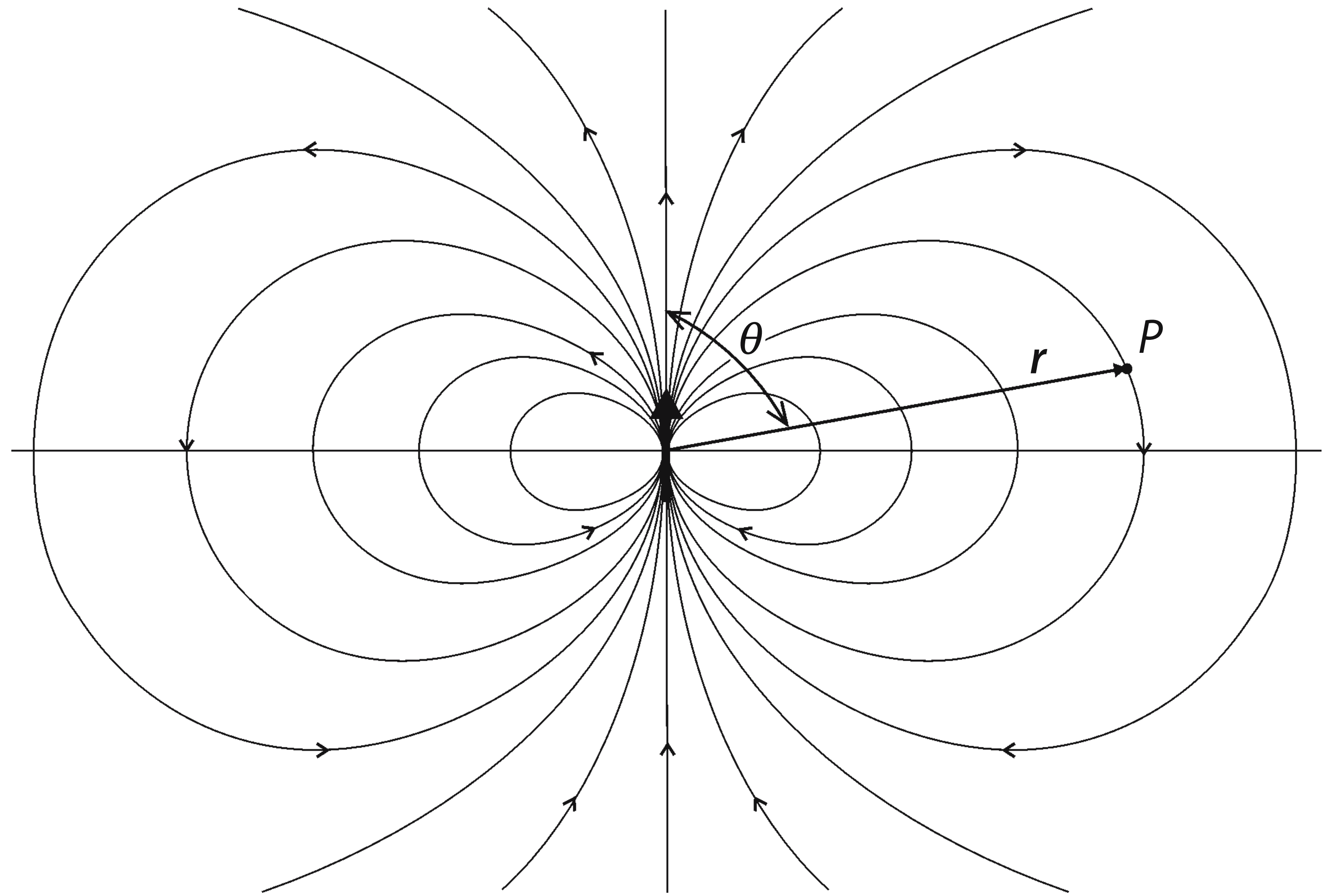
Does not work for highest energy particles
=> use natural shielding from magnetic field of Earth (and/or Sun)

Orbital inclination and geomagnetic cutoff determine the amount of radiation a spacecraft (or an astronaut) receives

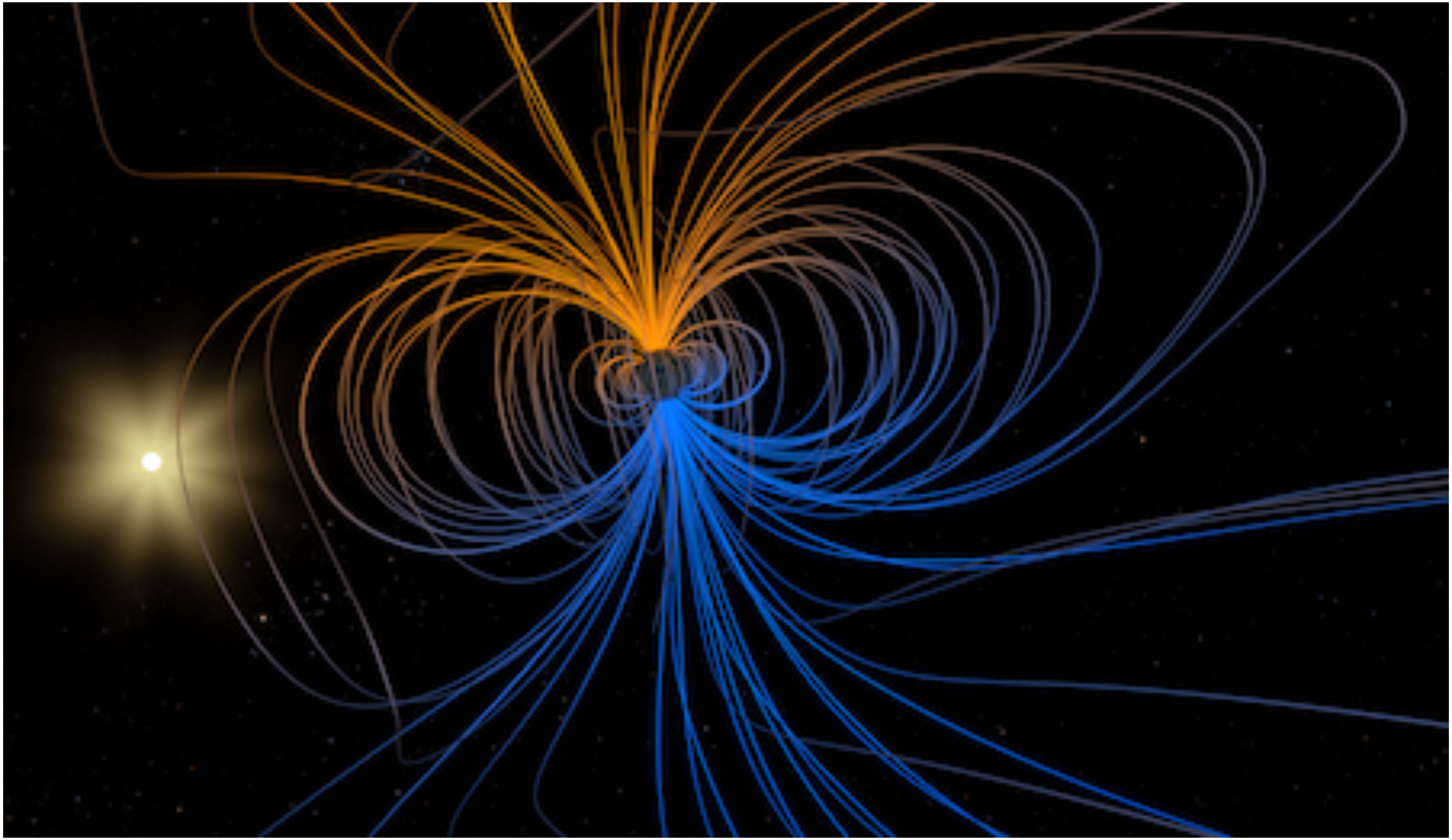


Low Earth, low inclination orbits experience high geomagnetic shielding (except SAA).
High inclination orbits traverse the polar region with "open" magnetic field lines reconnected with IMF (energetic plasma).

Fig. 1.2. Magnetic dipole field lines of force. The *arrow* indicates the magnetic dipole, ***r*** is the vector distance and θ colatitude, as referred to a point P in polar coordinates

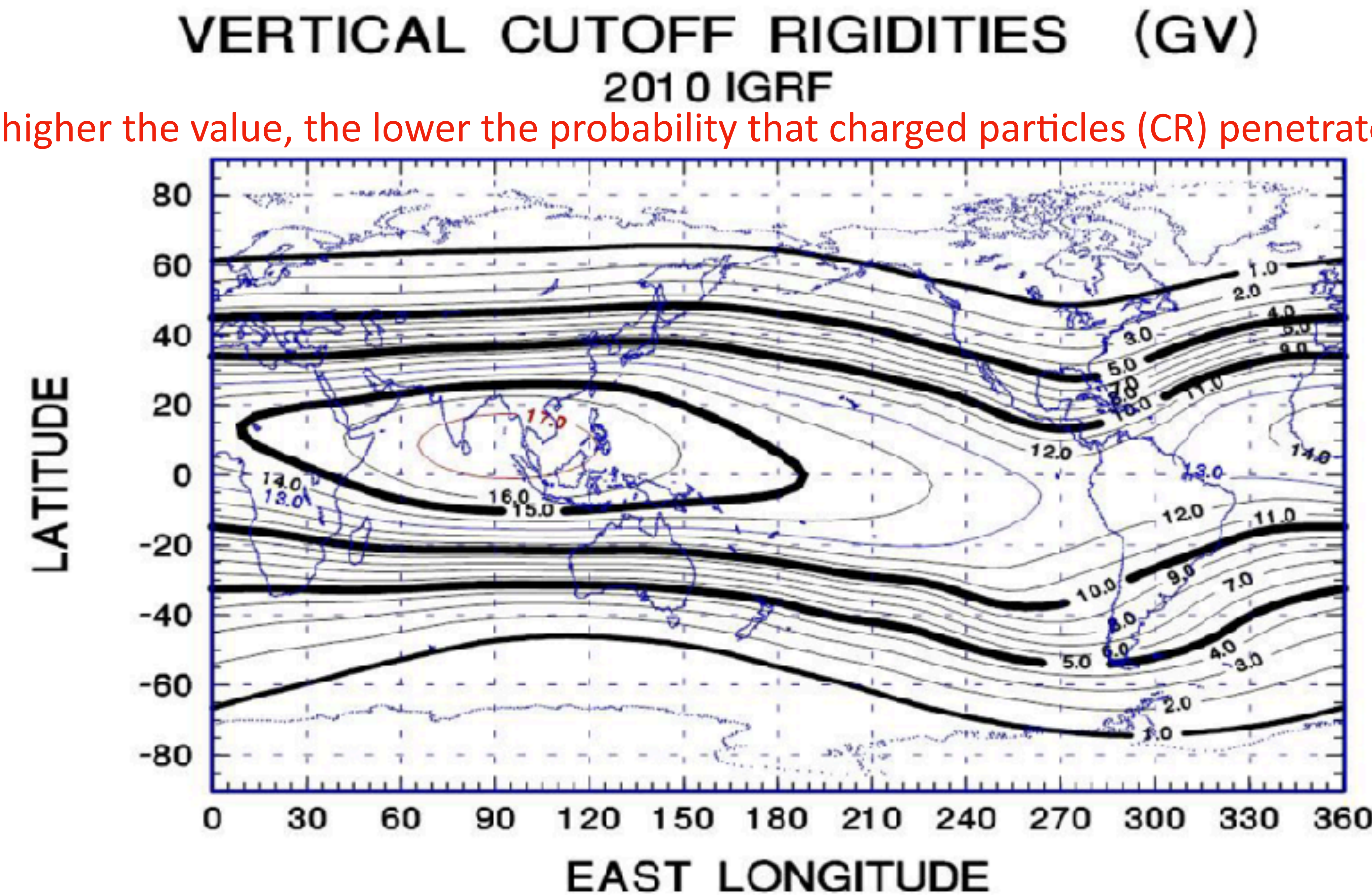


Magnetosphere = interaction of planetary magnetic field with solar wind (IMF)



Geomagnetic cutoff rigidities

Quantitative measure of the shielding provided by Earth's magnetic field



the higher the value, the lower the probability that charged particles (CR) penetrate the B field (magnetosphere)

Figure 1. *Iso-rigidity contours for vertical geomagnetic cutoff rigidities for Epoch 2010.*

https://www.faa.gov/data_research/research/med_humanfacs/oamtechreports/2010s/media/201904.pdf

Rigidity = momentum (.c) per unit charge (volts)

$$R \equiv r_L B c = \frac{pc}{Ze}$$

Charged particles with large momentum will require a stronger field to be deflected from their original trajectory.
Those that are deflected are "cut off".

Closed field lines at low latitudes are effective in limiting charged particle access.

Charged particles traversing the earth's magnetic field undergo a force that results in a curved path. The presence of non-dipole terms and the offset of the magnetic center with respect to the geocenter greatly complicates the geomagnetic cutoff problem. The higher order components of the magnetic field also complicate the problem, making the calculations more complex.

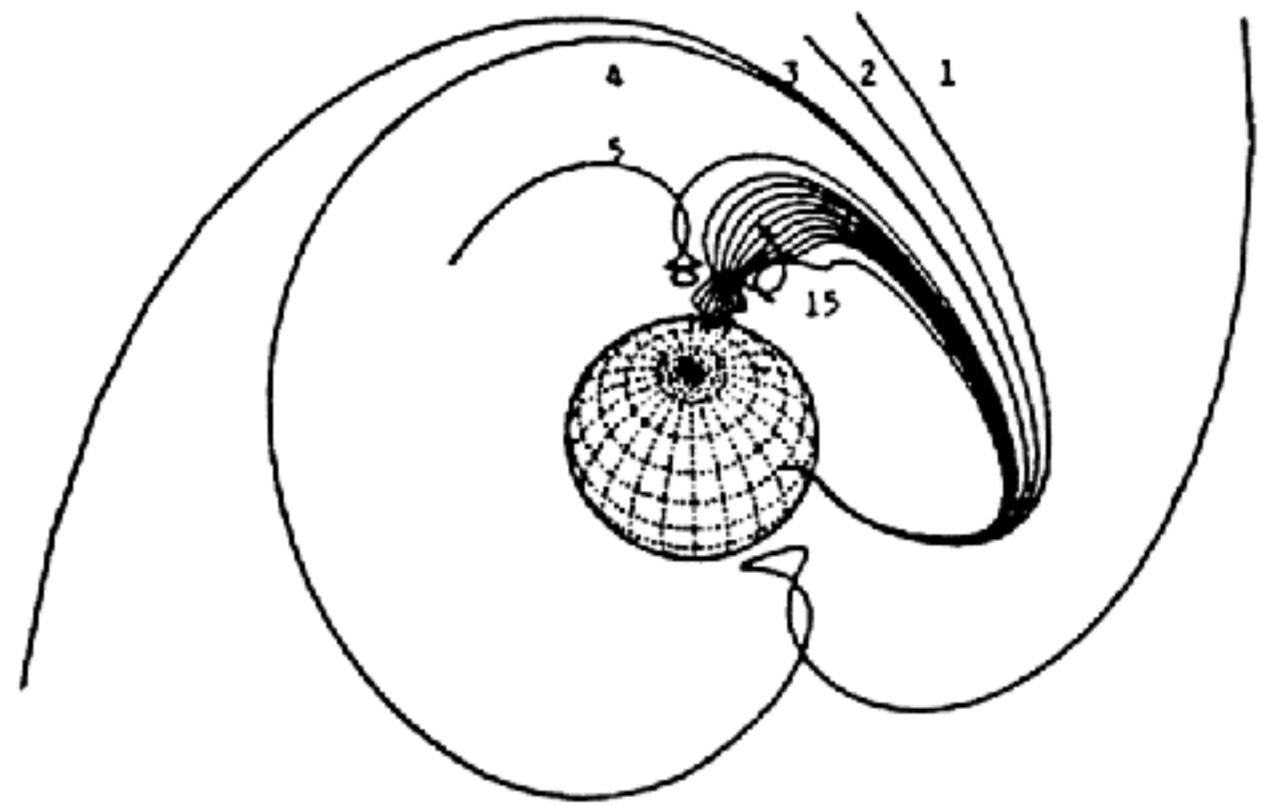


Fig. 2. Illustration of the cosmic ray trajectory-tracing process. The highest rigidity (most resistant to geomagnetic bending) is labeled 1 and the lowest rigidity is labeled 15.

doi:10.1016/j.asr.2004.09.015

Charged particle penetration and displacement

The rate at which an electron transfers energy to a material is the **Linear Energy Transfer (LET)**, and is expressed in terms of the energy transferred per unit distance traveled: typically keV μm^{-1}

The higher the LET, the more complex the cell damage it creates and the more harmful the radiation is.

The total distance a particle travels in a material before losing **all** its energy is its **range**. It depends on the particle's initial energy and material's density.

Radiation length (range) is very often given in **g cm^{-2}** units, which is density independent (liquid water and air have similar ranges). Just divide by material mass density (g cm^{-3}) to get travelled distance in **cm**

The range of a 160 MeV proton is 17.6 cm in (liquid) water.
In air it is 16700 cm (167 m).

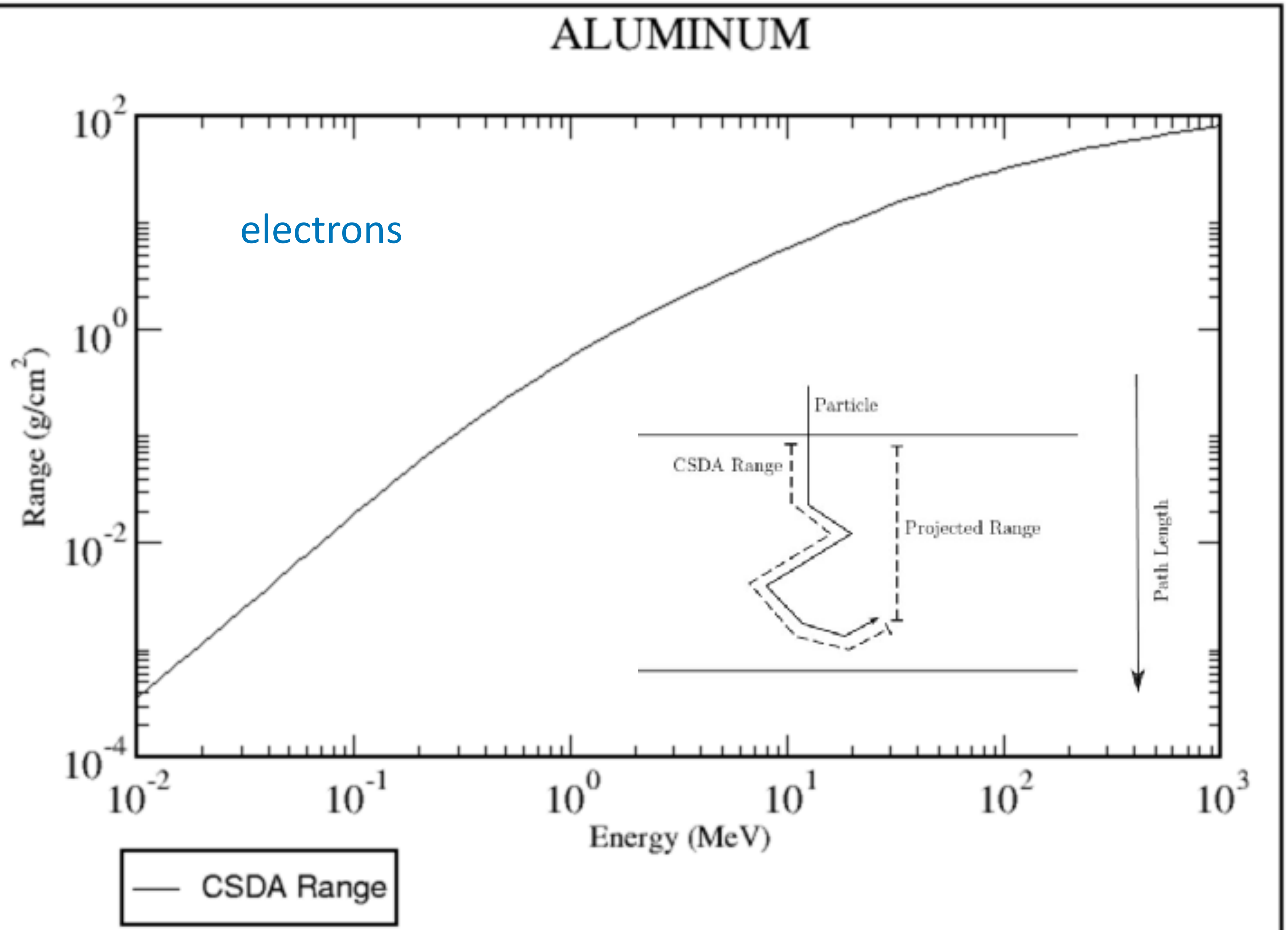
Most of this very large difference comes from the fact that air under normal conditions is a gas with a mass density of only 0.0012 g/cm^3.
Density of water is 1 g/cm^3.

