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Space Environment

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CONTENTS

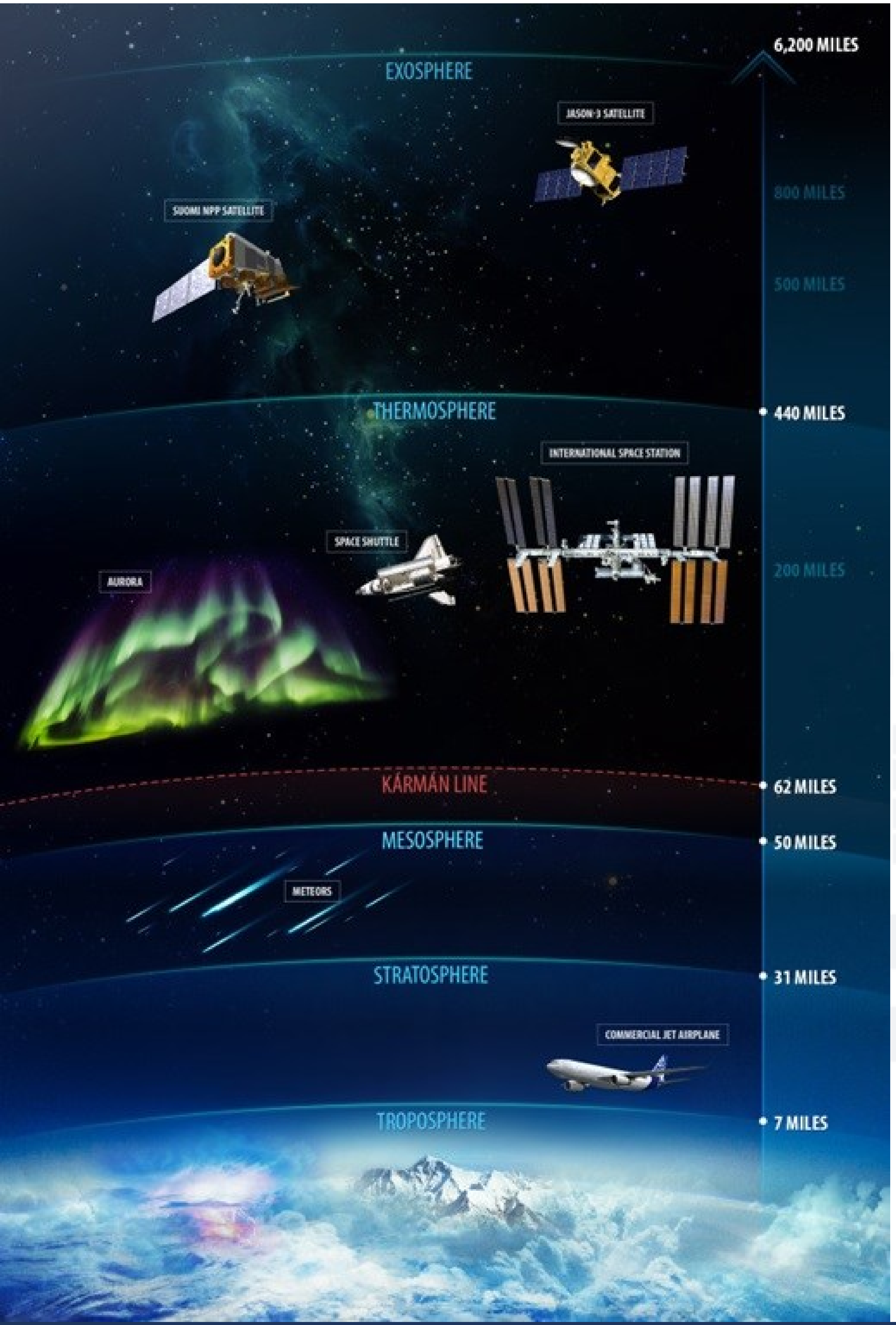
From ground to space

WHAT IS SPACE?

There is no a unambiguous definition of space, i.e. where it begins.

- It would be important to demarcate its boundaries: for instance, with respect to the applicability of cosmic/space law.

The threshold of access to space is set at various altitudes according to the principle that determines it:



- historically, **Karman's line** is taken as a reference: it identifies the altitude where **orbital dynamic forces** become more important than **aerodynamic forces**, i.e. when the atmosphere alone is not sufficient to support an aircraft at just suborbital speeds;
  - this definition is **determined by technology**, which can vary over time: indeed, this altitude, which was set by Karman at **80 km**, is now set at **100 km**: we can place an ideal threshold in this range;
- from 50 km, the **air density** is about one thousandth of that one at sea level;
- another boundary is set at **120 km**, i.e. at the altitude where the effect of **atmospheric drag** becomes relevant;
- if we had to consider the end of the atmosphere, then this one slowly becomes thinner, so we would have to wait hundreds of kilometres from the ground.

WHAT IS A SPACE MISSION ?