Range in water = 17.6 * 1 ~ 20 g/cm^2

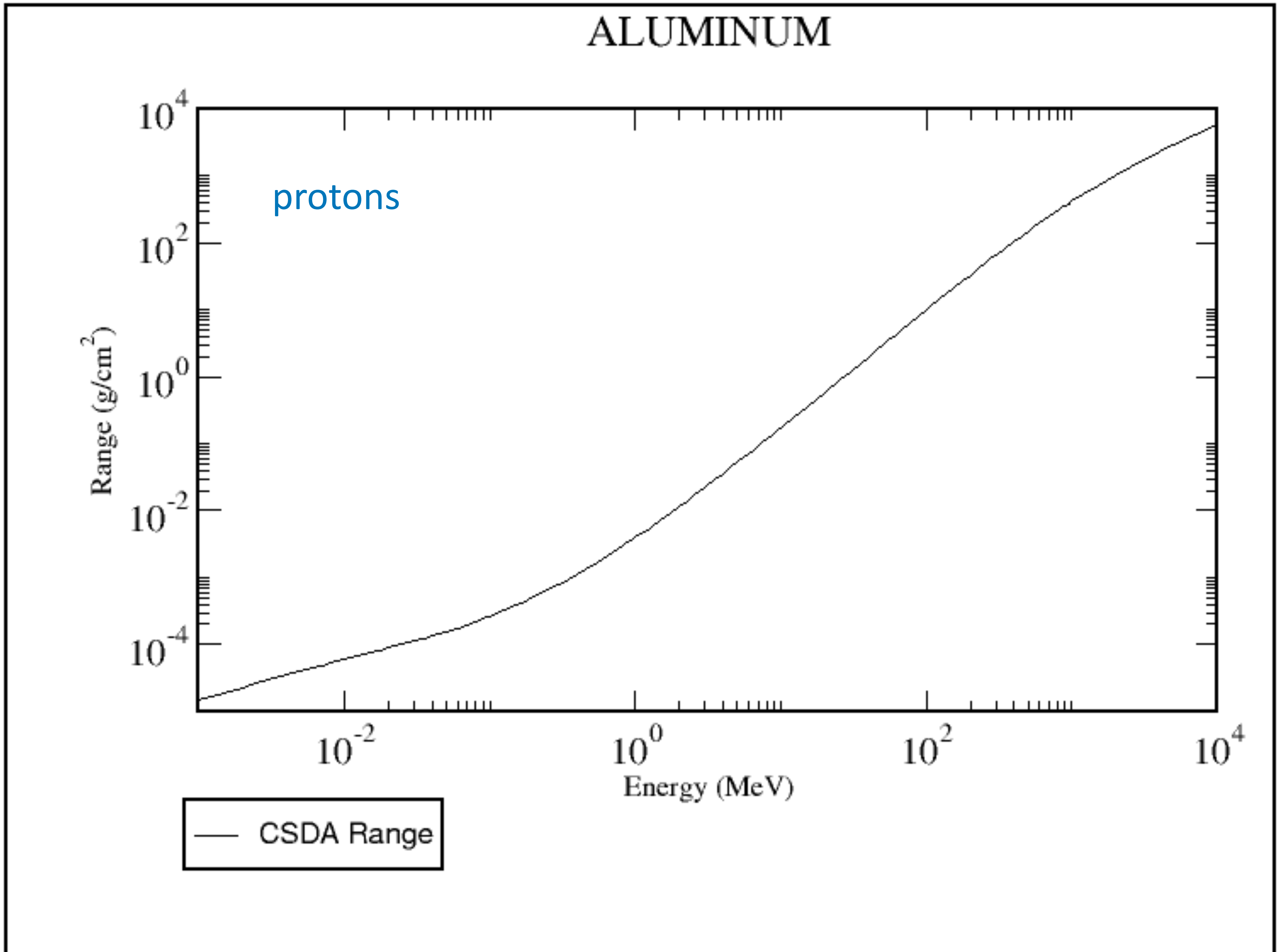
Range in air = 16700 * 0.0012 ~ 20 g/cm^2

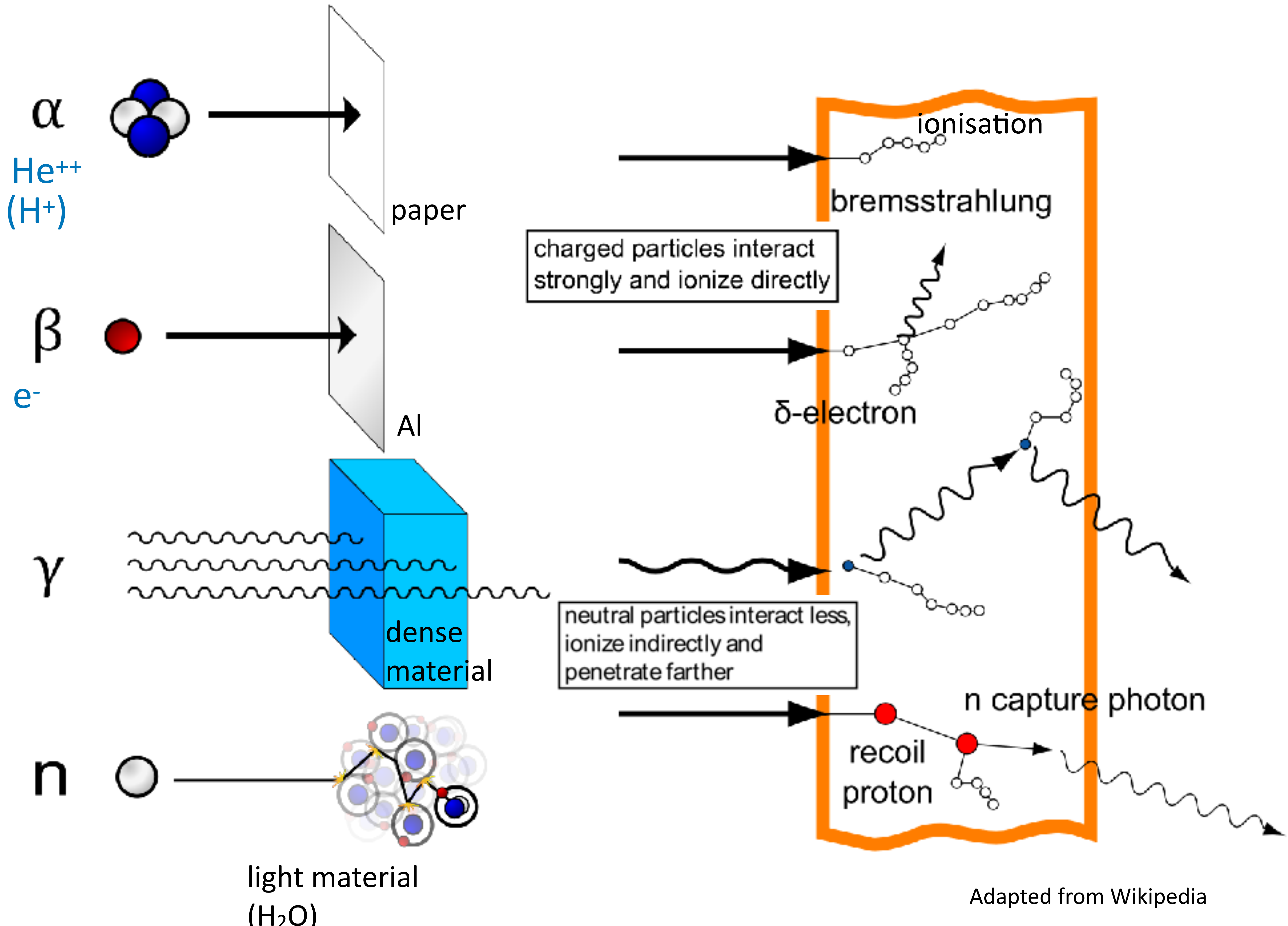
ESTAR : Stopping Power and Range Tables for Electrons

similar things for protons and He^{2+}



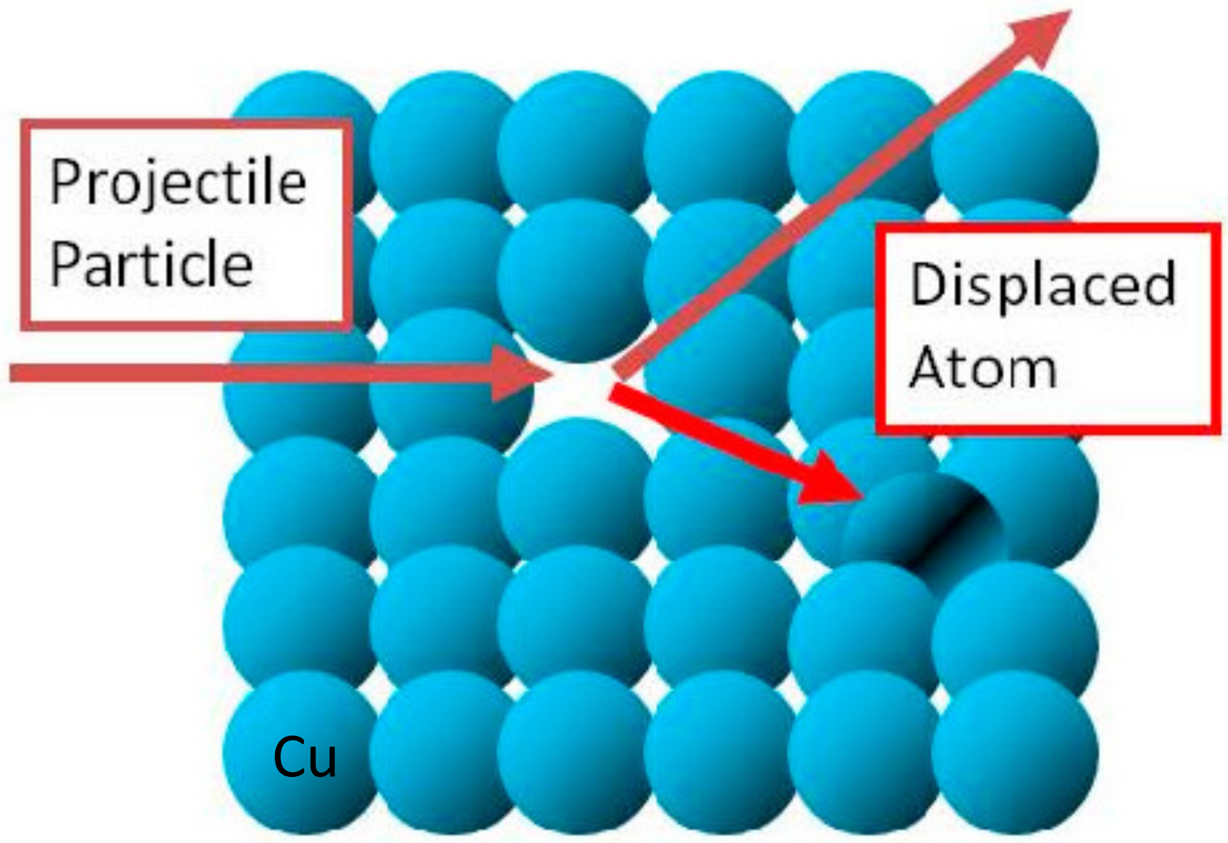
https://physics.nist.gov/PhysRefData/Star/Text/ESTAR.html


ALUMINUM
protons
Range (g/cm^2)
10^{4}
10^{2}
10^{0}
10^{-2}
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
Energy (MeV)
CSDA Range



Adapted from Wikipedia

Penetrating energetic particles may also cause **displacement** of constituent atoms from their proper crystal lattice locations
=> Defects in the crystal structure that appear as low points (wells) in the electric potential.
These wells trap conduction electrons
=> Electric resistance is increasing



https://wpo-altertechnology.com/displacement-damage-testing/

The minimum kinetic energy needed to displace an atom from its lattice site is called the **threshold displacement energy**.

Especially harmful to solar cells, where the accumulated displacement damage and increased resistance gradually reduce power output

Radiation Units

Definitions

1.1 Activity (Radio)activity

Activity is the number of radioactive events per second, typically given in becquerel (Bq) or curie (Ci). 1 Bq is defined as 1 event per second and 1 Ci is defined to be 37 GBq (approximately the activity of 1 g of ^{226}Ra):

$$\text{SI}\quad 1\,\text{Bq} = 1\,\text{events/s}$$
$$1\,\text{Ci} = 3.7\times10^{10}\,\text{events/s}$$

$$1\,\text{Ci} = 37\,\text{GBq}$$

1.2 Absorbed dose

The dose a material receives is the energy it absorbs from a radioactive source per unit mass of the dosed material. Common units of absorbed dose are the gray (Gy) and rad, defined as follows:

$$\text{SI}\quad 1\,\text{Gy} = 1\,\text{J/kg}$$
$$1\,\text{rad} = 100\,\text{ergs/g}$$ radiation absorbed dose (rad) 1erg=10^{-7}J

$$1\,\text{Gy} = 100\,\text{rads}$$

The **dose** refers to the amount of energy deposited by radiation in specific materials through ionisation

Total Ionising Dose (TID)

http://www.doylegroup.harvard.edu/wiki/images/f/f7/Radiation_units_and_limits.pdf

1.3 Exposure

Exposure characterizes the level of radioactivity in some area independently of the material the radiation is incident on, unlike absorbed dose. One exposure unit (X unit) is the quantity of X- or gamma radiation that ionizes 1 C of total charge in a kilogram of air. The more commonly used exposure unit is the roentgen (R), defined to ionize 1 statcoulomb of total charge in a cubic centimeter of standard air:

$$\begin{aligned} 1\,\mathrm{X\ unit} &= 1\,\mathrm{C/kg\ air} \\ 1\,\mathrm{R} &= 1\,\mathrm{SC/cm^3\ air} \\ \\ 1\,\mathrm{X\ unit} &= 3881\,\mathrm{R} \end{aligned}$$

To convert between from exposure in R to absorbed dose in rads for a general material m, the exposure must be scaled by the ratio $0.877(\mu/\rho)_m/(\mu/\rho)_{air}$, as in Cember Eq. 6.12. Here μ is the energy absorption coefficient (the inverse of the absorption length) and ρ is the material density. In general, μ depends on the radiation type and energy.

1.4 Equivalent dose (Dose equivalent)

Dose equivalent normalizes each type of radiation to its propensity to cause biological damage, or its relative biological effectiveness (RBE). It is computed as

$$\text{Dose equivalent } H = \text{absorbed dose } D \times \text{quality factor } Q.$$

Quality Factor (Q) considers the type of radiation and its energy that together alter the biological effect in terms of the cancer risk. For x-rays, gamma rays, and beta rays, $Q = 1$; for alpha particles, $Q = 20$. The SI unit of equivalent dose is the sievert (Sv), defined to be the dose equivalent of 1 Gy for radiation with a quality factor $Q = 1$. The more common unit is the roentgen equivalent in man (rem), defined to be 0.01 Sv so that 1 roentgen deposits approximately 1 rem in human biological soft tissue:

$$\begin{aligned} 1\,\text{Sv} &= 1\,\text{Gy with } Q = 1 \\ 1\,\text{rem} &= 0.01\,\text{Sv} \end{aligned}$$

$$\begin{aligned} 1\,\text{rem} &\leftrightarrow 1\,\text{rad (x-rays)} \\ 1\,\text{rem} &\leftrightarrow 0.877\,\text{R (x-rays, air)} \end{aligned}$$

The effective dose takes into account the amount of energy the radiation deposits in the different tissues, the harmfulness of the radiation type and the sensitivity of the exposed tissues and is proportional to the chance for developing radiation-induced cancer. Based on epidemiological studies this chance is estimated at about 5% per sievert.

Radiation Sources

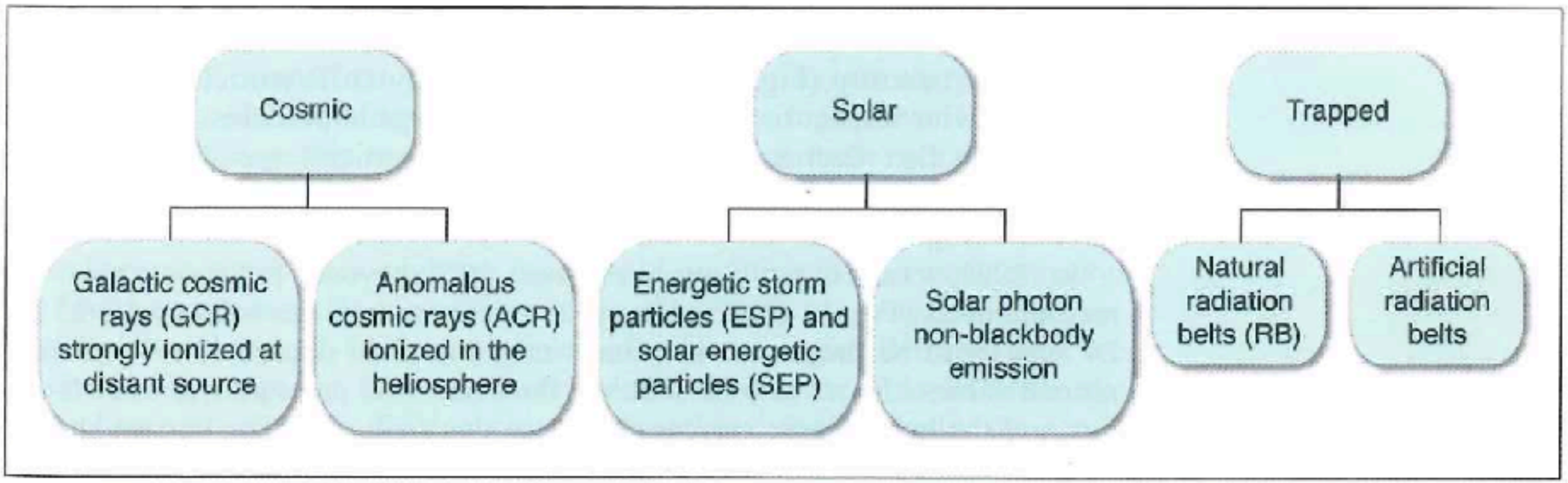


Fig. 13-4. Radiation Sources for the Space Environment. These are the three main sources of radiation that affect our lives on and near Earth.

Table 13-3. Properties of Energetic Particle and Photon Populations. This table lists the key properties of energetic particles and photons. (GCR is galactic cosmic ray; ACR is anomalous cosmic ray; SEP is solar energetic particle; ESP is energetic storm particle; CIR is co-rotating interaction region.) The spatial scales are referenced to the size of the heliosphere. Global scales involve the entire heliosphere, local scale is on the order of interplanetary distances. *(Courtesy of Margaret Ann Shea at the AF Research Laboratory)*

At room temperature, particles have thermal energies ~ 0.025 eV (kT)

Population	Temporal Scales	Spatial Scales	Energy Range*	Acceleration Mechanism
GCR H^+, He^{++}	Continuous	Global	GeV–TeV	Supernova shock
ACR O^+, N^+, Ne^+, He^+	Continuous	Global	10 MeV–100 MeV	Diffusive shock—heliosheath
SEP Solar flares	Seconds to hours	Local to large	keV–100 MeV e^-, H^+, He^{++} + heavier ions	Reconnection, shock stochastic heating
ESP CME shocks	Days	Large	keV–10 MeV	Diffusive shock and shock drift
CIR	27 days	Large	keV–10 MeV	Diffusive shock
Bow Shock	Continuous	Local	keV–MeV	Shock drift
Artificial	Rare	Local	keV–MeV	Nuclear detonation
X ray, γ ray	Minutes	Local (solar)	keV–MeV	Reconnection, nuclear reactions

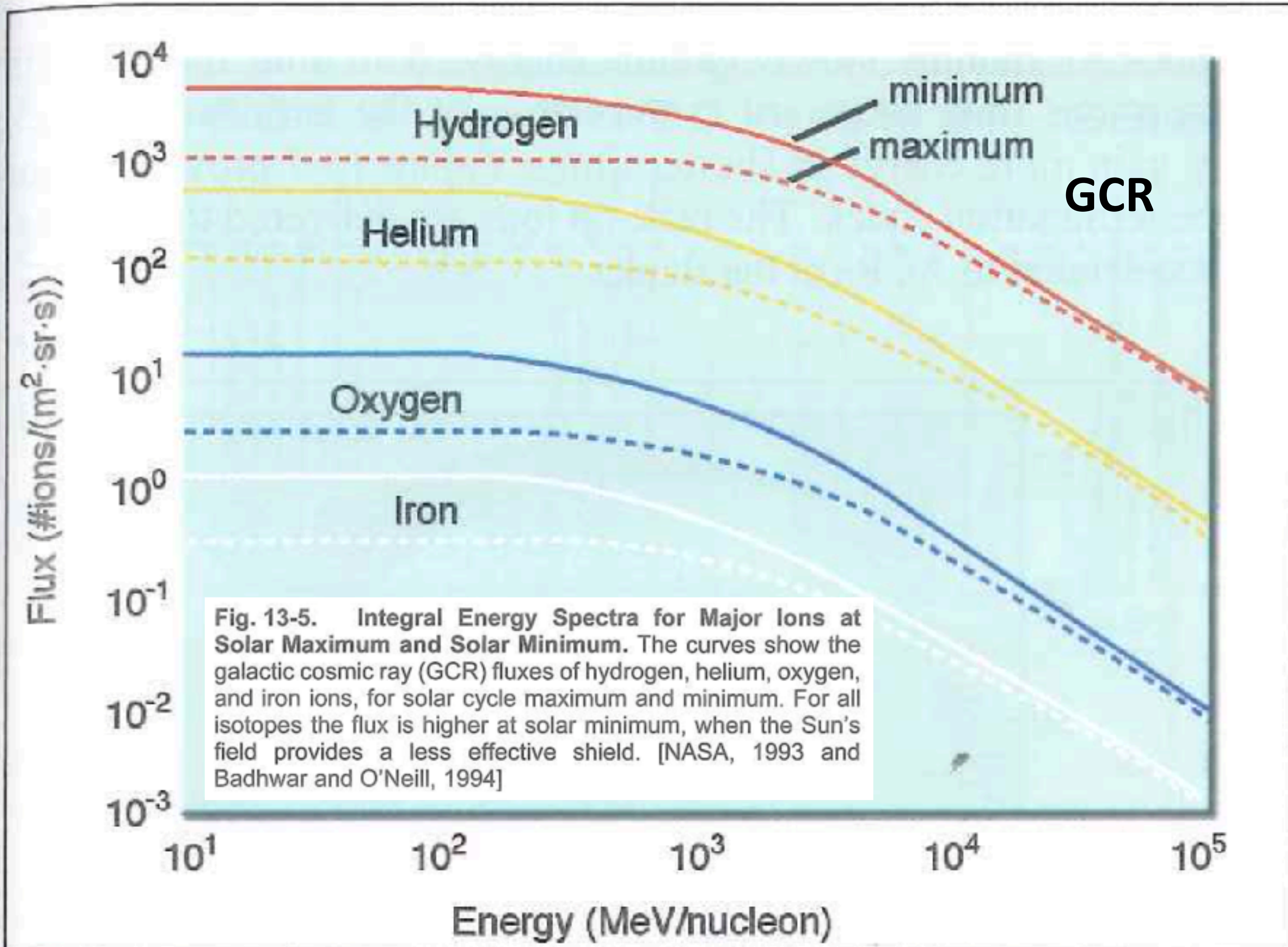
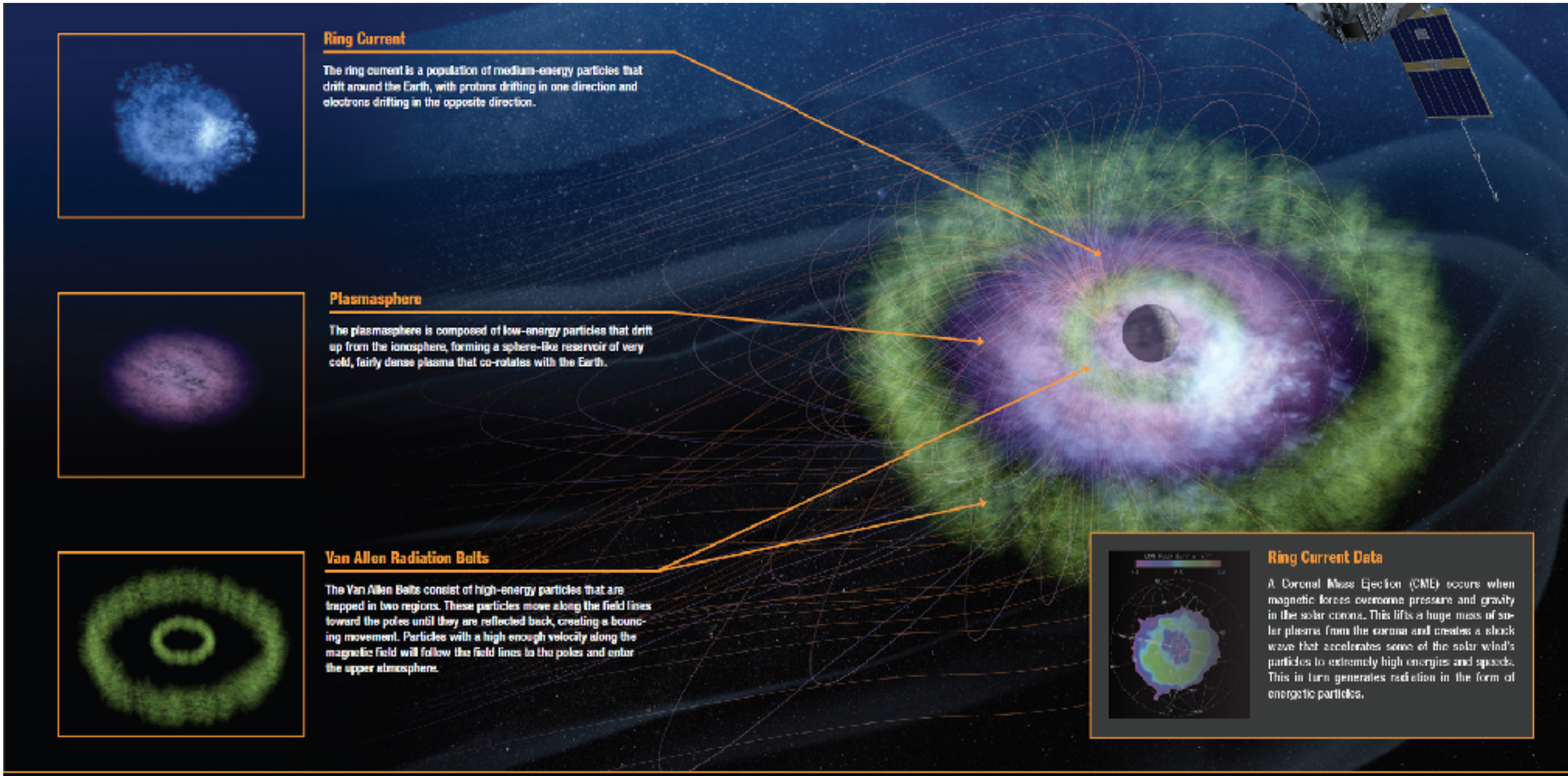


Fig. 13-5. Integral Energy Spectra for Major Ions at Solar Maximum and Solar Minimum. The curves show the galactic cosmic ray (GCR) fluxes of hydrogen, helium, oxygen, and iron ions, for solar cycle maximum and minimum. For all isotopes the flux is higher at solar minimum, when the Sun's field provides a less effective shield. [NASA, 1993 and Badhwar and O'Neill, 1994]

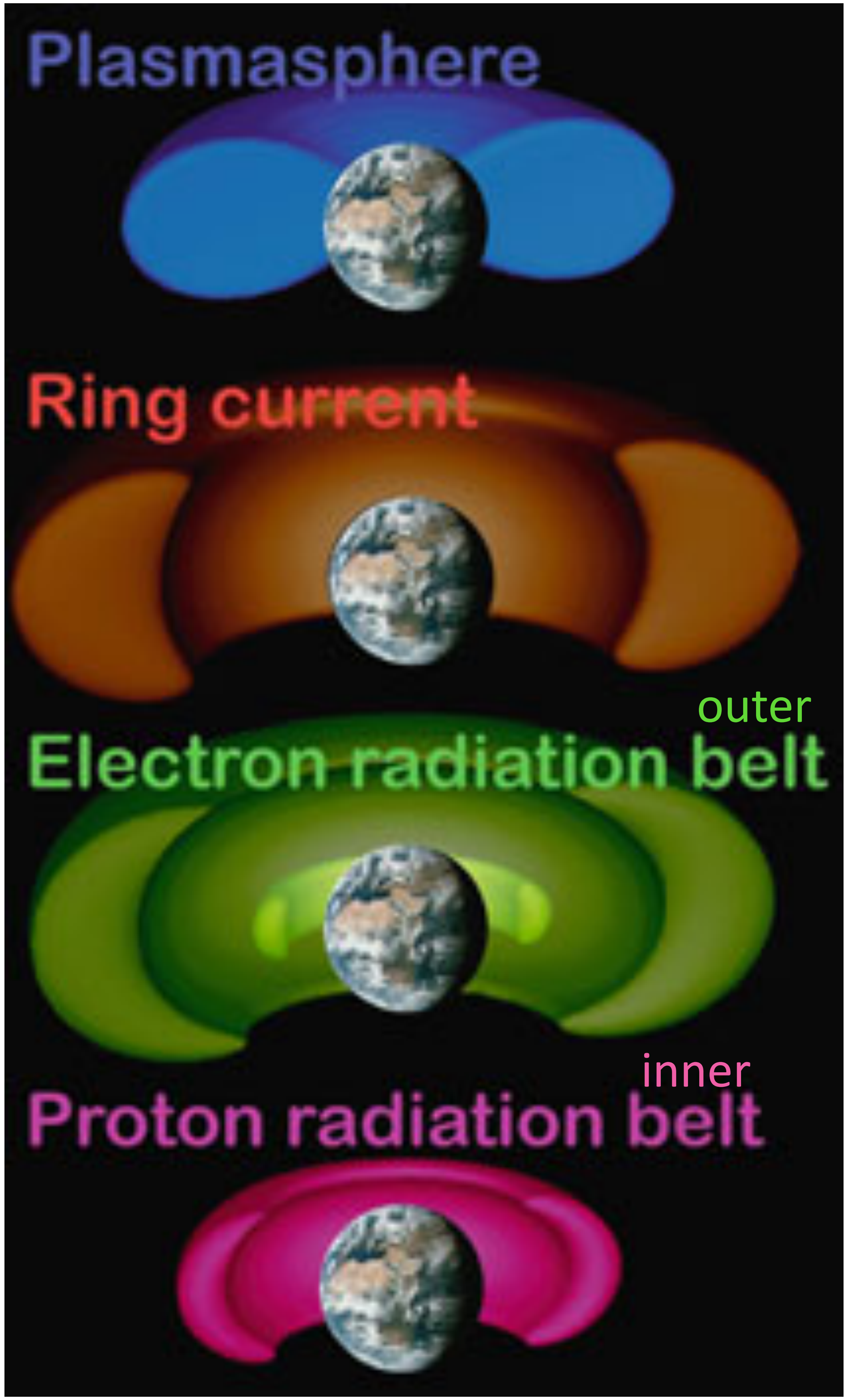
Trapped particles in the Inner Magnetosphere

~ r < 6 R_E (GEO)

is a natural cavity in which various types of charged particles are **trapped by Earth's intrinsic magnetic field.** The kinetic energy of these trapped particles ranges from ~eV to ~10^8 eV.



https://www.nasa.gov/mission_pages/sunearth/science/inner-mag-mos.html



The **inner magnetosphere** is composed of three populations of charged particles that are trapped in the Earth's magnetic field.

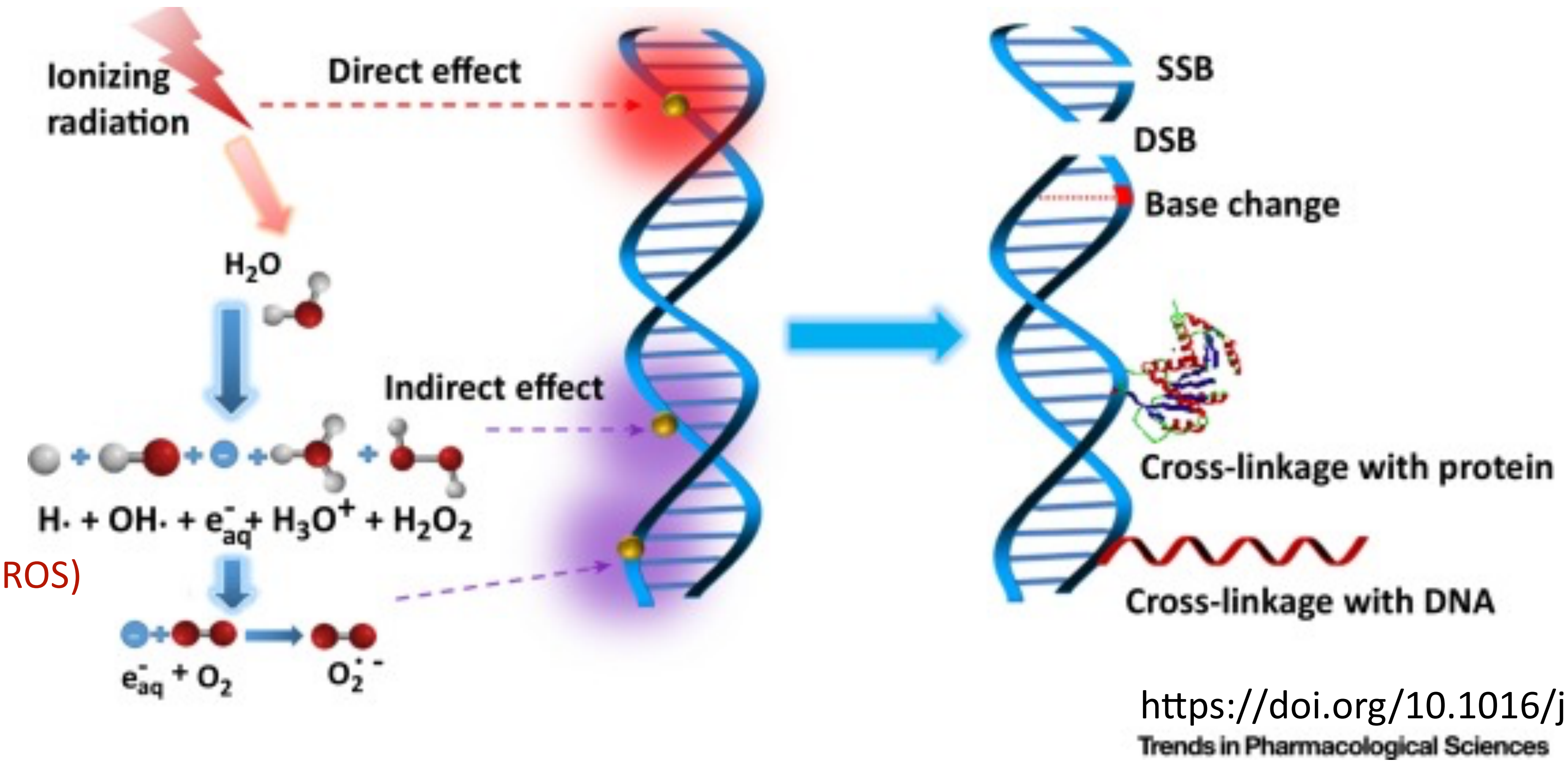
Plasmasphere: low-energy (eV) particles that drift up from the *ionosphere*, forming a reservoir of very cold, fairly dense plasma that co-rotates with the Earth.

Ring Current: population of medium-energy (1-100 keV) particles that *drift* around the Earth, with protons drifting in one direction and electrons drifting in the opposite direction.

Van Allen Radiation Belts: high-energy (> 100 keV) particles that are *trapped* in two regions. These particles move along the field lines toward the poles until they are reflected back, creating a bouncing movement.

13.1.2 Energetic Particle Radiation Environment for Humans and Hardware

Particle Radiation Environment--Physical Damage and impacts to Humans



https://doi.org/10.1016/j.tips.2017.11.003

- An energetic charged particle passing through a living cell produces a region of dense ionisation along its track. The ionisation of water and other cell components damages DNA molecules near the particle path and otherwise compromises cell chemistry, thus inhibiting cell function.
- Direct hits to DNA molecules do even more damages (SSB, DSB).

Ionising Radiation (IR) directly damages DNA (direct effect) and also damages DNA by indirect effects in which IR dissociates the water molecules to generate reactive oxygen species (ROS), and then, the ROS damage DNA. There are several types of DNA damage, such as single-strand break (SSB), double-strand break (DSB), base damage, cross-linking with protein or another DNA molecule.

Table 13-4. Recommended Limits to Radiation Exposure in Equivalent Dose. Here we list the maximum allowed dose of radiation for humans in various types of exposure. [US Nuclear Regulatory Commission, Part 20]

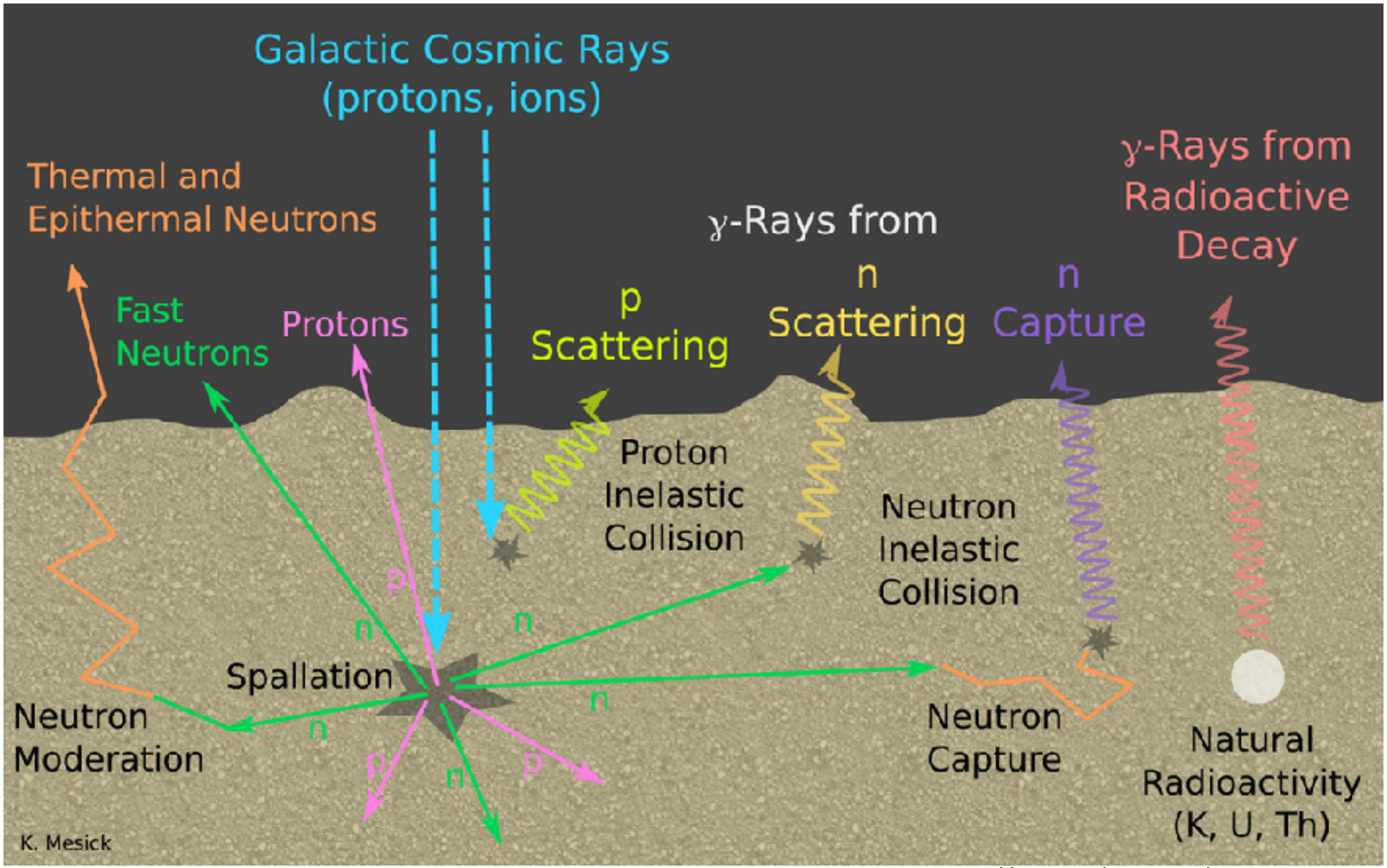
Exposure	Maximum Dose (Sv)	Equivalent Dose (rem)
Occupational exposure	50 mSv in one year	~5 rem in one year
Astronaut exposure	50 mSv in one year	~5 rem in one year
Public exposure in the US	5 mSv in one year	~0.5 rem in one year
Early-fetus exposure	0.5 mSv/month	~0.05 rem in one month
Average chest X ray	0.01 mSv–0.05 mSv	~0.001 rem–0.005 rem
Natural background	~3 mSv in one year	~0.3 rem in one year

1 rem = 0.01 Sv

Though the total dose from GCRs is small, their high energies allow them to penetrate most surfaces easily. During solar minimum, the unshielded interplanetary dose to the blood-forming organs (BFO) in astronauts is approximately 0.6 Sv/year (>>0.05)

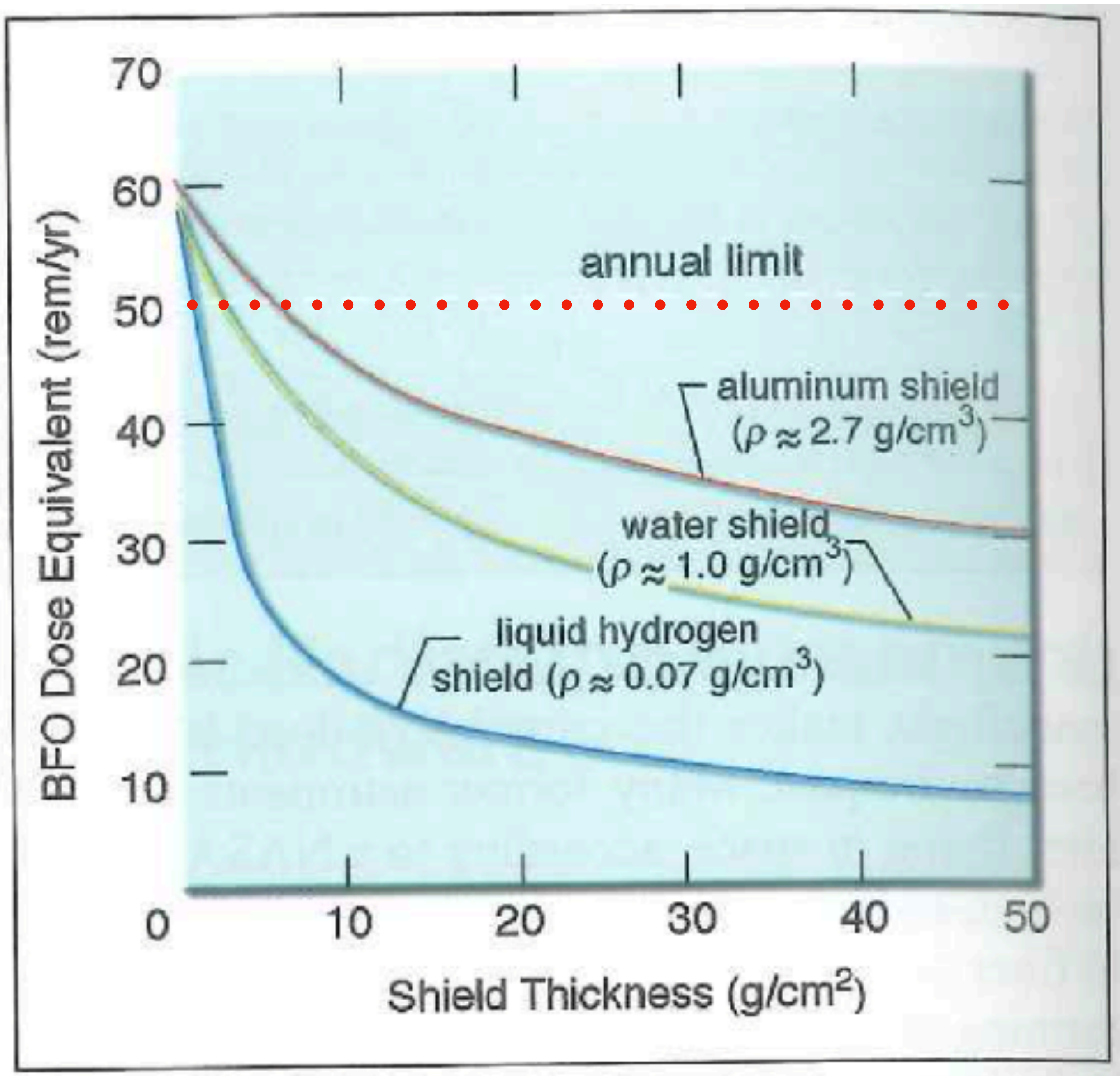
=> use shielding!