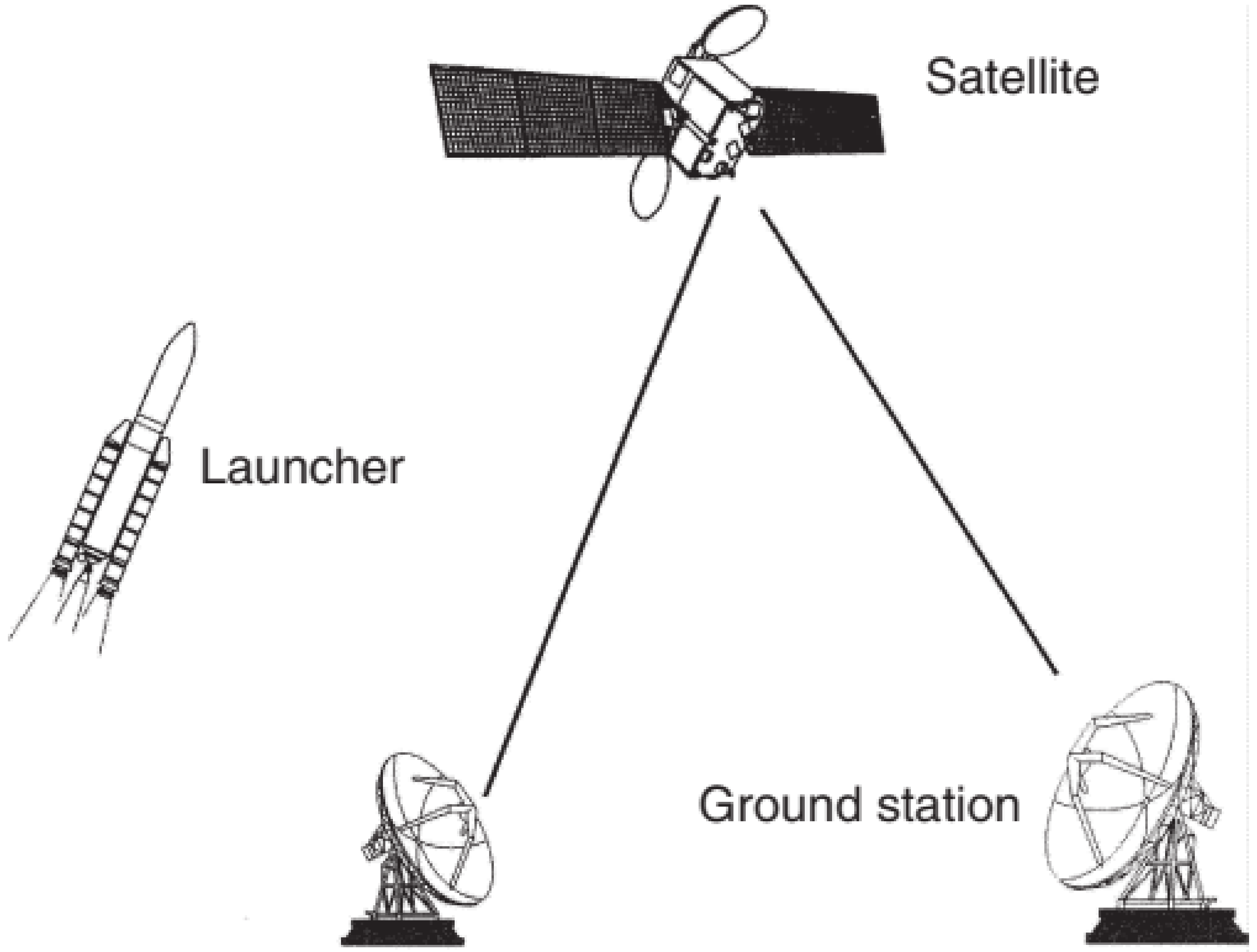
Nor there is official definition of space mission: however we can assume that it is ***a human activity, part of which takes place in (outer) space***.

An aspect of this definition of a space mission is important:

- '*a part of which takes place in space*', whereby not the entire mission operates beyond the Karman limit;
- rather, for the most part, the activity takes place on the **ground**.

Thus, a space mission is composed of several parts, called **segments**:

- space segment,
- ground segment,
- launch segment.



MECHANICAL LAUNCH ENVIRONMENT

Launch environment subjects payloads (spacecraft) predominantly to **mechanical stress**.

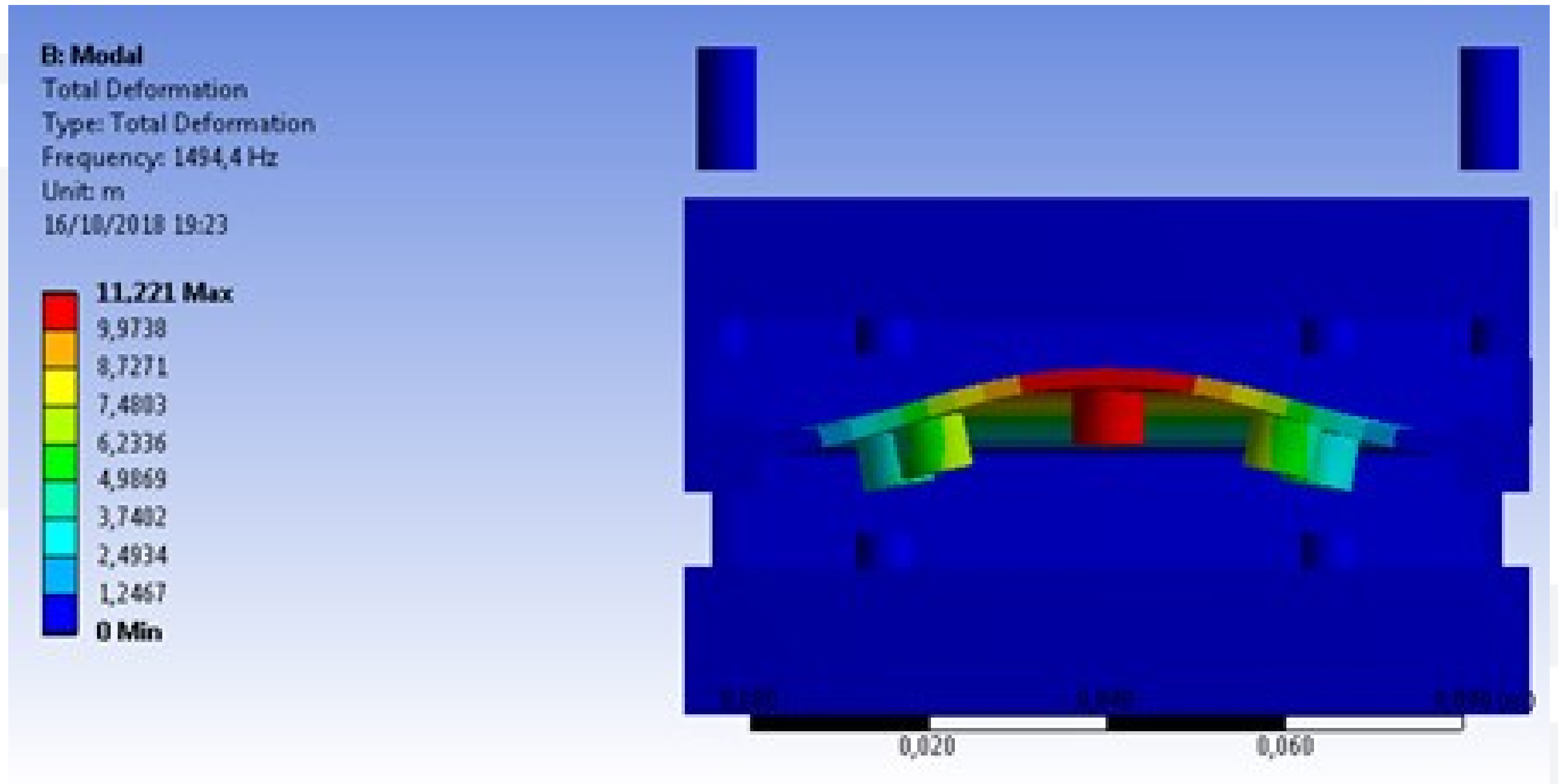
A satellite launch imposes quite severe **loads** on its structure, not only due to the **acceleration** of the launch vehicle, but also due to **vibrations**; during the ascent phase, the launch vehicle undergoes a separation of the launch stages, achieved by firing rockets, which can impart very strong **shocks** to the spacecraft.

Therefore, satellites and especially microsatellites must be designed to be **mechanically robust**. This applies not only to the spacecraft structure, but also to the electrical components:

- **COTS electronics** and their **welds** must be sufficiently robust to mechanically support the device;
- electronic components must **not be mounted too much above** the printed circuit boards (PCBs);
- **"heavy" devices** (e.g. large capacitors, crystals, etc.) must have **additional support** in terms of straps to hold them in place;
- **coatings**, (vacuum-rated) plastic foams, silicone rubber can also play a useful role in providing additional mechanical support (even though, they might not be suitable for the space environment).

SPACE MISSION ISSUES

One factor that must be considered very carefully is that of **mechanical resonance**. **Satellites** often fall within a mass stiffness range that leads them to have **resonance frequencies** on the order of a few tens of Hertz: this is precisely the frequency range in which launch vehicles tend to produce large vibrational energies, and thus satellites may experience a significant amplification (or Q-factor) of the loads imparted.



QSL at S/C CoG	**case 1**	Longitudinal*	– 14.5 g	
		Lateral**	–3 g	
	case 2	Longitudinal*	+ 10 g	
		Lateral**	+3 g	
Sine vibrations		Lateral direction	5 – 70 Hz: 2.0 g 70 – 110 Hz: 1.0 g 110 – 125 Hz: 0.2 g	
		Longitudinal direction	5 – 70 Hz: 2.0 g 70 – 110 Hz: 1.0 g 110 – 125 Hz: 0.2 g	
Random vibrations		Flight limit levels	20 to 100 Hz: 0.025 g2/Hz 100 to 2000 Hz: –3 dB/octave	
SRS (Shock response spectrum)		For S/C Separation event	100-1000 Hz	1000-10000 Hz
			40-1000 g	1000-800g

Each new structure must undergo **mechanical stress qualification tests** that are representative of the intended launch vehicle: for this reason, the **launchers** provide the stress ranges and **profiles** to which the payloads will be subjected.