Thin to moderate shielding is effective in reducing the projected equivalent dose rate, but increasing shield thickness beyond this does little to improve its effectiveness. This is because of the large number of secondary particles, including neutrons, produced (in all directions) from nuclear interactions between GCRs and and shield nuclei

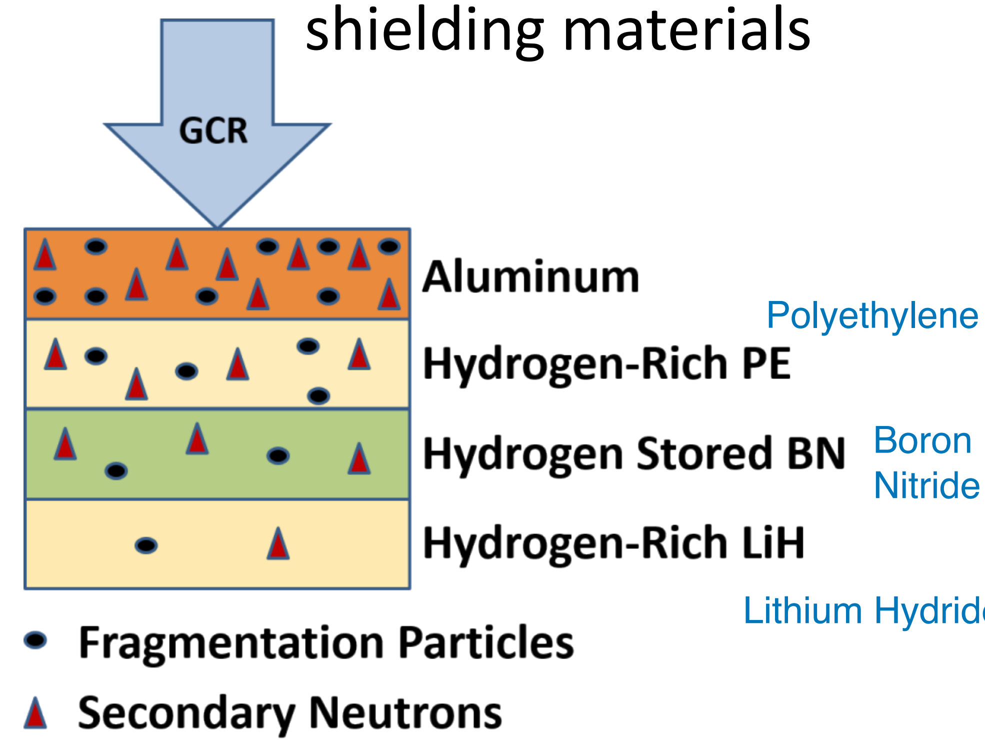


https://doi.org/10.1029/2018EA000400

Fig. 13-9. Material Shielding Effectiveness against Galactic Cosmic Rays (GCRs) at Solar Minimum. This plot shows how well aluminum, water, and liquid hydrogen shield blood-forming organs (BFO) against GCRs. [NASA, 1993]



Use complex Multi-layered shielding materials



https://doi.org/10.1016/j.radphyschem.2022.110131

Typical shielding capacities

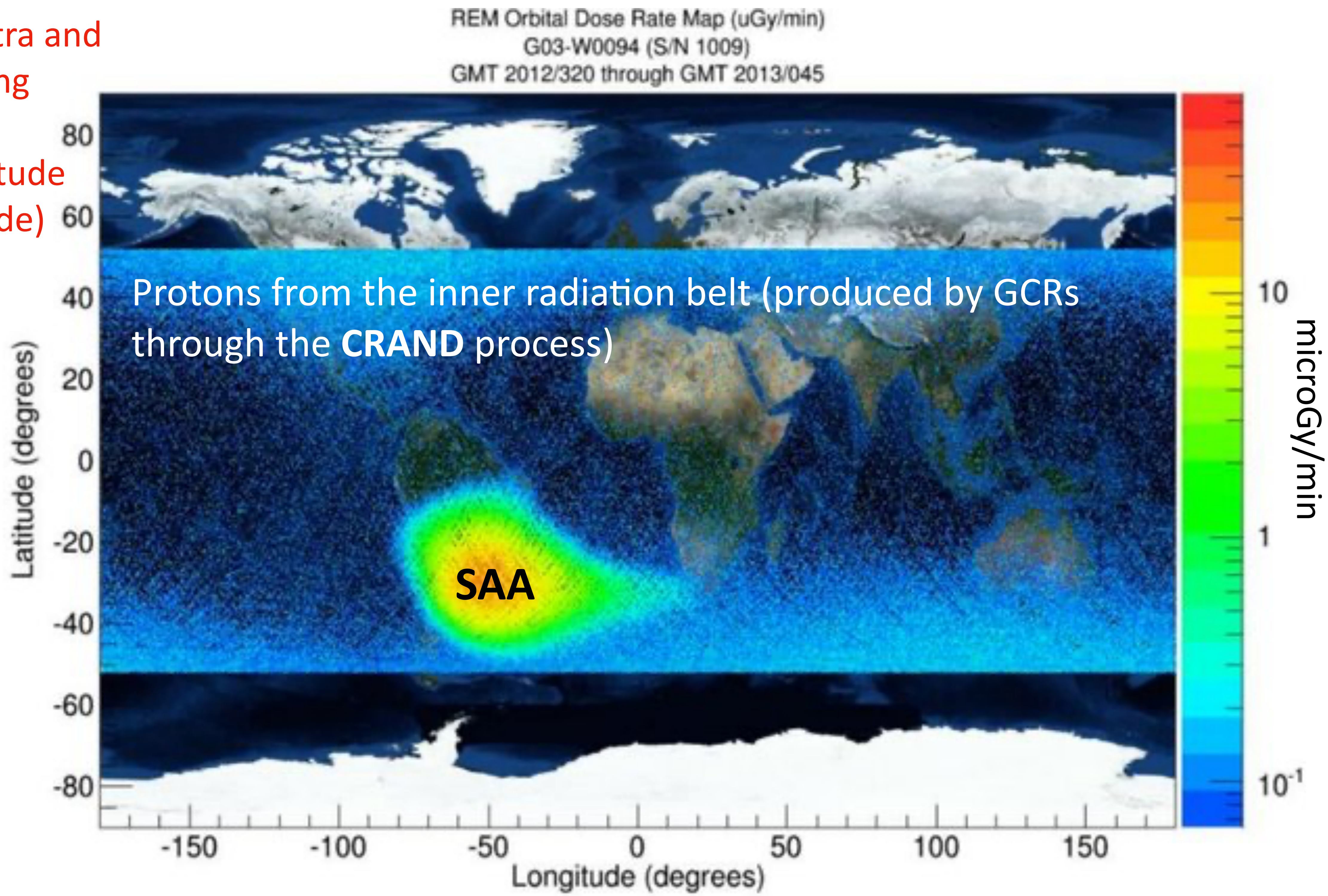
- Space suit: 0.25 g cm^{-2}
- Apollo command module: 7-8 g cm^{-2}
- ISS (most heavily shielded areas): 15 g cm^{-2}
- Future Moon bases shelters: 20 g cm^{-2}

Adjust thickness according to used material density

During a large solar storm (hours), an astronaut walking on the Moon may absorb 4 Sv of radiation dose (BFO), 10x less in the command module.
Limit is 0.05 Sv/year

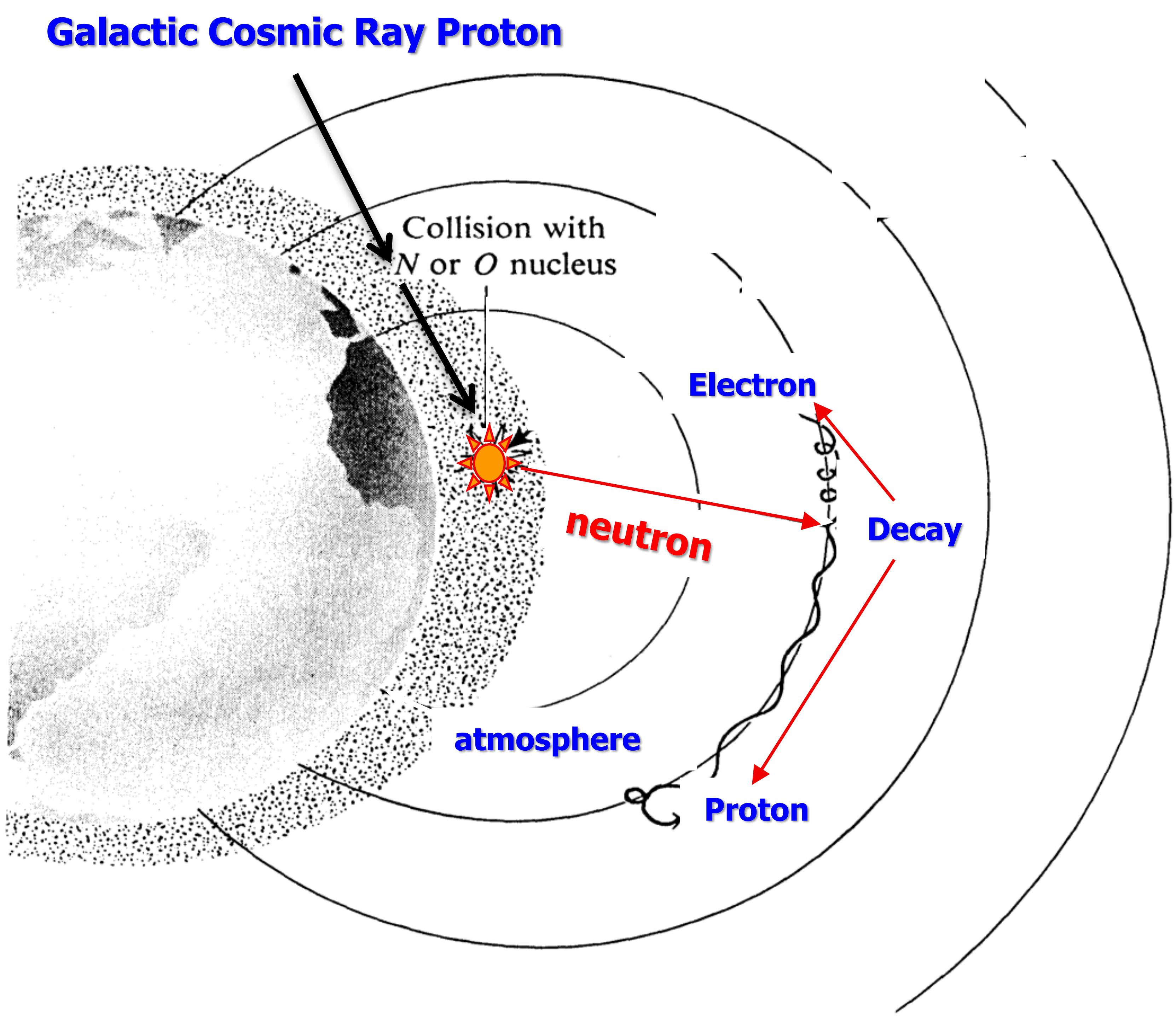
Proton spectra and flux are strong functions of altitude, latitude (and longitude)

Connection between GCR and proton radiation belt

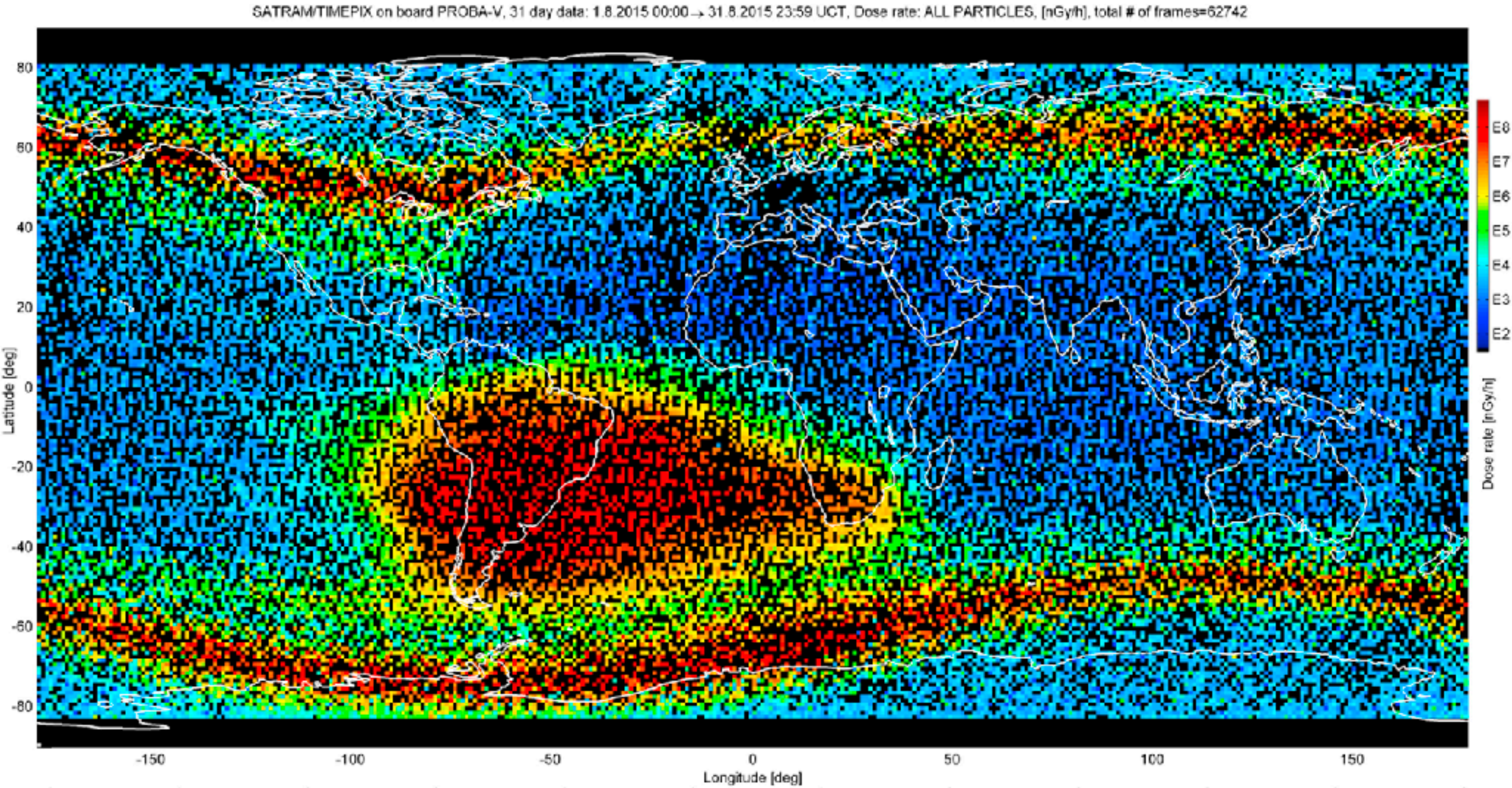


Radiation measurements taken outside **on the ISS** (International Space Station) at about **400 km altitude**. Each dot is a color coded measurement. Note that most of the radiation is found above South America and the South Atlantic in a region known as the **South Atlantic Anomaly**. Here the proton flux above 50 MeV is increased ~1,000 times relative other locations at the same altitude [NCRP 2010 page 26]. Zero inclination orbits do not pass through this region and spacecraft in these orbits receive relatively little radiation. Image credit NASA.

The Cosmic Ray Albedo Neutron Decay process (CRAND) is the dominant source of inner belt protons above ~50 MeV



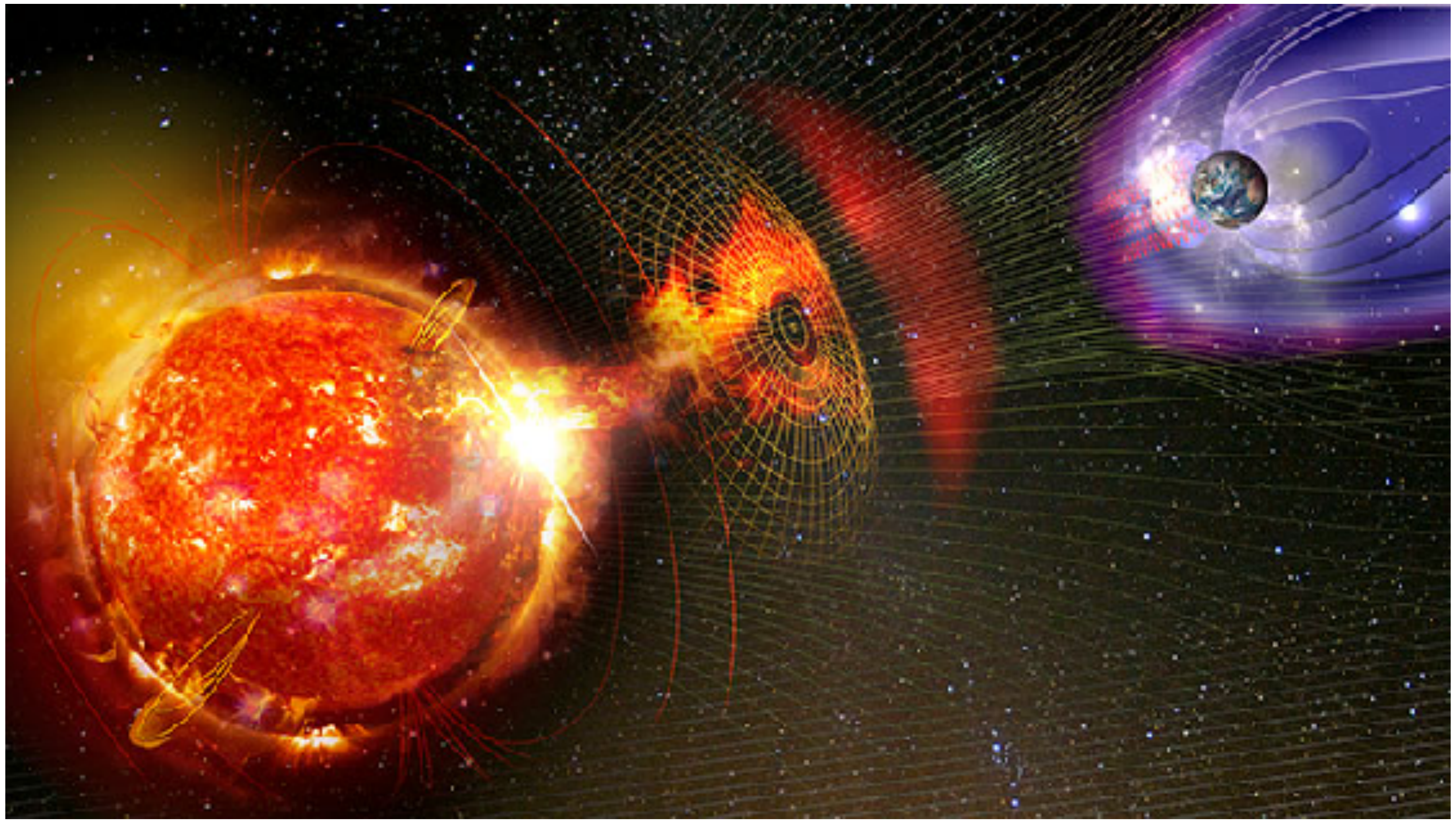
Spatial distribution of total dose rate measured by SATRAM along the 820 km LEO orbit of Proba-V. Results are shown for a 31-day period in 2015. The quantity displayed (total absorbed dose, displayed in nGy/h) span overs six orders of magnitude



https://doi.org/10.1016/j.pss.2016.03.009

During geomagnetic storms, GCR exposure often expands at lower latitudes (like the auroral regions) because storm dynamics compress the geomagnetic field and reduce the shielding effectiveness

However, increases in **solar activity** expand the atmosphere, enhancing the losses of protons in LEO (and the satellite hydrodynamic drag). Therefore, the trapped radiation dose in LEO decreases during solar maximum and increases during solar minimum



Particle Radiation Environment--Physical Damage and impacts to Hardware

Cosmic, solar and radiation belts particles are capable of penetrating most spacecraft shielding and depositing their energy in components, potentially causing problems called **device single events**

- Microelectronic components are most susceptible to performance degradation by these highly ionising particles
- Optics and polymeric materials (teflon, ...) are also affected

Damages by	single charged particles
	groups of energetic particles

The highest energy GCRs are subatomic particles carrying the energy of macroscopic objects!

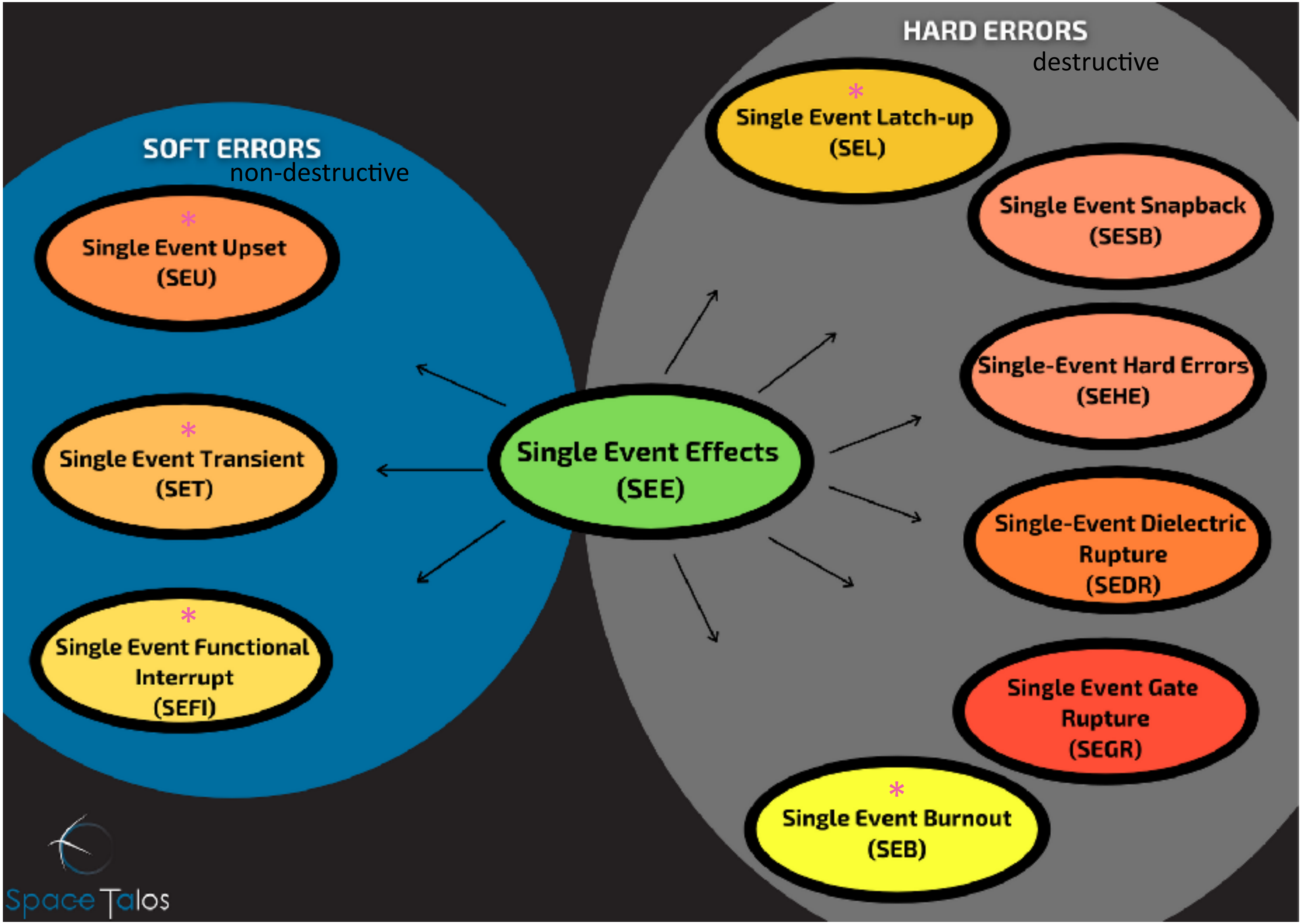
- Protons > 10 MeV penetrate typical spacecraft shielding and pose energy deposition risks.

- Ions > 30 MeV are capable of breaching integrated circuits (ICs) and thereby inducing faults.

The primary risk to the ICs is called **single-event effects (SEEs)**.

(caused by a single particle)

- Select radiation tolerant ICs (5 krad/yr, spot shielding)
- Include fault mitigation features (i.e. redundant parts)
- Use Error Detection And Correction (EDAC) procedures

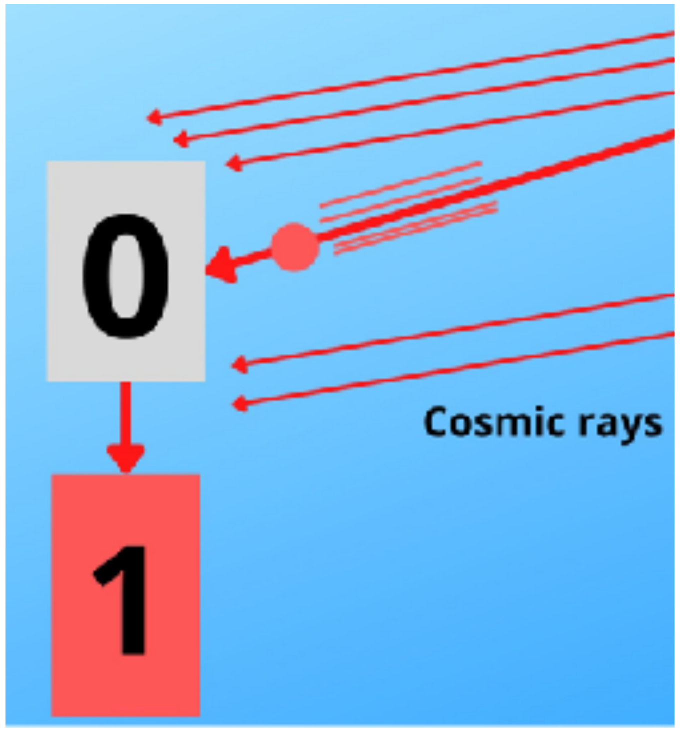


https://spacetalos.com

* discussed after

SEU – Single Event Upset

Change of state of an electronic device storage element caused by a single ionising particle. These events usually do not affect the reliability and function of a system over time and are easier to fix than hard errors.

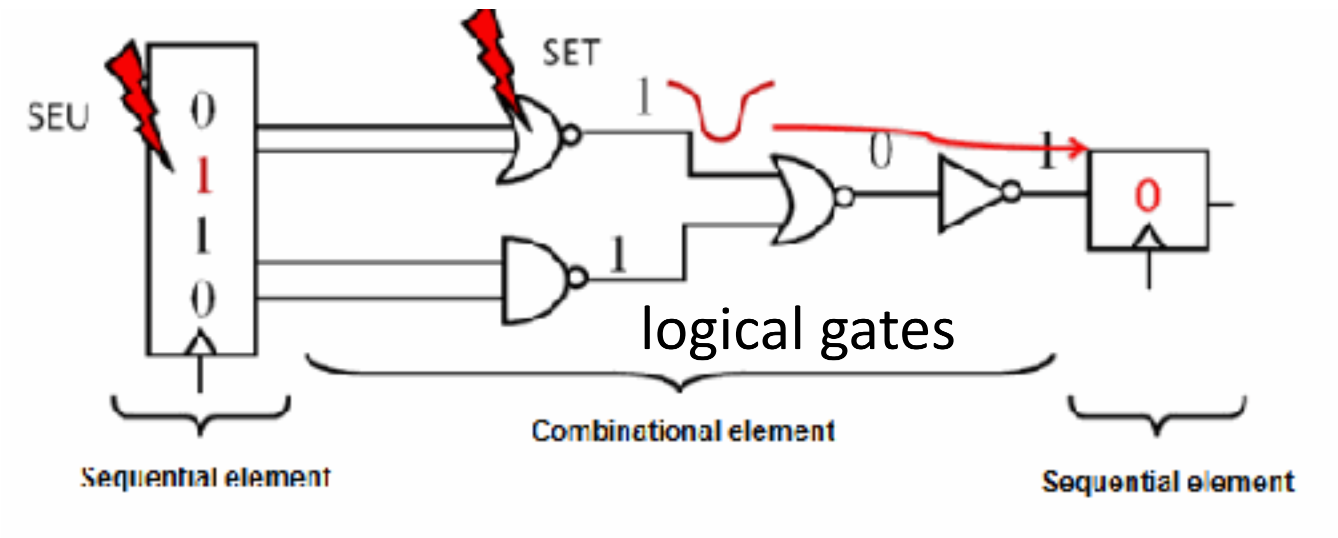


SEEs that result in one upset are called **Single Bit Upsets (SBU)**, whilst those resulting in multiple upsets are named **Multiple Cell Upsets (MCU)**.

Several upset cells that are part of the same logic word are referred to as **Multiple Bit Upsets (MBU)**. MBU causes multiple bit errors during one measurement. The SEUs usually affect latches, memory devices, and sequential logic.

SET – Single Event Transient

SET occurs when the motion of charges by a single particle, causes a temporary (transient) voltage glitch. This transient can recover quickly without other actions needed to clear the error condition. Nevertheless, the danger of it being latched at a wrong logic level is present and higher in faster devices. SETs affect mostly analog and mixed-signal circuits.



SEFI – Single Event Functional Interrupt

SEFI occurs when a disturbance of state registers interrupts the normal operation of circuits and the affected device enters a different operation mode or locks-up. In essence, *SEFIs are SEUs taking place at the control sections of the circuit*. These are more difficult to restore than other SEUs and usually, a software reset or a power-cycling is required.

SEL – Single Event Latch-up ("short circuit in semi conductors")

SEL is a type of hard fault which is usually catastrophic to the system. The passage of a single energetic particle can trigger a parasitic PNPN structure drawing an abnormally high operating current. If the power input is not reset in time the device is at risk of suffering from a potentially disastrous overcurrent episode that can result in structure overheating and melting.

The SEL can occur with Complementary Metal-Oxide-Silicon CMOS and BiCMOS devices in structures such as the electrostatic discharge (ESD) or over-voltage protection circuits. SELs do not take place in Silicon-on-Insulator (SOI) devices, which suppress any parasitic PNPN structures (thyristor).

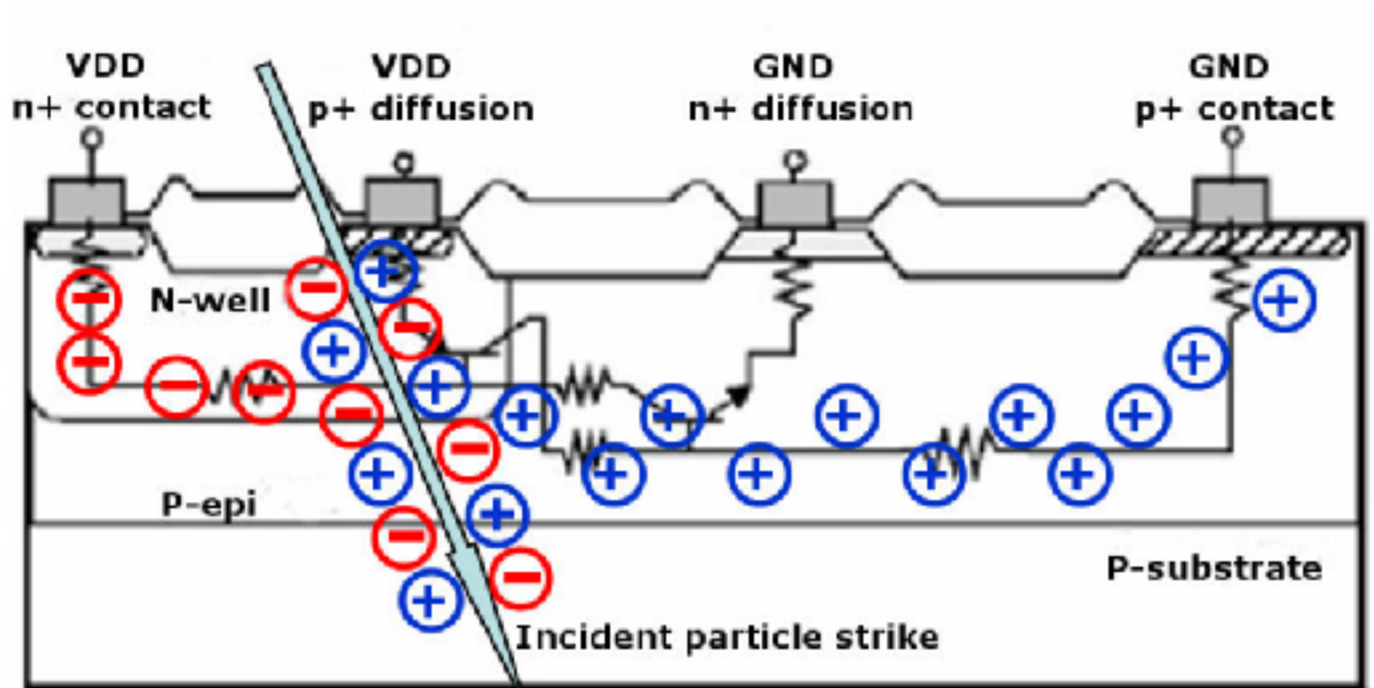


Figure 3. Initial electron-hole pairs and current tracks created by incident particle strike.

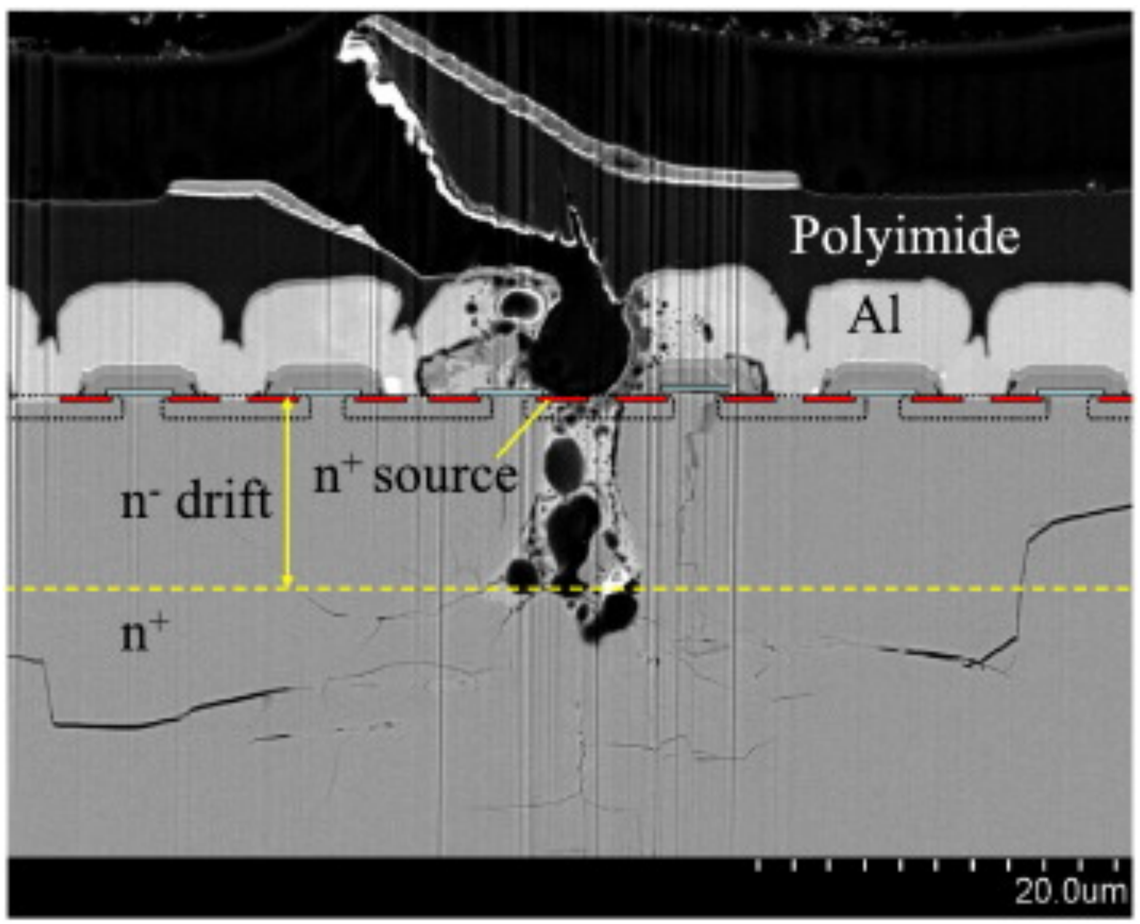
https://core.ac.uk/download/pdf/216050263.pdf

SEB – Single Event Burnout

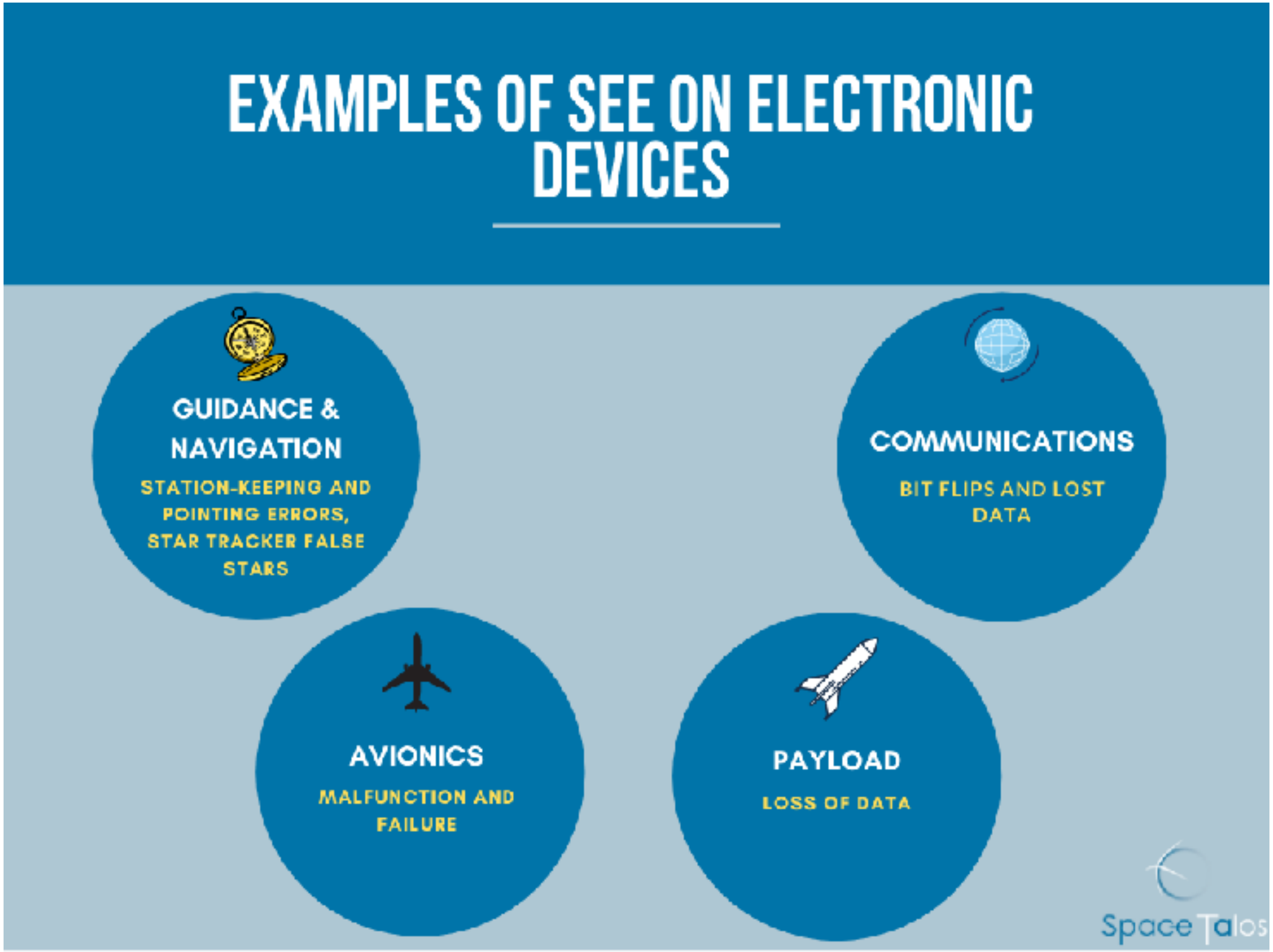
Joule heating

SEB is caused by a single energetic particle charge (primarily heavy ions) that results in localised high-current state in the body of the device. This type of hard error often results in catastrophic failure.

The SEB affects primarily bipolar transistors and N-channel power MOSFET transistors in space, but has also been observed in high voltage diodes in terrestrial applications.



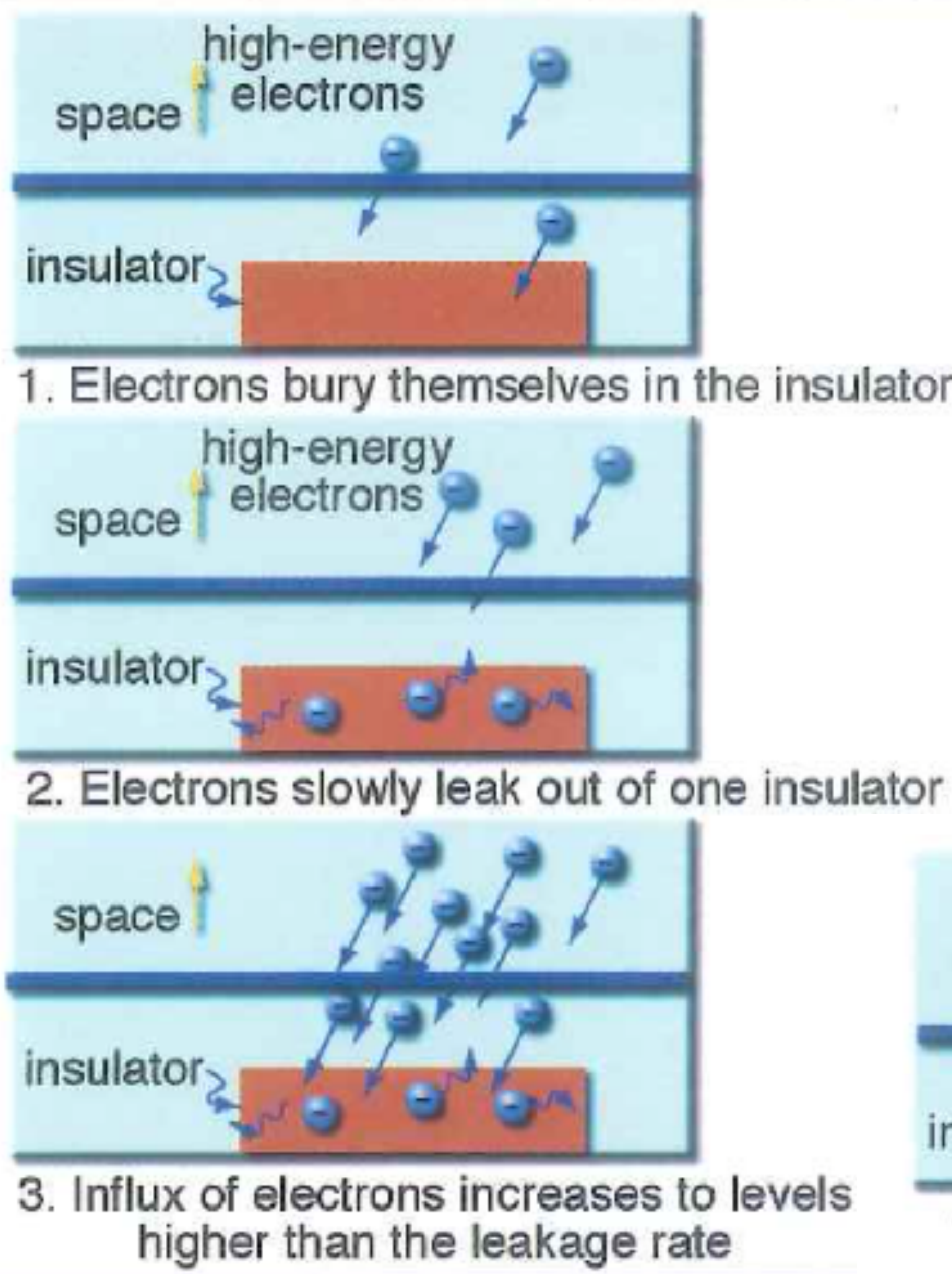
https://doi.org/10.1016/j.microrel.2015.06.081


EXAMPLES OF SEE ON ELECTRONIC DEVICES
GUIDANCE & NAVIGATION
STATION-KEEPING AND POINTING ERRORS, STAR TRACKER FALSE STARS
COMMUNICATIONS
BIT FLIPS AND LOST DATA
AVIONICS
MALFUNCTION AND FAILURE
PAYLOAD
LOSS OF DATA
SpaceTalos

DDC – Deep Dielectric Charging

Multiple energetic particles (electrons) lodge in material, building charge as they accumulate.

Charge-deposition into dielectric occurs when electrons with energies of 2-10 MeV penetrate deep into spacecraft structures over periods of days.



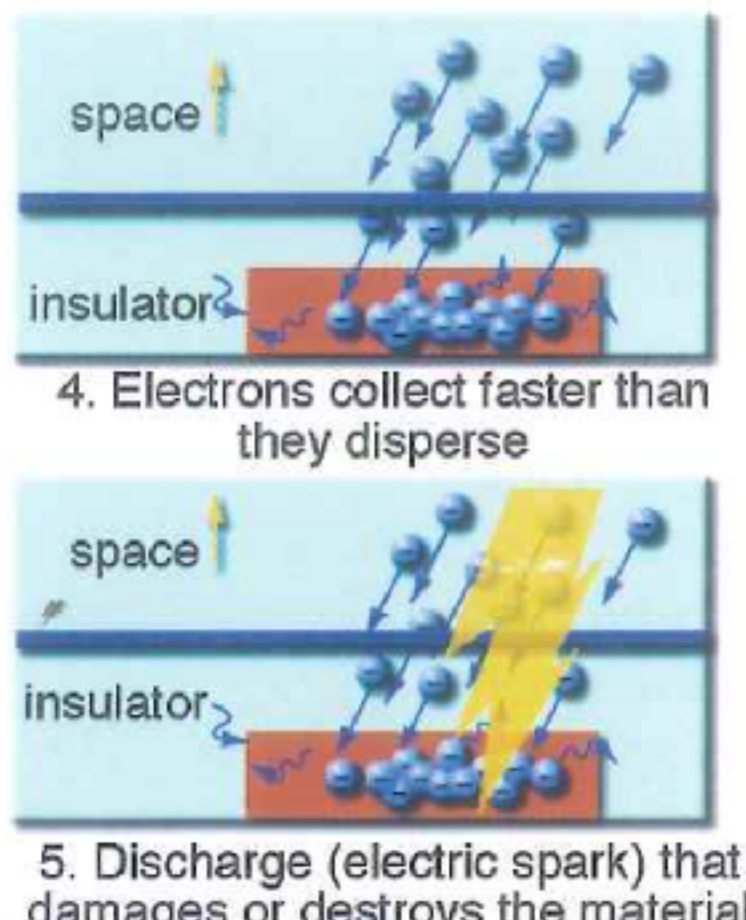
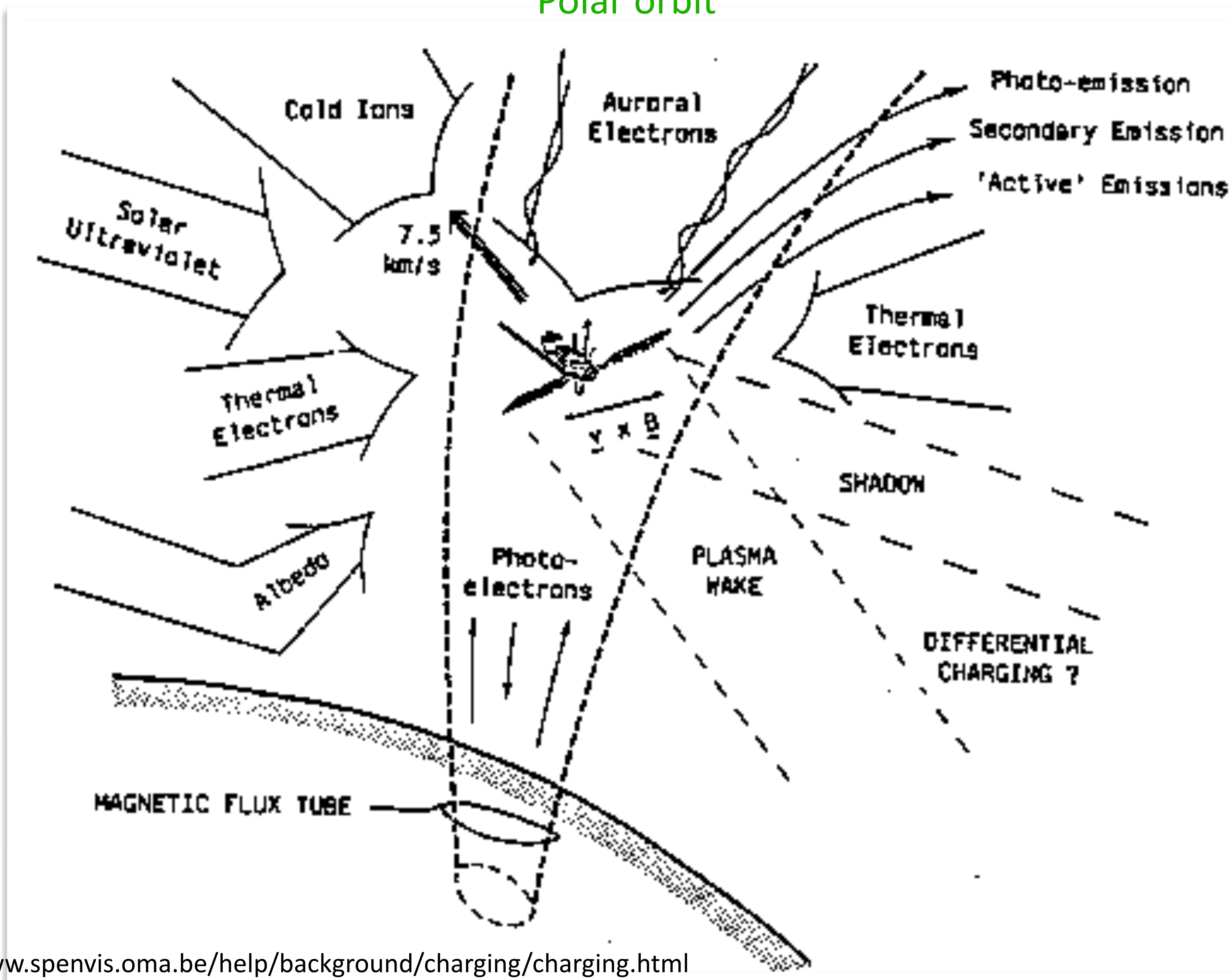