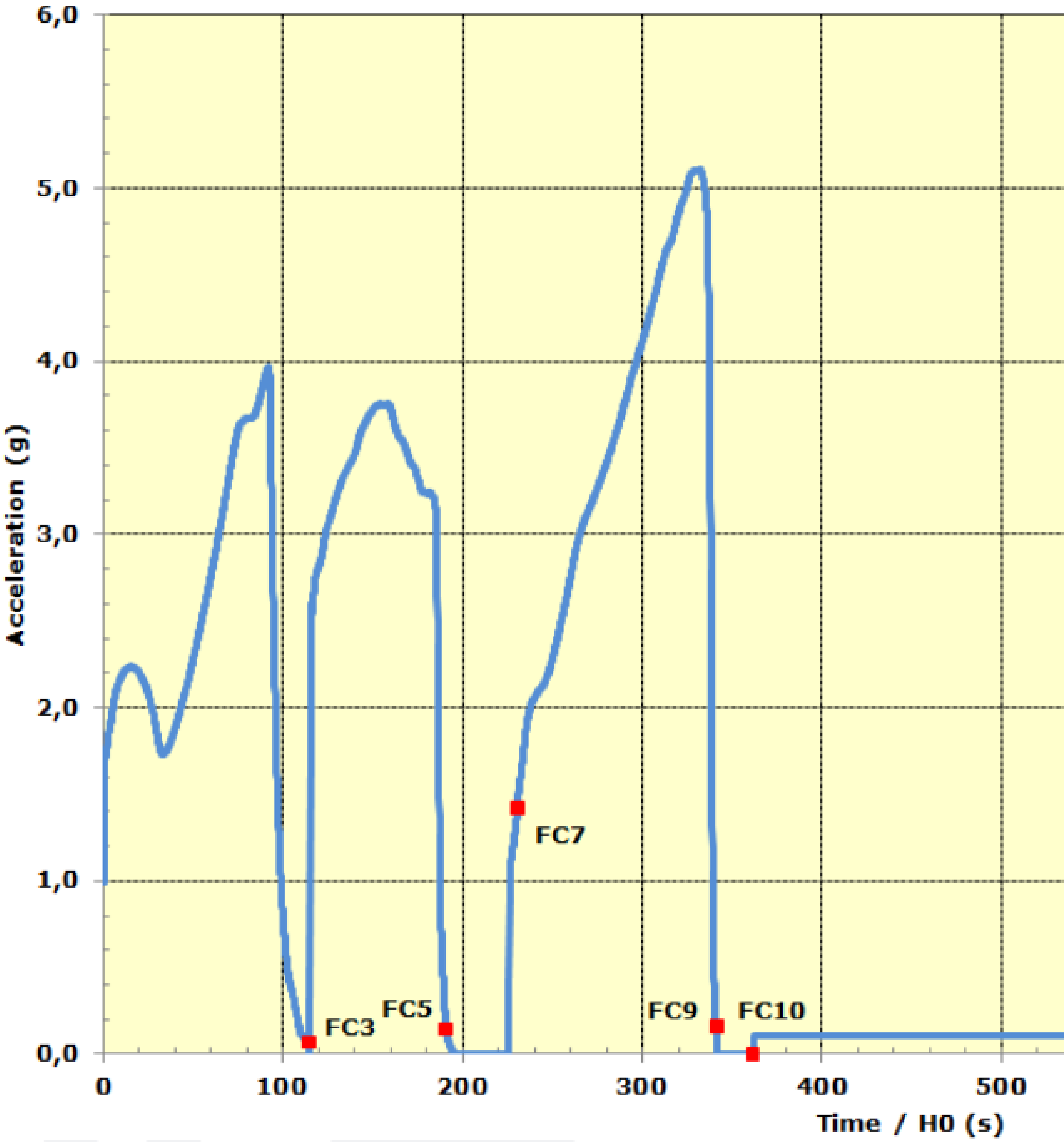
(Quasi) static loads

During ground and flight operations, the spacecraft is subject to **static and dynamic loads**:

- these excitations may be logistical (transport), aerodynamic (transonic phase buffeting) or propulsive (longitudinal acceleration).

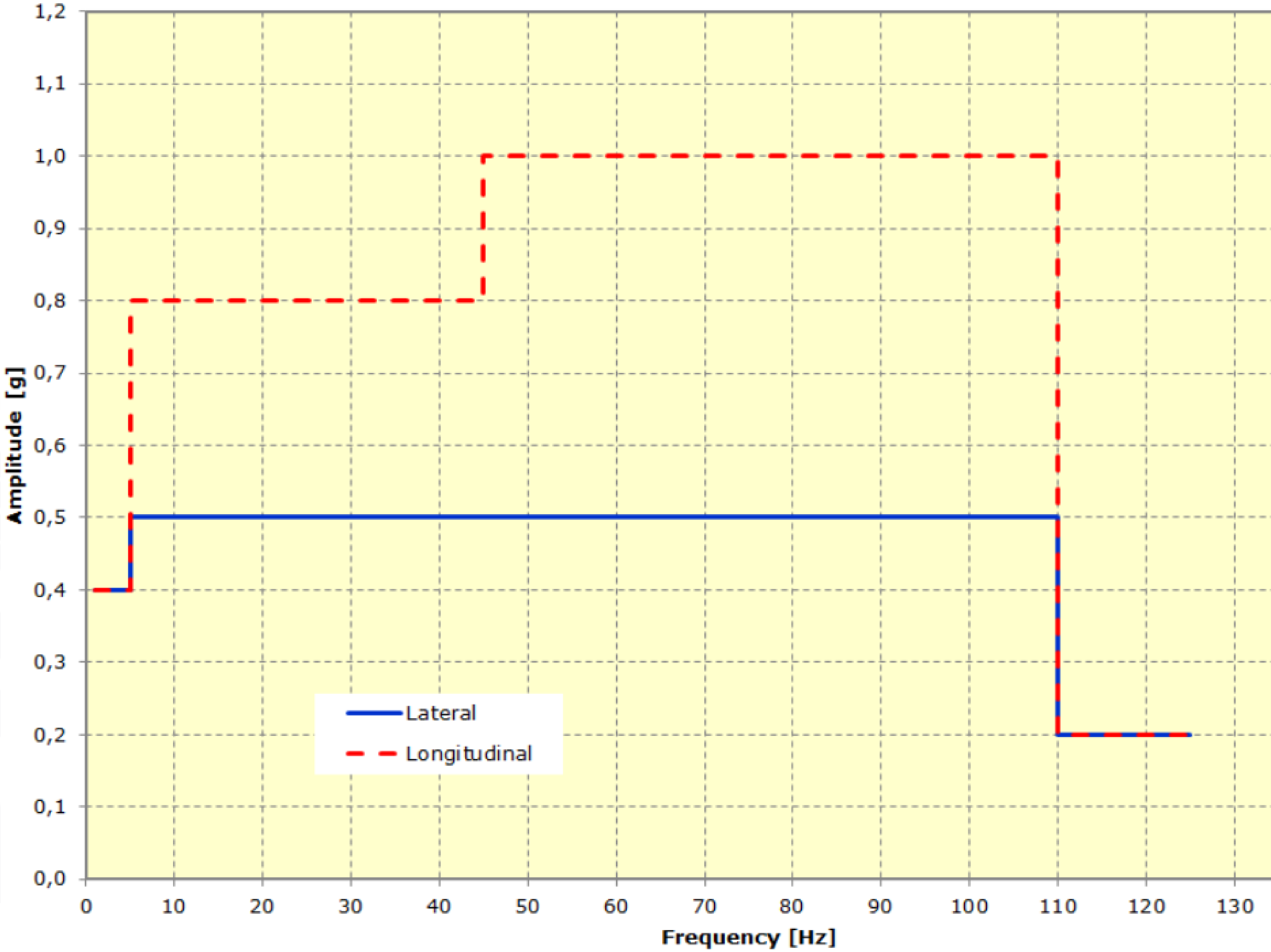
A quasi-static event consists of **time-independent** or **slowly-varying loads**, so that the dynamic response of the structure is not significant:

- in the launch context, quasi-static loads are typically expressed as **longitudinal or lateral accelerations applied to** the spacecraft's **Centre of Gravity** (CoG);
- in figure, a typical evolution of the **longitudinal static acceleration over time for a launch vehicle** during the ascent flight: **the highest** longitudinal acceleration occurs **just before the third stage cutoff**.