Fig. 13-15. Deep Dielectric Charging Process. These diagrams show how electrons cause deep dielectric charging when they penetrate spacecraft electronic components. The problem is most acute during intervals of large high-energy electron flux, when the charges have insufficient time to diffuse away from the location of deposition. *(Courtesy of Geoff Reeves at the Los Alamos National Laboratory)*

13.1.3 Energetic Plasma, Photon, and Neutral Atmosphere effects on Hardware

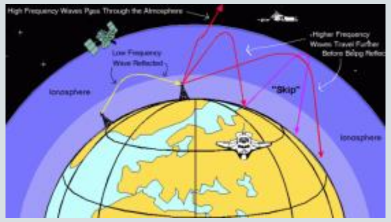
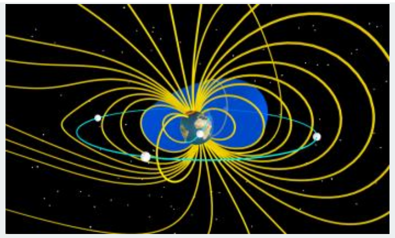
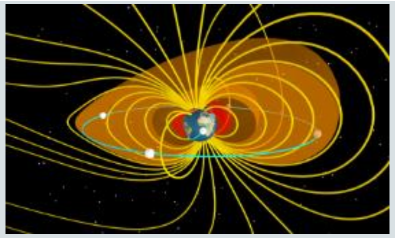
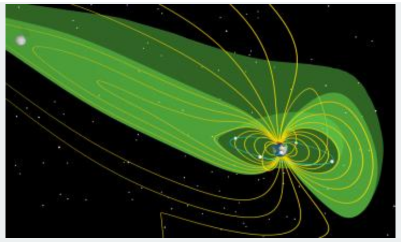
Spacecraft Surface Charging

Polar orbit



https://www.spenvis.oma.be/help/background/charging/charging.html

Plasma environments around the Earth

REGION	Density* (cm^{-3})	Temp. (eV)	Location	Notes	
Ionosphere	1,000,000 at peak	< 1	Peak at 300 km	Includes LEO (ISS, cubesats etc.)	
Plasma-sphere	1000	~1	Outer edge at L = 3-6	Hot, expanded ionosphere	
Radiation (Van Allen) Belts	~0.00001	~ 1,000,000	L < 8	High energy trapped particles	
Outer magneto-sphere	< 1	< 10,000	L > 6	Highly dynamic on short (min) timescales	
Solar wind	1-10	1-10	Outside magnetosphere	Velocity of 400-1000 km/s	

Colin Forsyth, UCLondon, EPIC Electric Propulsion Lecture Series 2018

Since electrons and ions are free in a plasma, they can move at different speeds and have different temperatures

In near-Earth space, ion and electron temperatures are relatively close (within an order of magnitude)

However, their thermal speeds will be different:

$$v_{th} = \sqrt{\frac{2k_B T}{\pi m}}$$

m_e =9.1x10^{-31} kg
m_p =1.67x10^{-27} kg

Electrons with same temperature as protons will move 42 times faster

Imagine a 2D plane, thermal particle flux through (to) that plane is

$$Flux = n v_{th}$$

$$Flux = n\sqrt{\frac{2k_B T}{\pi m}}$$

Since m_e<<m_p, the electron flux to the plane is far greater than the proton flux

If the particles do not pass through the plane, but stick to it, the plane will start to **charge negatively**

This is the basis of spacecraft charging

Recall that current can be described as

$$I = nAvq_e$$

$$I = FLUX \times Aq_e$$

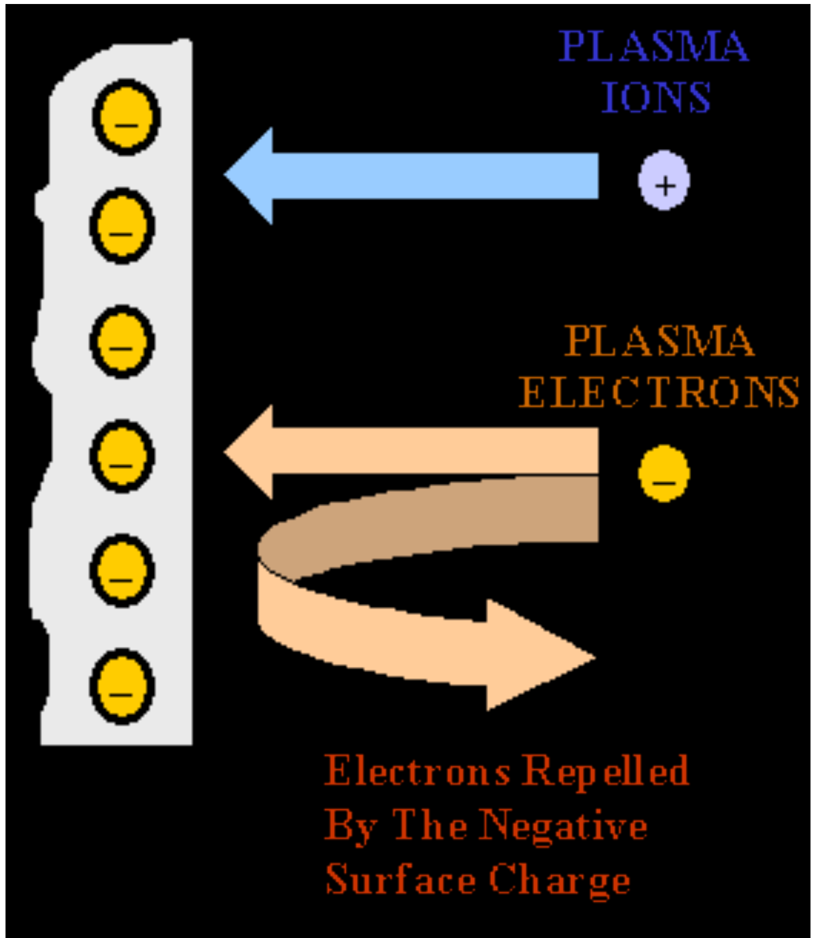
As such, we can consider spacecraft charging in terms of currents.
A spacecraft will charge up to a point at which there is no net current onto the spacecraft

$$I_{e-flux} + I_{i-flux} + I_{???} + \cdots = 0$$

Assuming that all particles hitting a spacecraft stick to the spacecraft, then a spacecraft in a (shadow) plasma in which the electron and proton temperatures are similar will start to charge negatively

As the spacecraft begins to charge, it will attract positively charged particles (increasing their inbound flux) and repel negatively charged particles (decreasing their inbound flux) until it reaches equilibrium

This does not mean no flux onto the spacecraft, it means that the net flux onto the spacecraft is balanced



After Grard et al., [1983]

$$v_{th} = \sqrt{\frac{2k_B T}{\pi m}}$$

$$v_{pot} = \sqrt{\frac{2q_e \phi}{m}}$$

For a negatively charging spacecraft, ion flux is $F_i = n\,(v_{th} + v_{pot})$

electron flux is $F_e = n\,(v_{th} - v_{pot})$

For the currents to balance, the fluxes must balance

- quasi neutrality implies that n_i and n_e = n
- they pass through the same area

If the electron and ion temperatures match, then the electrostatic potential maybe estimated as:

$$\sqrt{\phi} = \sqrt{\frac{Tk_B}{\pi q}}\left(\frac{\sqrt{m_i} - \sqrt{m_e}}{\sqrt{m_e} + \sqrt{m_i}}\right) \sim 0.5\sqrt{E_{th}}$$

The only variable is plasma temperature

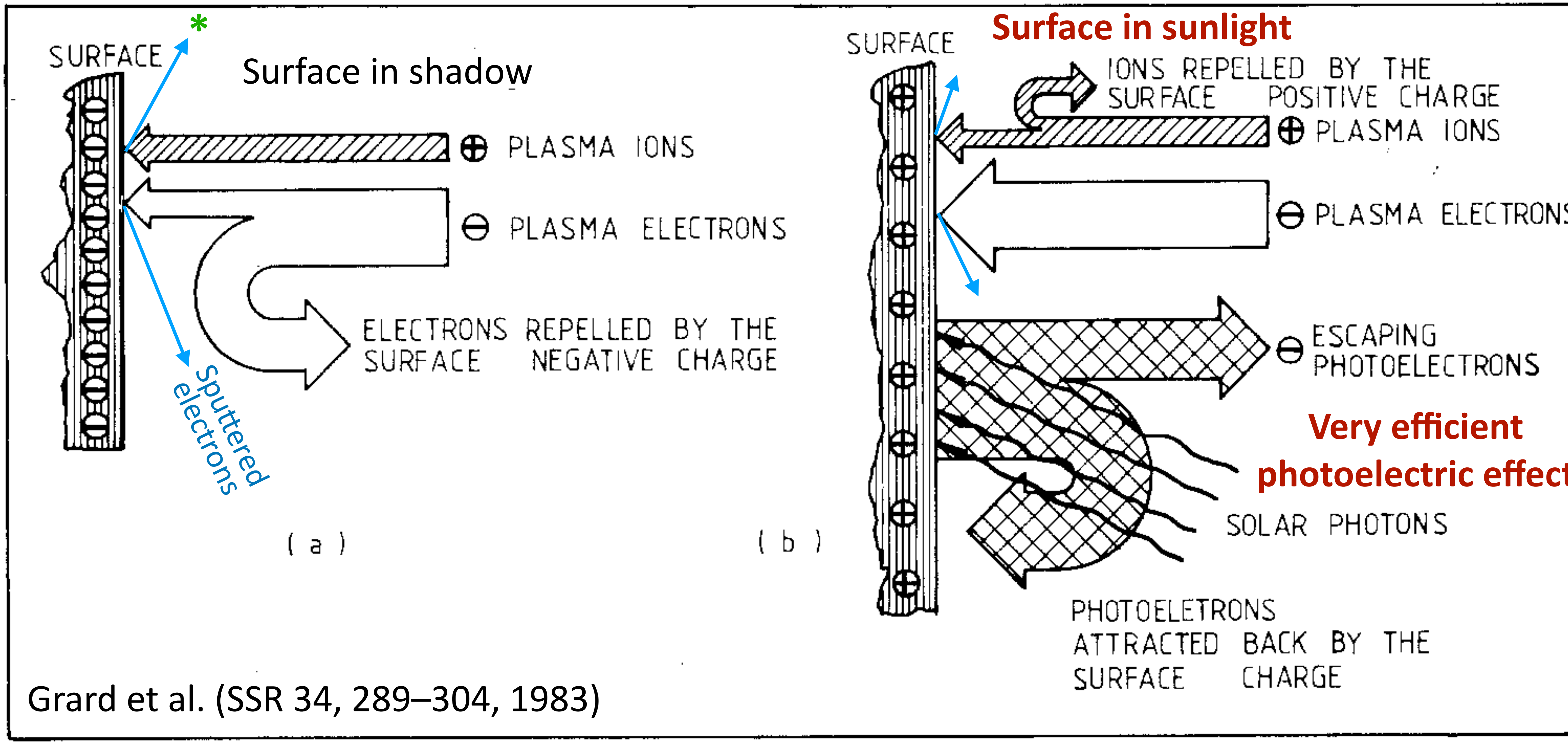


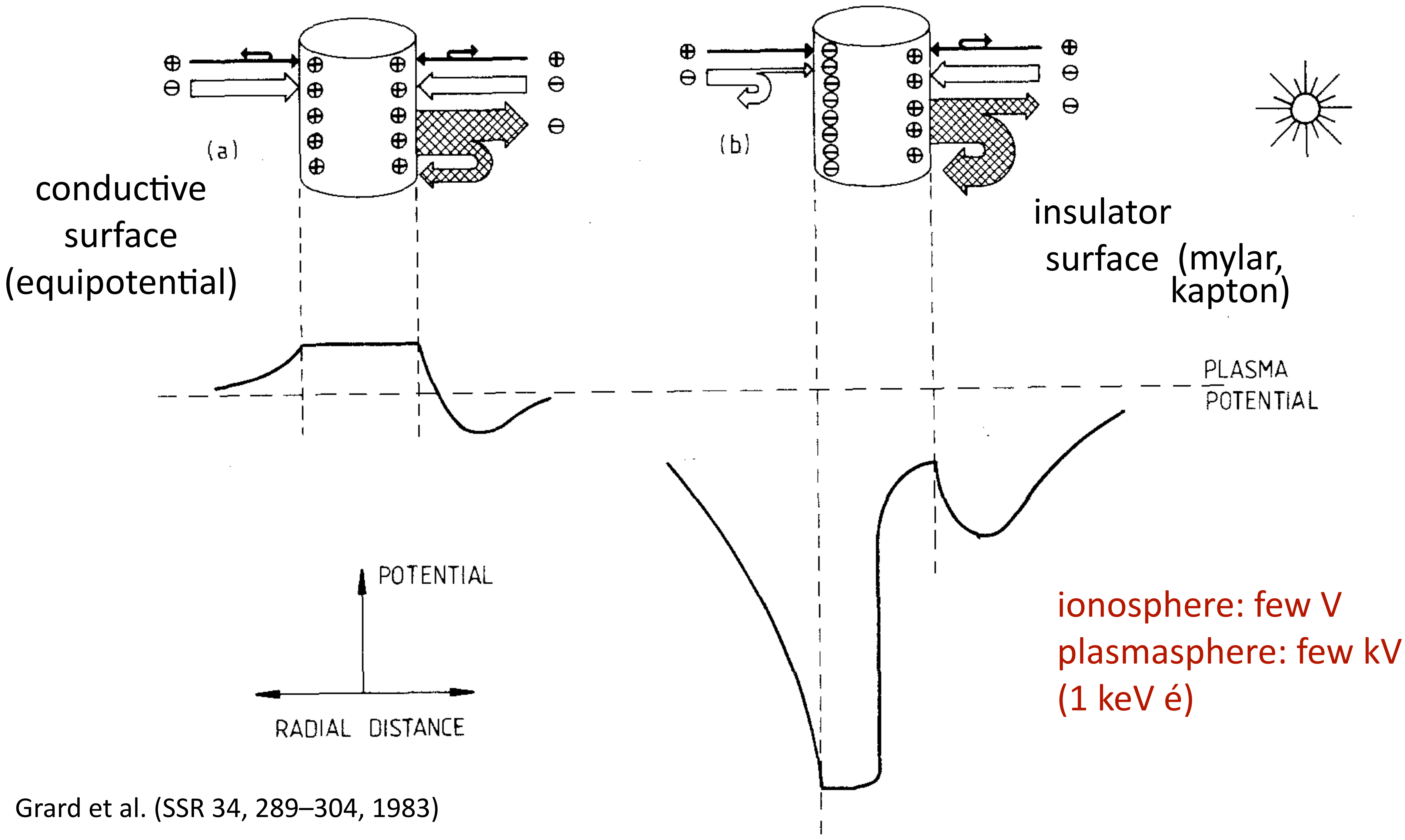
Fig. 2. Qualitative illustration of the charging of a surface by a plasma. The width of the arrows is proportional to the flux of each particle species; the equilibrium potential is reached when the sum of the currents collected and emitted by a surface element is zero. (a) Surface in shadow: the current balance requires equality between the flow of the plasma ions and that of the plasma electrons impinging on the surface. (b) Surface in sunlight: equilibrium is achieved when the flow of escaping photoelectrons is equal to the difference between the incoming flows of plasma electrons and ions.

* if ion energy is >>, collision can cause atom sputtering => erosion, change in surface properties, ...

Differential charging - shadowing

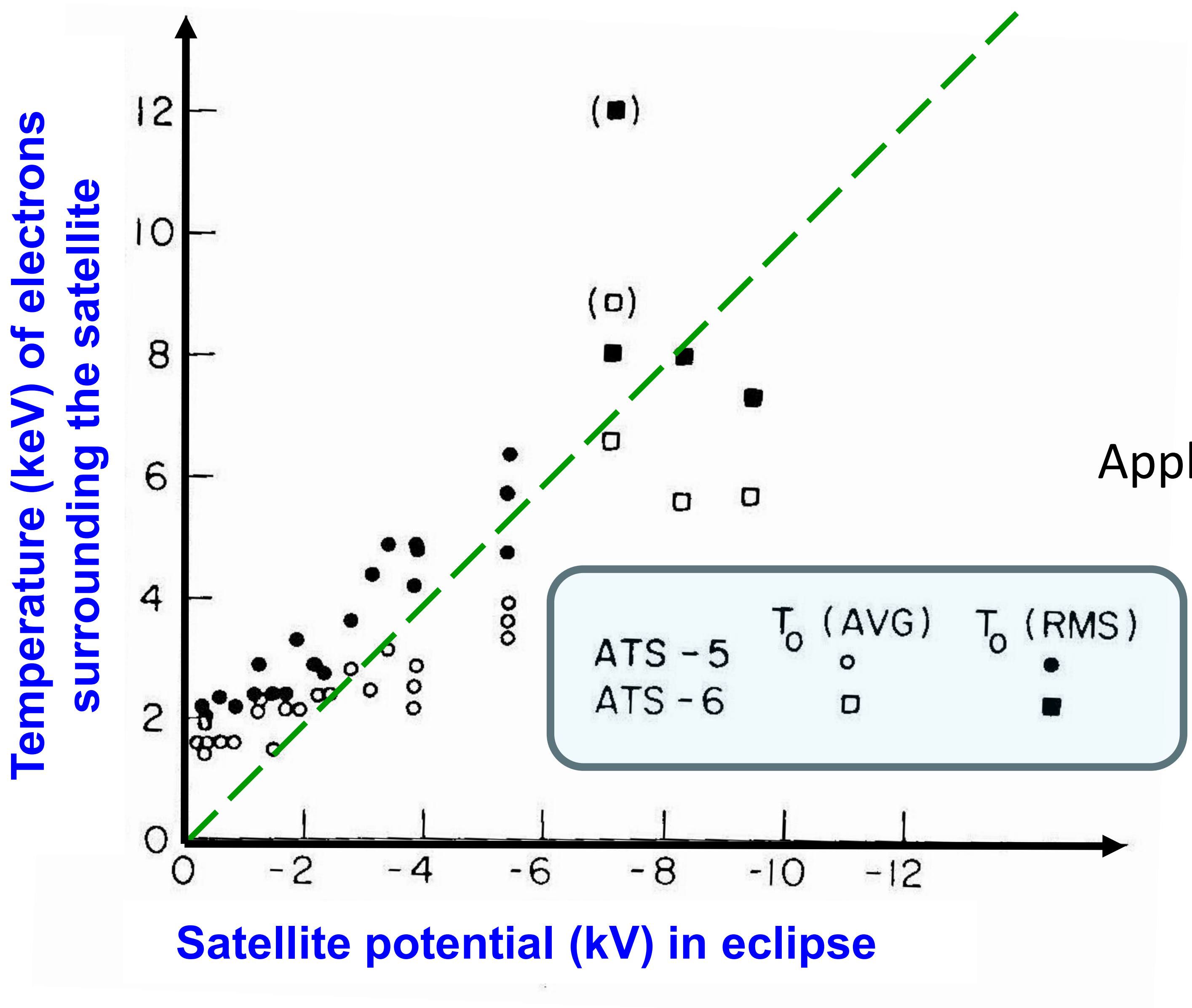
- Photo-electric effect affects those parts of the spacecraft in sunlight

Fig. 3. Schematic representation of particle flows to and from a satellite for the case of (a) a conductive surface and (b) an insulator surface. The lower portion gives a qualitative plot of the associated potential profiles in a hot plasma.