Sine-equivalent vibrations

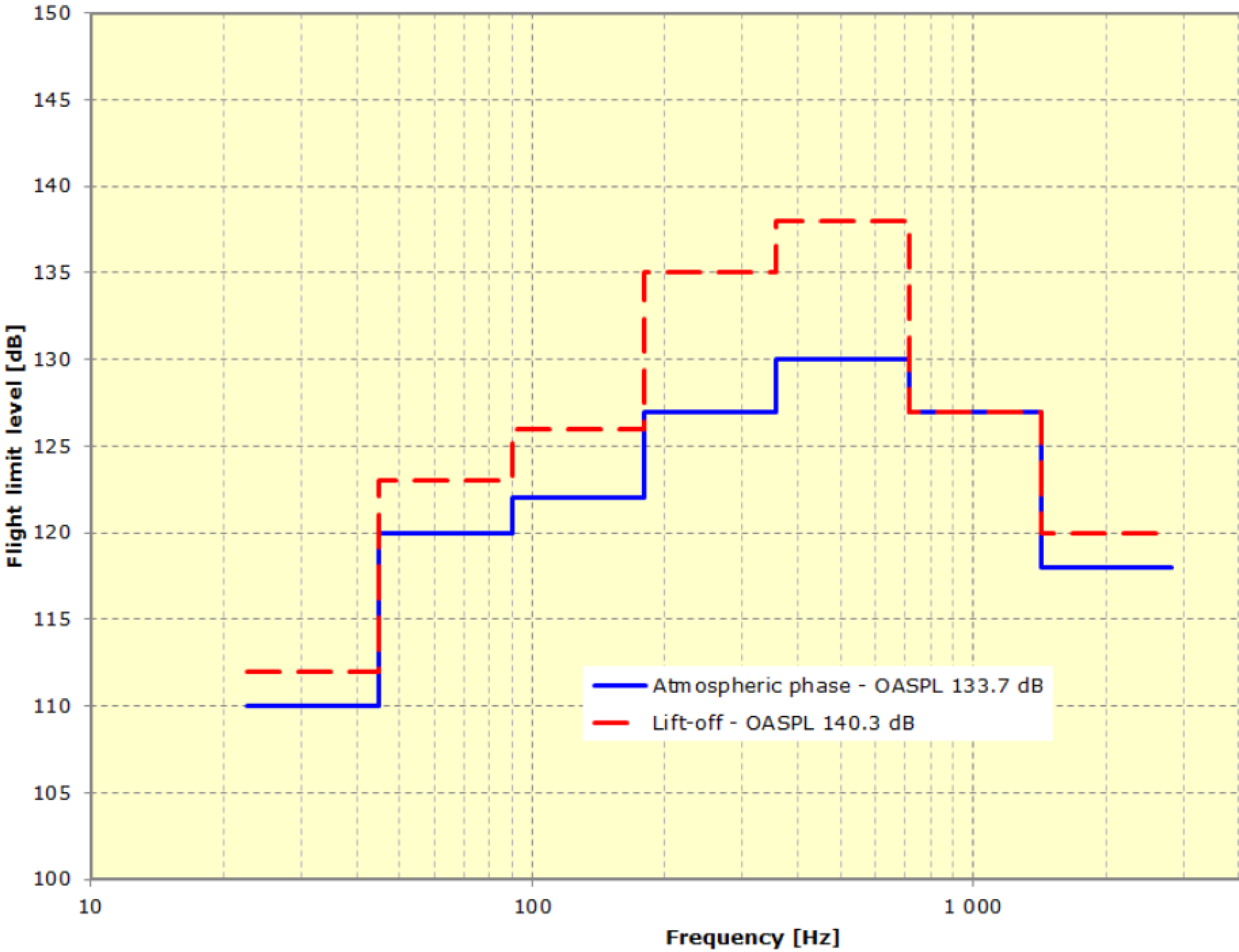
Sinusoidal excitations are **low-frequency vibrations** that occur during **atmospheric flight** as well as during certain **transient phases**.



Random vibrations

Random vibrations are **pressure fluctuations** primarily generated by the **propulsion system** and the **vibro-acoustic response**, i.e. noise, generated by the adjacent **structure**:

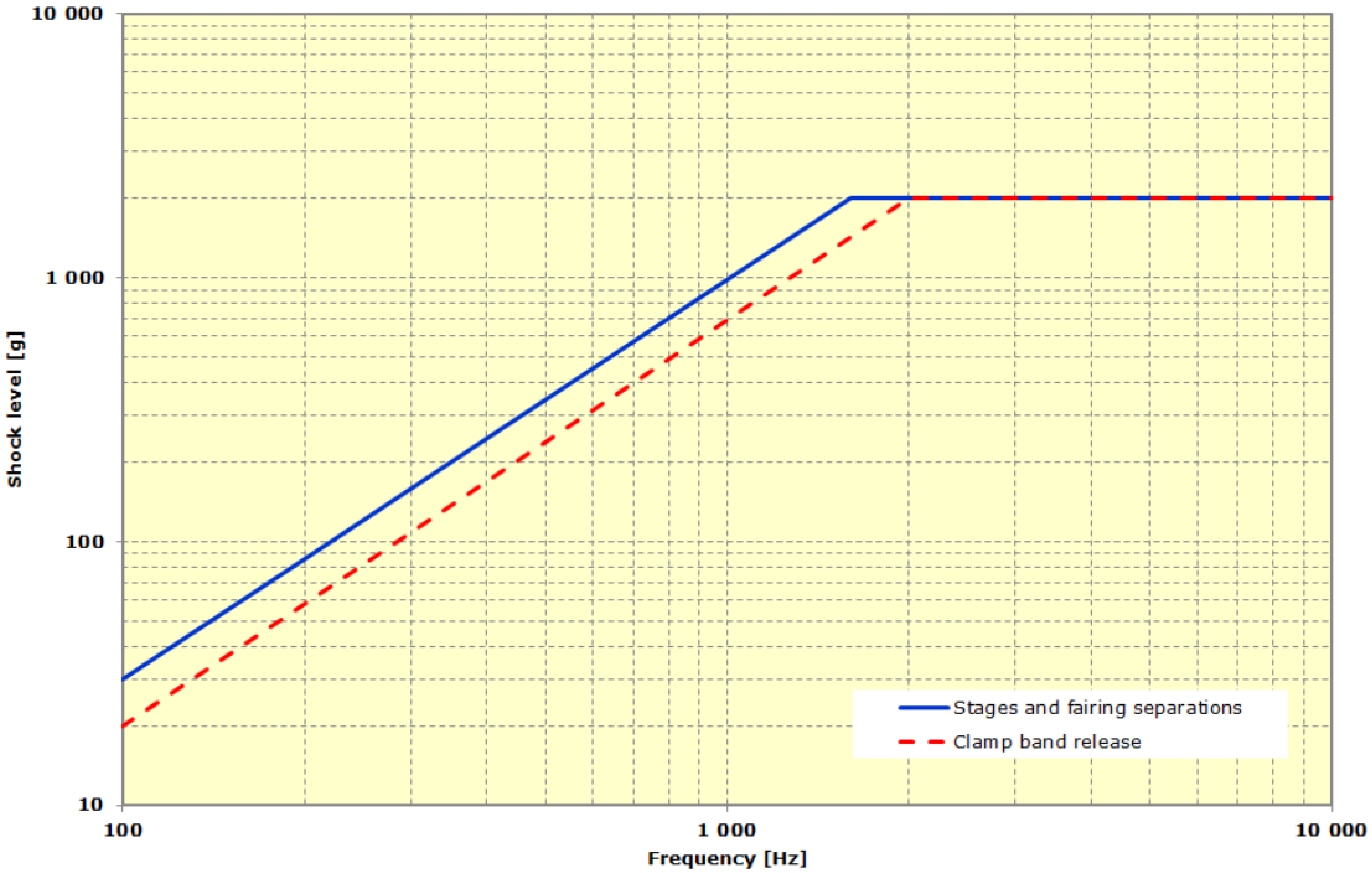
- both **frequency** and **amplitude** of this type of vibration are **not constant**.
- **several frequencies** can act at the **same time**: therefore a statistical approach is used;
- **maximum** excitation **levels** are obtained during the launch **first stage**.



Shocks

Shocks occur during **stage separations**, when explosive devices developed to allow a part to detach from the main vehicle:

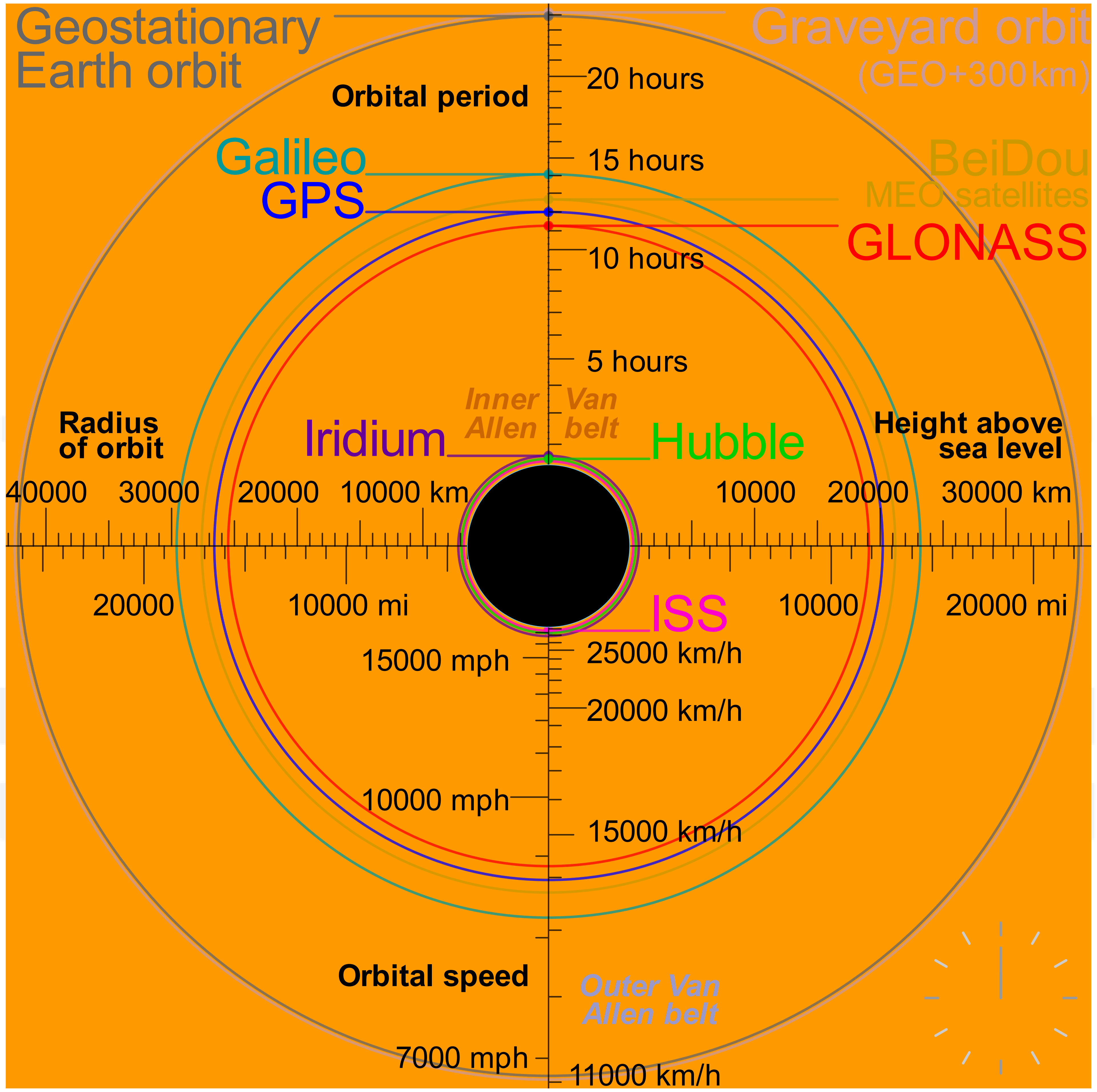
- the satellite is then subjected to **strong accelerations that decay rapidly** over time;
- acceleration given in the time domain is then converted into a **shock response spectrum** (SRS).