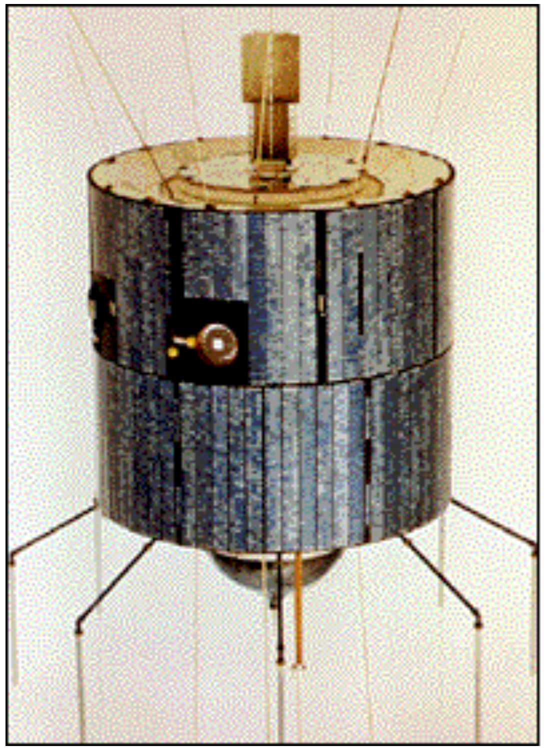


Grard et al. (SSR 34, 289–304, 1983)

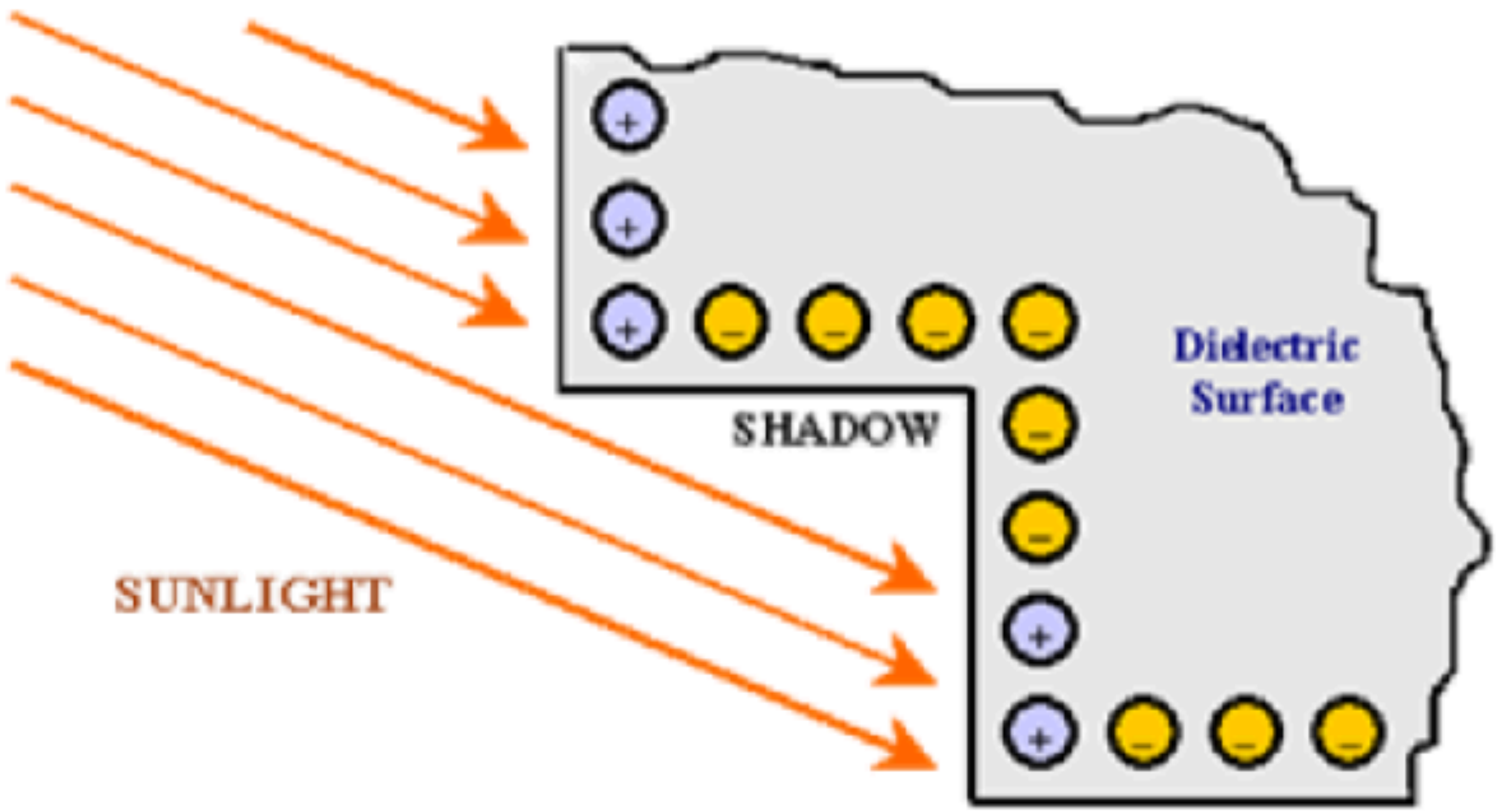
Example of spacecraft charging



Garrett & Rubin [1978]



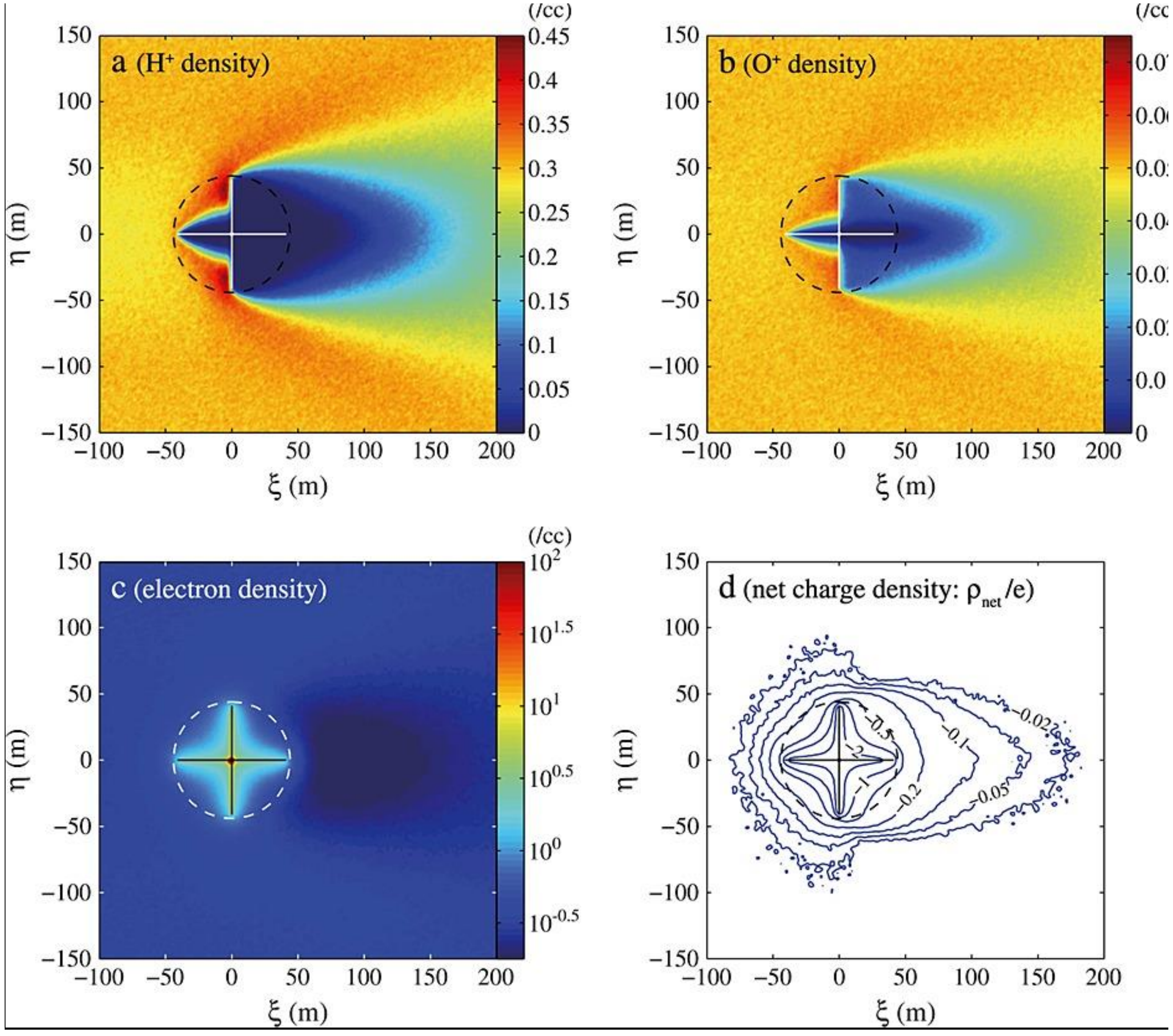
Applications Technology Satellites


Dielectric
Surface
SHADOW
SUNLIGHT

Differential charging - plasma wake

The spacecraft will create a wake through the plasma as it goes

- Plasma has a sound speed which is dependent on temperature
- if a spacecraft is supersonic, it will create a wake in the plasma
- Greater issue at low altitude, where the plasma is really cold



Differential charging - surface conductivity

Surface conductivity will vary

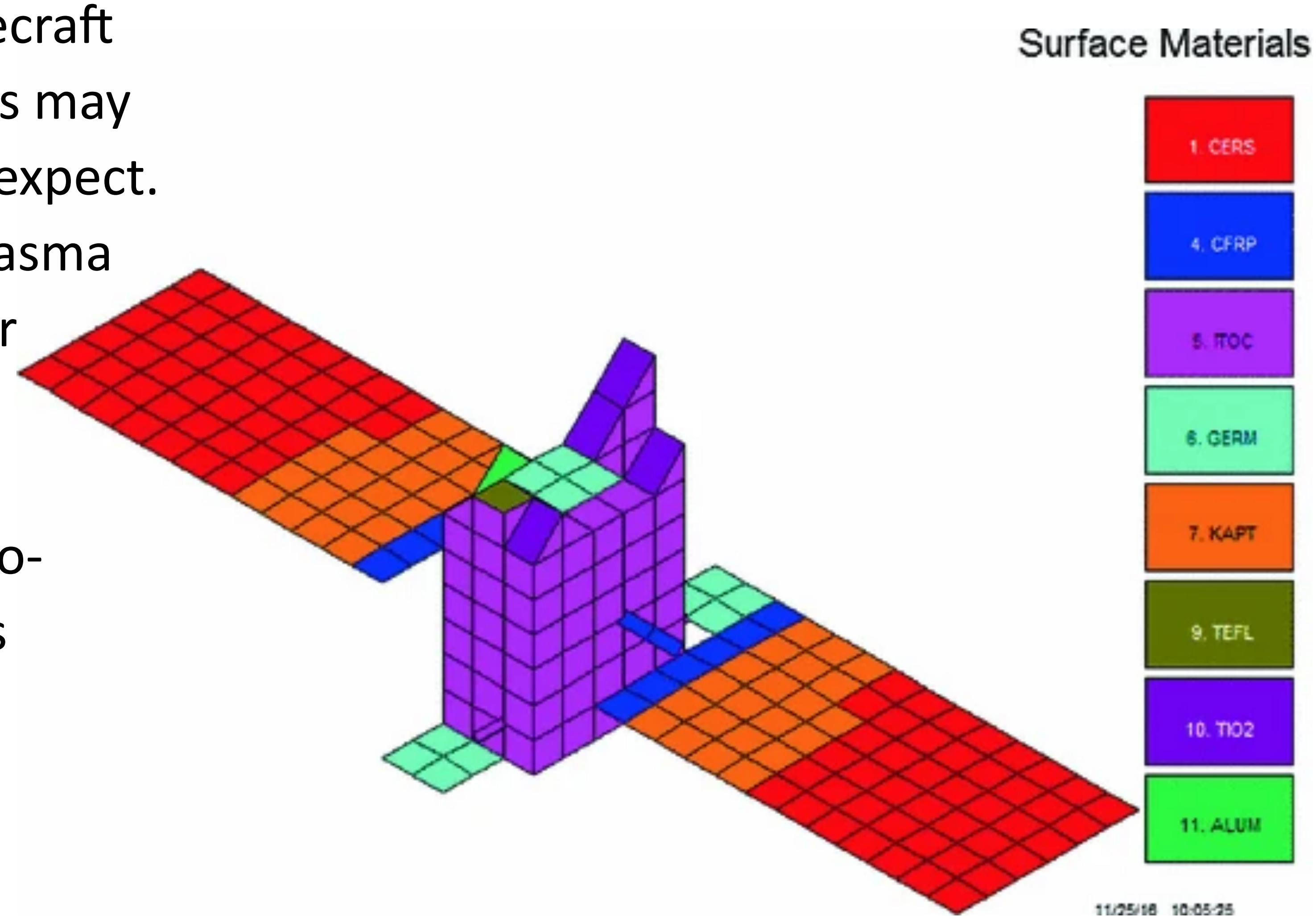
- Thermal blankets may or may not be electrically conducting
- Antennae tend to be metallic
- Solar panels are glass coated
- Instruments may be designed to conduct or insulate
- ...

Insulated parts of the spacecraft exterior are at greater risk of differential charging since charge cannot move and dissipate

Passive Mitigation

- Surface materials
  Where possible, use materials that give a low yield of secondary or photo-electrons
- Surface conductivity
  Design the spacecraft so that the surface is uniformly conducting (or as close as possible)

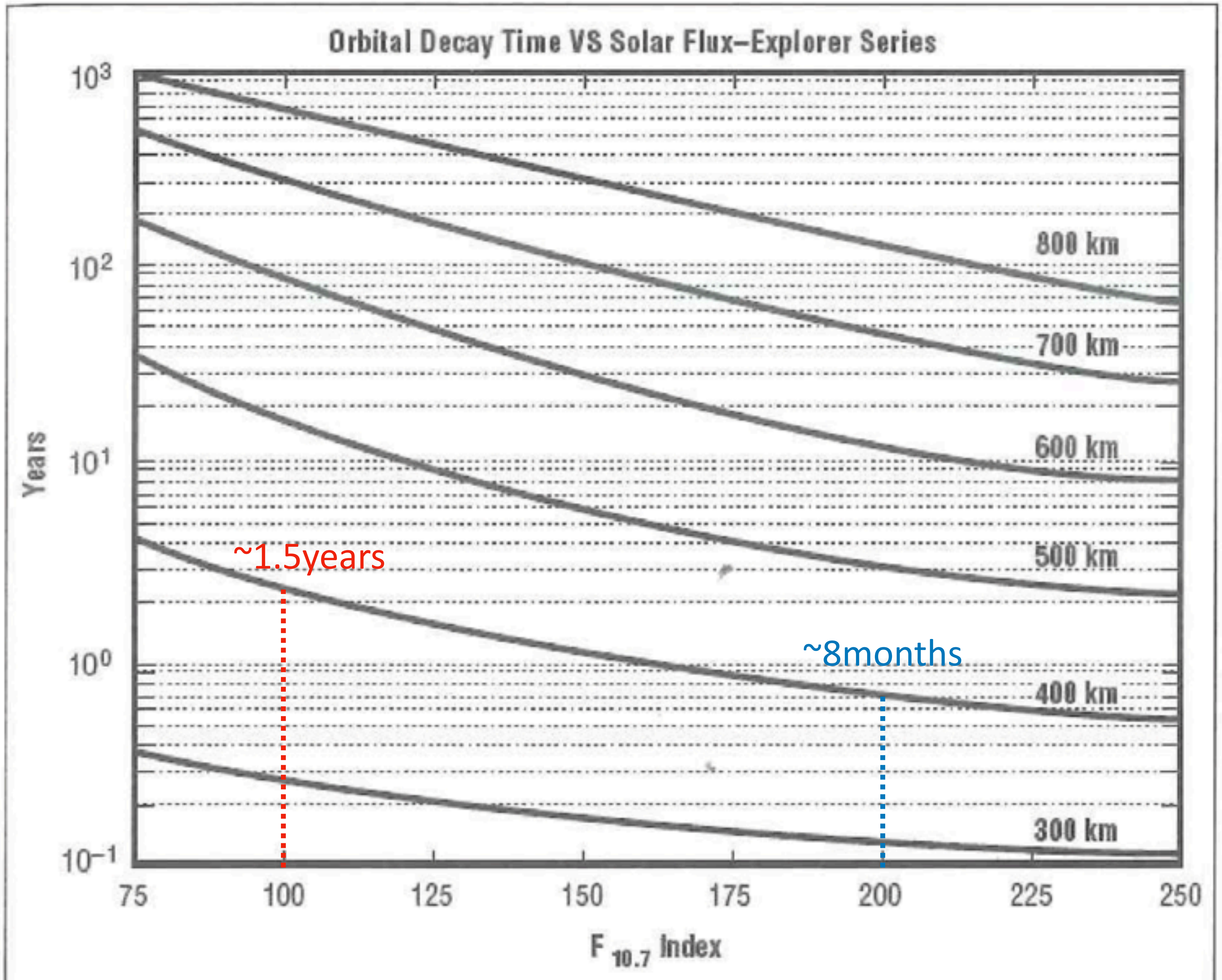
- Design modelling
  - Computer modelling of the spacecraft can indicate where problem areas may be and what level of charging to expect.
  - E.g. SPIS (from ESA/Spacecraft Plasma Interaction Network in Europe) or Nascap (from NASA)
- Orbital design
  - Consider eclipses (changing photo-emissions), plasma environments (changing thermal fluxes)
- Ground experiments



STOP 2024

13.1.4 Satellite Drag

Long term variations in **atmospheric density**, such as those driven by solar cycle variations in solar EUV flux (F10.7 index), have order-of-magnitude effects on the lifetime of LEO satellites.



https://farside.ph.utexas.edu/teaching/celestial/Celestial/node94.html

A bit of counter-intuitive "rocket science"

The **drag force** per unit mass that the atmosphere exerts on an orbiting satellite can be modelled as

$$\mathbf{F} = -\frac{1}{2}\frac{\rho\, C_D\, A}{m}\, \dot{r}\, \dot{\mathbf{r}}, \quad v^2$$

- atmospheric mass density at the satellite's altitude (ρ)
- drag coefficient (C_D)
- cross-sectional area of the satellite perp. to its direction of motion (A)
- satellite mass (m)
- satellite velocity (vector) ($\dot{\mathbf{r}}$)

The dimensionless drag coefficient depends on satellite's shape.
For a spherical satellite C_D ~2.2

F is proportional to v^2 and is oppositely directed to direction of motion

The density distribution of the terrestrial atmosphere is conveniently modelled as

$$\rho(r) = \rho_0 \exp\left[-\frac{(r-R)}{H}\right]$$

- radial distance from the Earth's center (r)
- terrestrial radius: 6.4x10^{6}m (R)
- density at ground level: 1.3 kg m^{-3} (ρ_0)
- atmospheric scale height ~8 km (ground) (H)

$$H = \frac{kT}{\mu m_H g} = \frac{\left(1.38\times10^{-23}\frac{J}{K}\right)(288K)}{(28.96)\left(1.67\times10^{-27}kg\right)\left(9.81\frac{m}{s^2}\right)} \approx 8\,km$$

Assuming that the atmospheric drag force is small compared to the force of gravitational attraction between the Earth and the satellite --and can, thus, be treated as a perturbation-- the satellite's orbit can be modelled as Keplerian ellipse whose six elements evolve slowly in time under the influence of the drag.

=> Gauss Planetary Equations https://farside.ph.utexas.edu/teaching/celestial/Celestial/node164.html

averaged over 1 orbital period

drag force

$$\left\langle \frac{\dot{a}}{a} \right\rangle = -\frac{C_D A\, a\, \rho(a)}{m}\, n \oint e^{\alpha \cos E} \frac{(1 + e \cos E)^{3/2}}{(1 - e \cos E)^{1/2}} \frac{dE}{2\pi},$$

orbit radius decreases

$$\langle \dot{e} \rangle = -\frac{C_D A\, a\, \rho(a)}{m}\, n\, (1 - e^2) \oint e^{\alpha \cos E} \frac{(1 + e \cos E)^{1/2}}{(1 - e \cos E)^{1/2}} \cos E \frac{dE}{2\pi},$$

eccentricity decreases (orbit more circular)

$$\mu = G\,(M + m)$$

the satellite's orbit-averaged kinetic and potential energies are

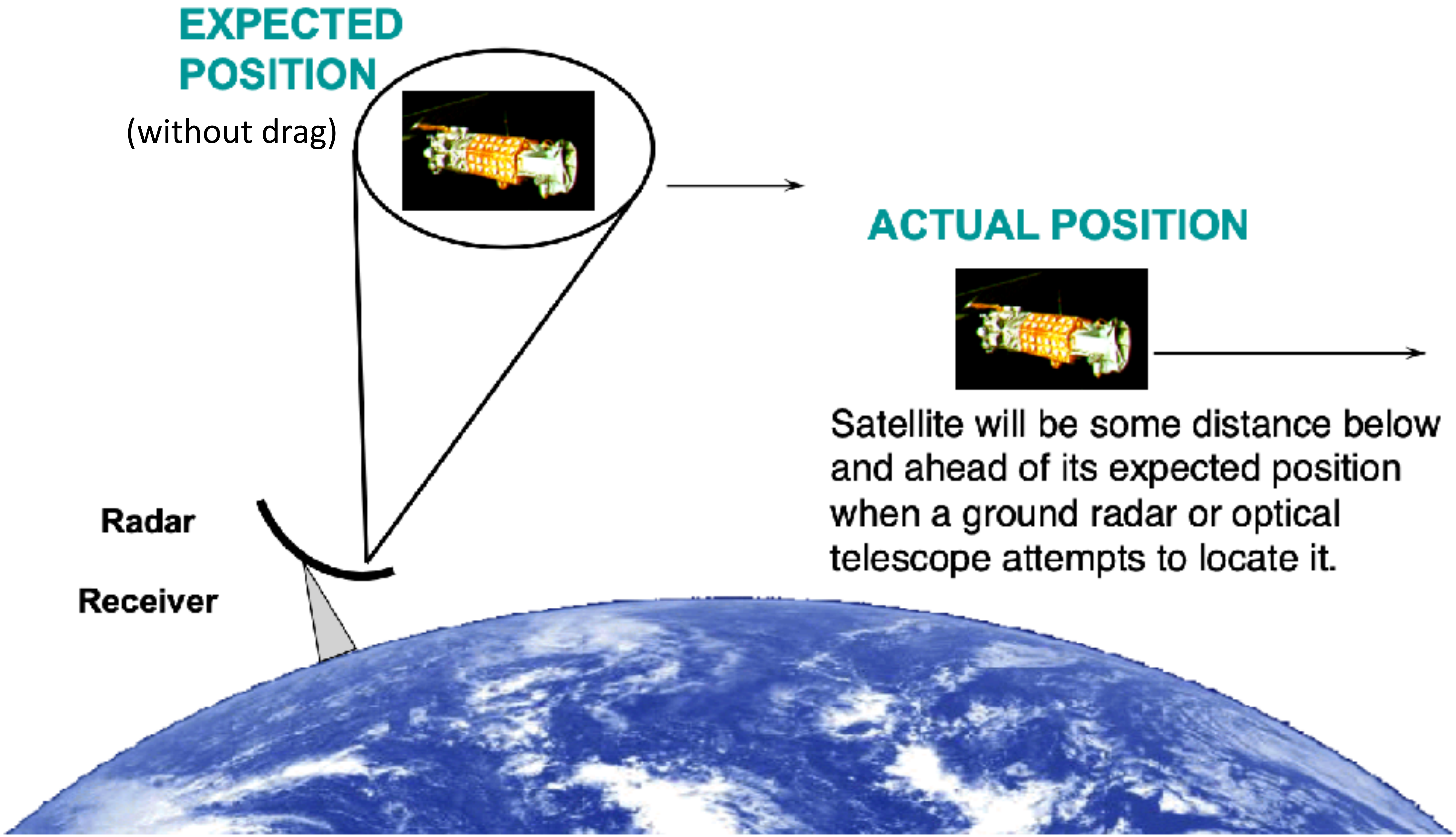
$$\langle K \rangle = \frac{\mu}{2\,a}$$

if a decreases, K increases: **speed increases**!

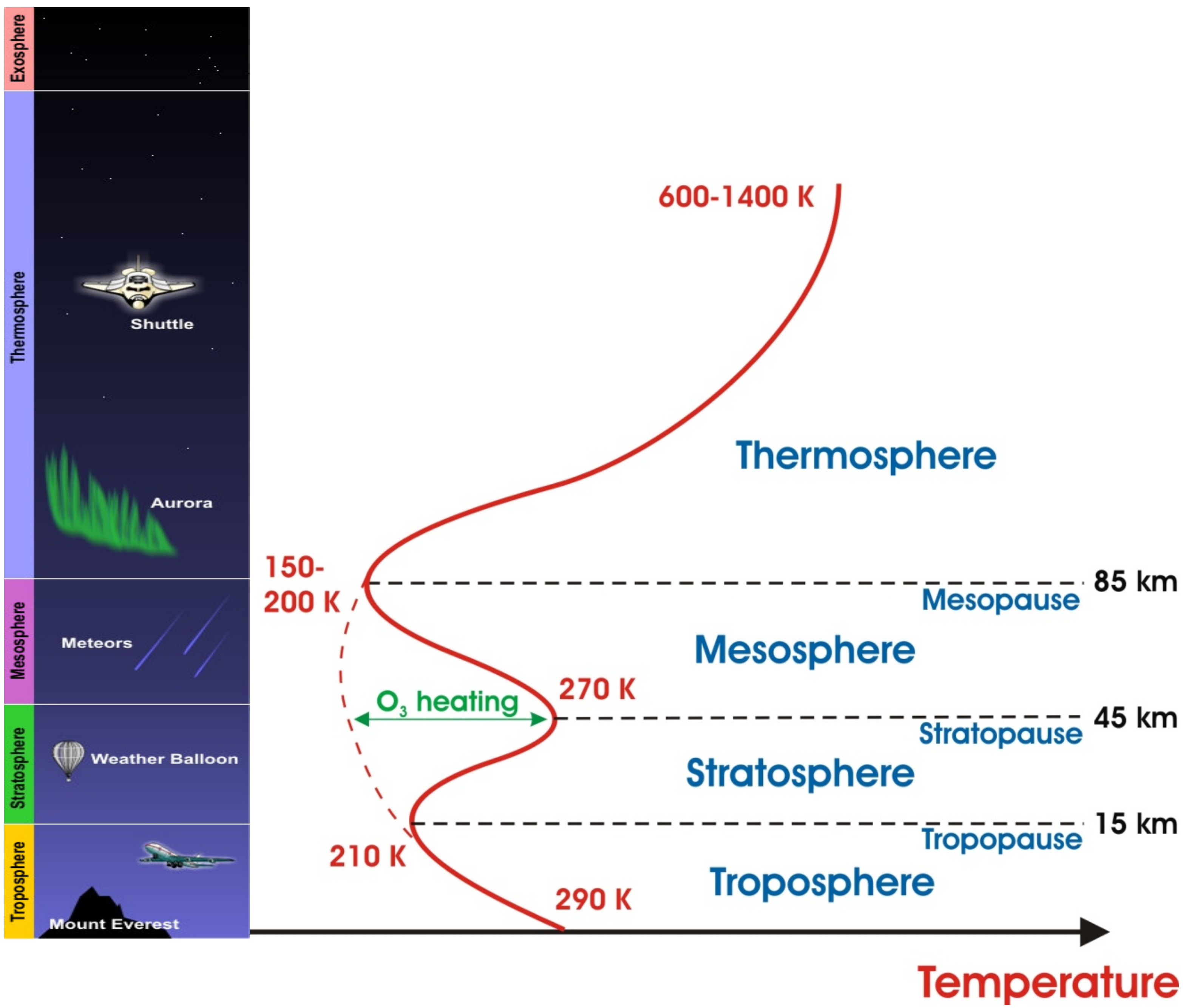
$$\langle U \rangle = -\frac{\mu}{a}$$

if a decreases, U decreases and energy is conserved

(small) drag force decreases speed, but (large) gravitation force increases speed much more, as a result of the decrease of altitude



credit: Yihua Zheng



The outer gaseous shell of a planet's atmosphere that exchanges energy with the space plasma environment: **Thermosphere**

- **Energy sources**:
  - Absorption of Extreme UV radiation (10 -200nm)
  - Joule heating by electrical currents
  - Particle precipitation from the magnetosphere
  - Dissipation of upward propagating waves (tides, planetary waves, gravity waves)

- **Energy sinks**:
  - Thermal conduction into the mesosphere
  - IR cooling by CO_2 NO, O
  - Chemical reactions

credit: Yihua Zheng

Solar Emission
(UV, Xr, vis)

thermosphere

$O_2 + h\nu \rightarrow \mathbf{O + O}$

energy

$O_3 + h\nu \rightarrow \mathbf{O_2 + O}$

stratosphere

HEAT HEAT HEAT HEAT HEAT

$O(^3P) + O_2 + M \rightarrow O_3 + M + 25\ \text{kcal}\ (7.6 \times 10^{-35} \exp(890/RT))$

$O(^3P) + O_3 \rightarrow 2O_2 + 93\ \text{kcal}\ (5.6 \times 10^{-11} \exp(-5\,700/RT))$

$O(^3P) + O(^3P) + M \rightarrow O_2\ (^1\Sigma_g^+) + M + 80.8\ \text{kcal}\ (10\,\%)\ \ (2.7 \times 10^{-33})$

$O(^3P) + O(^3P) + M \rightarrow O_2\ (^1\Delta_g) + M + 95.8\ \text{kcal}\ (90\,\%)$

$O_2 + h\nu \rightarrow O_2\ (^1\Sigma_g^+) - 37.6\ \text{kcal}$

$3\ O(^3P) \rightarrow O\ (^1S) + O_2 + 21.8\ \text{kcal}\ (2.0 \times 10^{-34})$

$O(^1S) \rightarrow O(^1D) + h\nu + 51.2\ \text{kcal}\ (1.4)$

$O(^1S) + O_2 \rightarrow O(^3P) + O_2 + 96.6\ \text{kcal}\ (2.1 \times 10^{-13})$

$O(^1D) \rightarrow O(^3P) + h\nu + 45.4\ \text{kcal}\ (10^{-2})$

$O(^1D) + O_2 \rightarrow O(^3P) + O_2(^1\Sigma_g^+) + 7.8\ \text{kcal}\ (5.0 \times 10^{-11})$

$O(^1D) + N_2 \rightarrow O(^3P) + N_2 + 45.4\ \text{kcal}\ (7.0 \times 10^{-11})$

$O_2(^1\Sigma_g^+) \rightarrow O_2 + h\nu + 37.6\ \text{kcal}\ (0.085)$

$O_2(^1\Sigma_g^+) + N_2 \rightarrow O_2 + N_2 + 37.6\ \text{kcal}\ (1.5 \times 10^{-15})$

$O_2(^1\Sigma_g^+) + O_3 \rightarrow 2O_2 + O(^3P) + 12.4\ \text{kcal}\ (7.1 \times 10^{-12})$

$O_2(^1\Delta_g) \rightarrow O_2 + h\nu + 22.6\ \text{kcal}\ (2.8 \times 10^{-4})$

$O_2(^1\Delta_g) + M \rightarrow O_2 + M + 22.6\ \text{kcal}\ (4.3 \times 10^{-19})$

$O_2(^1\Delta_g) + O_3 \rightarrow 2O_2 + O(^3P) - 2.6\ \text{kcal}\ (6.7 \times 10^{-13} \exp(-3100/RT))$

$O_2(^1\Delta_g) + O(^3P) \rightarrow O_2 + O(^3P) + 22.6\ \text{kcal}\ (1.0 \times 10^{-16})$

$O(^1S) + H_2O \rightarrow 2OH + 80.0\ \text{kcal}\ (7.0 \times 10^{-11})$

$O(^1D) + H_2O \rightarrow 2OH + 28.8\ \text{kcal}\ (3.0 \times 10^{-11})$

$O(^1D) + H_2 \rightarrow OH + H + 43.6\ \text{kcal}\ (1.9 \times 10^{-10})$

$O(^3P) + H_2 \rightarrow OH + H - 1.8\ \text{kcal}\ (2.1 \times 10^{-11} \exp(-9400/RT)$

$O(^1D) + CH_4 \rightarrow CH_3 + OH + 43.7\ \text{kcal}\ (2.2 \times 10^{-10})$

$O(^3P) + CH_4 \rightarrow CH_3 + OH - 1.7\ \text{kcal}\ (5.3 \times 10^{-11} \exp(-7950/RT))$

$H + H + M \rightarrow H_2 + M + 104\ \text{kcal}\ (2.6 \times 10^{-32})$

$H + O_2 + M \rightarrow HO_2 + M + 47\ \text{kcal}\ (2.6 \times 10^{-33} \exp(1600/RT))$

$O(^3P) + OH \rightarrow H + O_2 + 16\ \text{kcal}\ (5.0 \times 10^{-11})$

$O(^3P) + HO_2 \rightarrow OH + O_2 + 55\ \text{kcal}\ (1.0 \times 10^{-11})$

$O(^3P) + H_2O_2 \rightarrow OH + HO_2 + 13\ \text{kcal}\ (1.0 \times 10^{-15})$

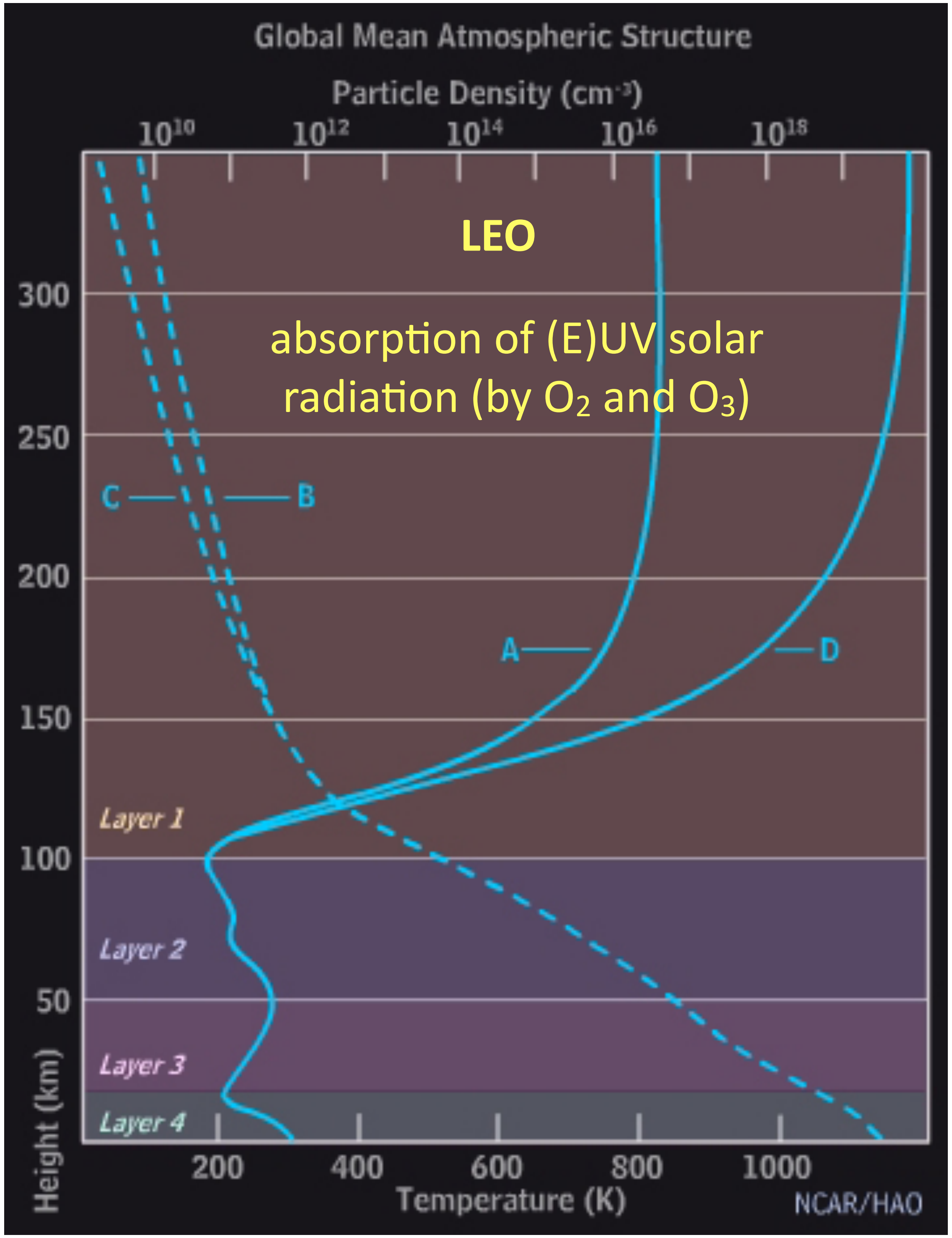
$H + O_3 \rightarrow OH + O_2 + 77\ \text{kcal}\ (2.6 \times 10^{-11})$

$H + HO_2 \rightarrow H_2 + O_2 + 57\ \text{kcal}\ (2.0 \times 10^{-13})$

$HO_2 + HO_2 \rightarrow H_2O_2 + O_2 + 42\ \text{kcal}\ (3.0 \times 10^{-12})$

$OH + HO_2 \rightarrow H_2O + O_2 + 72\ \text{kcal}\ (1.0 \times 10^{-11})$

https://www.tandfonline.com/action/showCitFormats?doi=10.3402/tellusa.v24i1.10619



Thermosphere:

- **Characteristics**
  - Very high temperatures, often exceeding 1000 k
  - Low neutral density
  - Matter sorted by gravity—heavier material at base
  - Dominated by atomic oxygen
- **Time Scales**
  - Solar cycle
  - Annual
  - 27 day
  - Equinoctal
  - Day /night

A Solar Min Temperature
D Solar Max Temperature

C Solar Min Density
B Solar Max Density

Courtesy of UCAR COMET

credit: Yihua Zheng

Atmospheric Density Variations at 400 km

Variations	change	frequency
Solar cycle	1600%	11 years
Semiannual	125%	12 months
Solar UV rotation	**250%**	**27 days**
Major geomagnetic storm	**800%**	**3 days**
Diurnal effect	250%	1 day

credit: Yihua Zheng

Sources of thermosphere heating

Prölss (2011) doi: 10.1007/s10712-010-9104-0

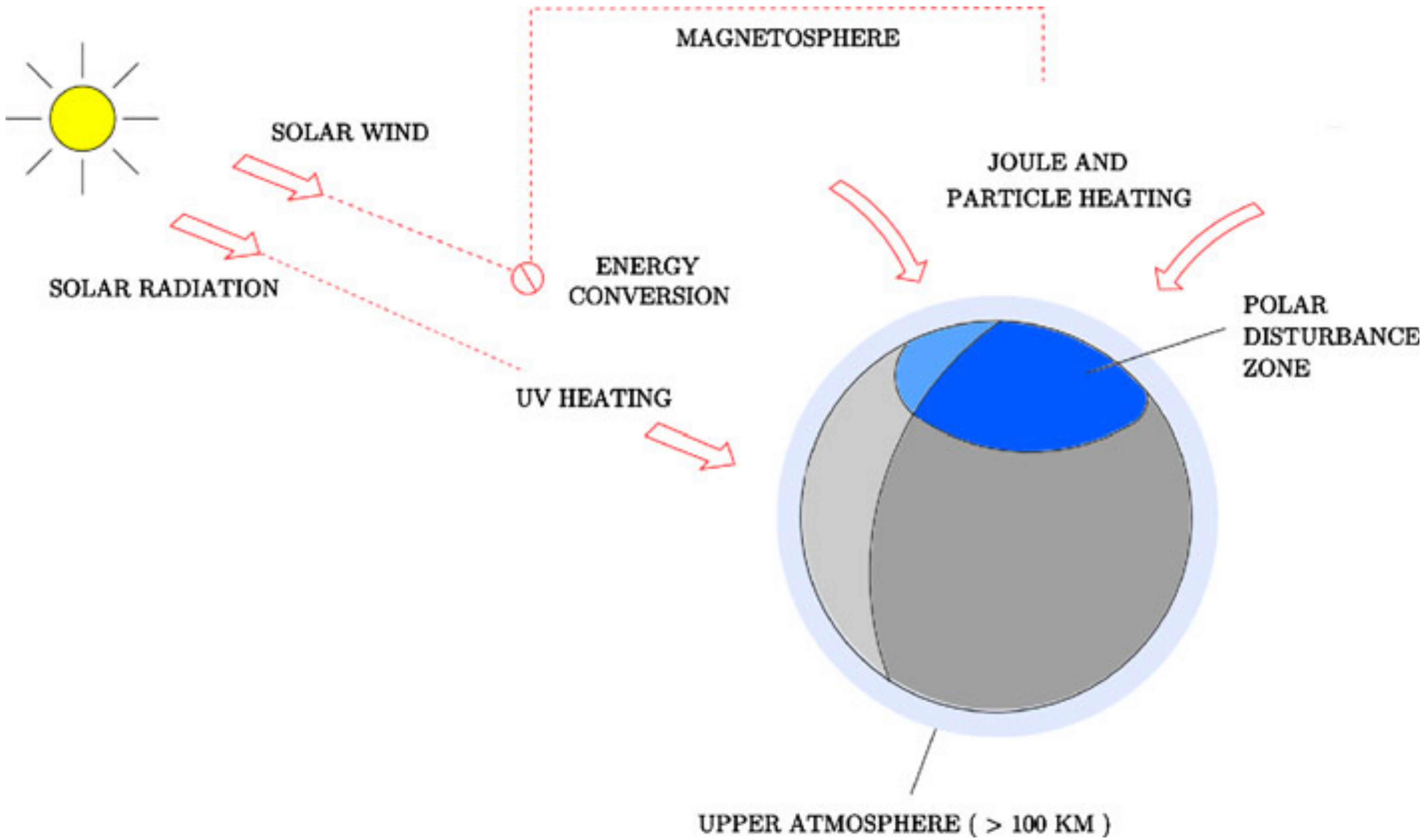


Fig. 1 Principal modes of energy transfer from the Sun to the Earth's upper atmosphere

Sources of thermosphere heating

Prölss (2011) doi: 10.1007/s10712-010-9104-0

(1) Absorption of solar high-energy electrons (β rays)

(2) Absorption of a flash of solar ultraviolet radiation

(3) Joule heating by (sub)storm currents

(4) Absorption of solar audio-frequency waves

(5) Heat conduction from the disturbed solar corona

(6) Heating by solar corpuscular radiation

(7) Energy deposition by storm-generated MHD waves

(8) Joule heating by currents induced in loops of magnetospheric flux tubes exposed to the variable interplanetary magnetic field

(9) Heat input by precipitating auroral particles

(10) Viscous heating by gravity waves generated in the polar upper atmosphere

(11) Heat conduction from the ring current

(12) Absorption of energetic ions precipitated from the ring current

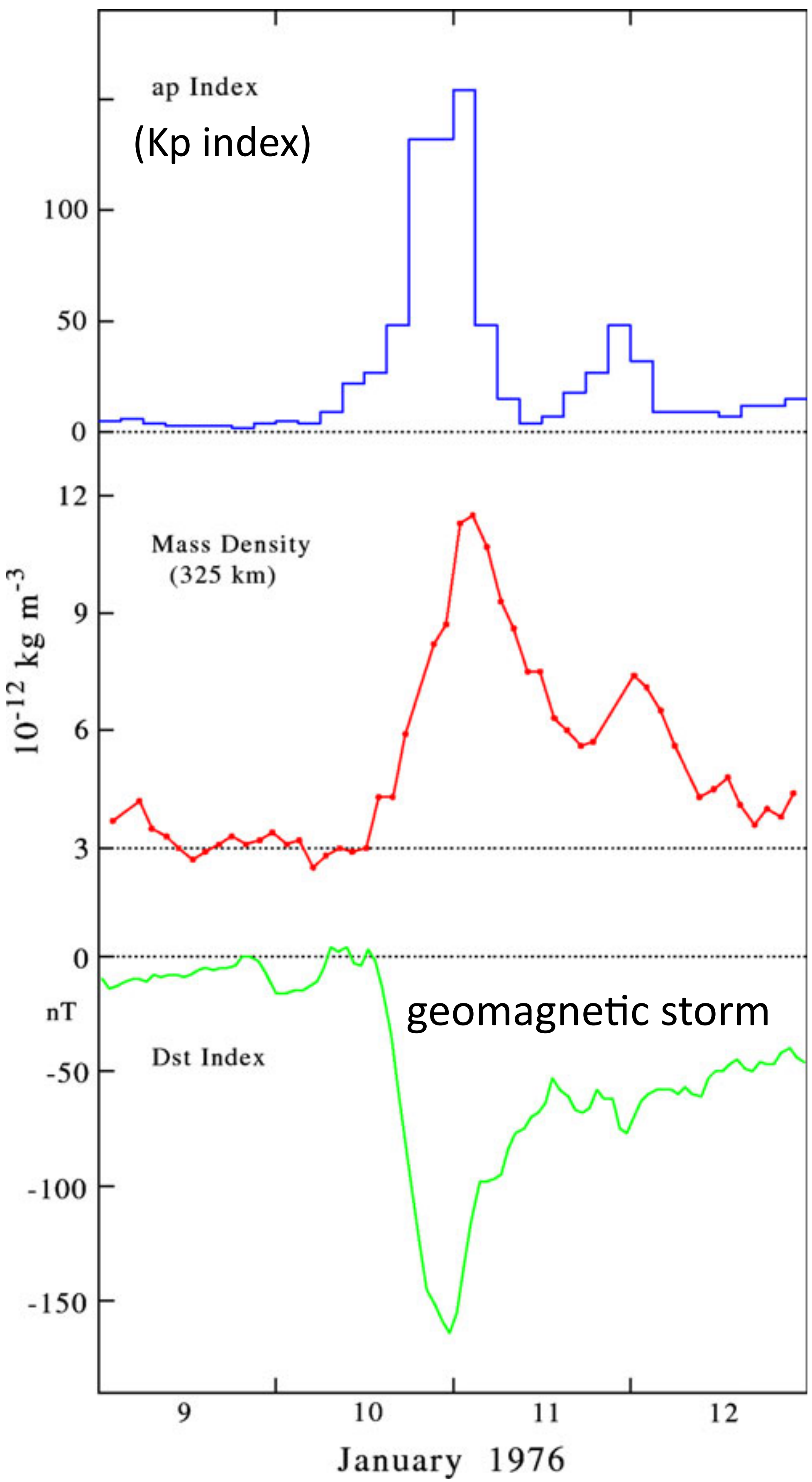
(13) Viscous heating by gravity waves generated in the middle atmosphere

(14) Joule heating by partial ring currents closing in the ionosphere

(15) Heat addition by heat conduction waves excited by MHD waves

(16) Absorption of neutralized energetic ring current particles

(17) Direct absorption of solar wind particles in the cusp region



$$\mathbf{F} = -\frac{1}{2}\frac{\rho C_D A}{m}\dot{r}\,\dot{\mathbf{r}},$$