Space physics

ONCE IN SPACE

Orbit review

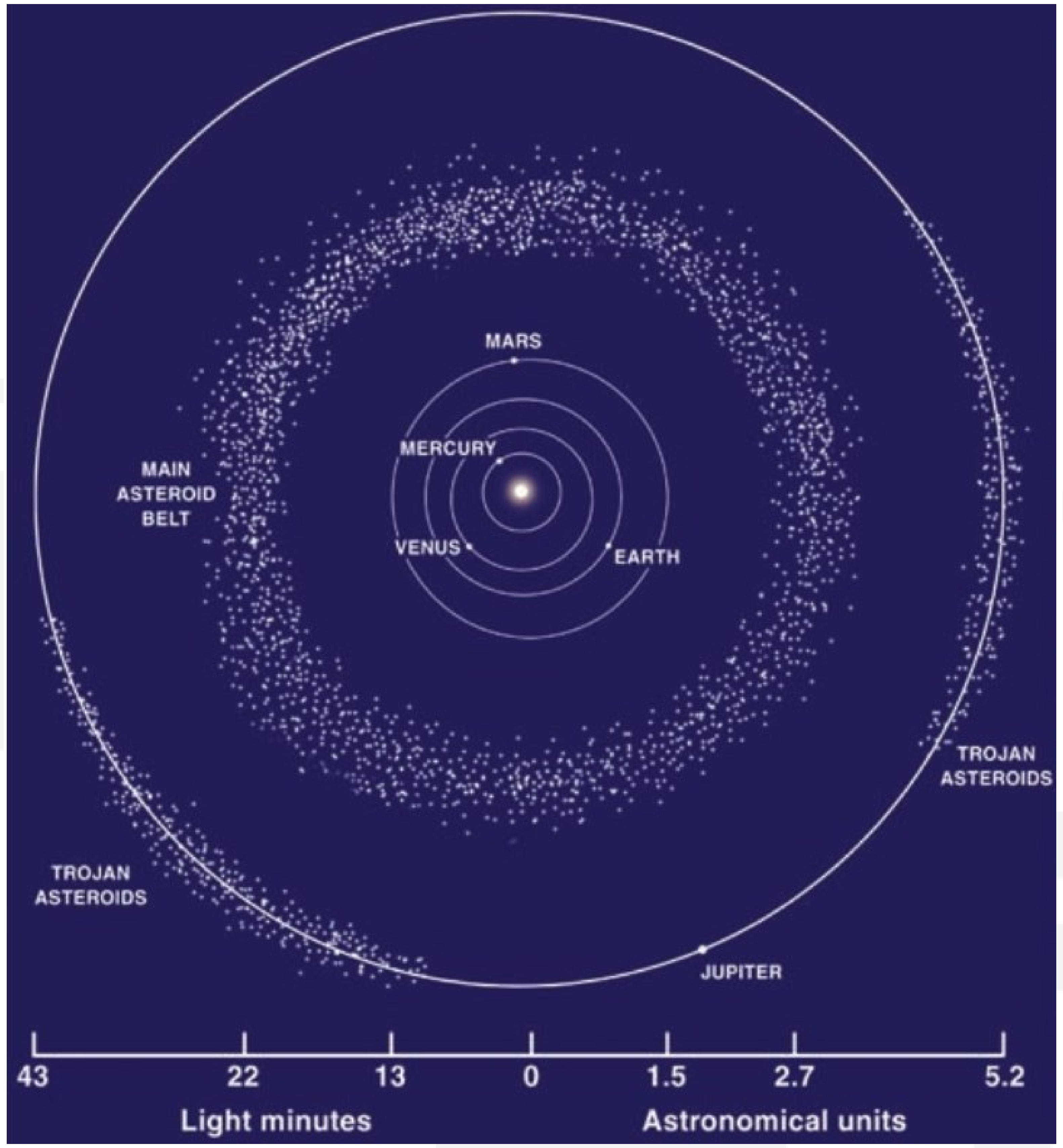


INTERPLANETARY ENVIRONMENT

Once in orbit, spacecraft experience special conditions:

- relatively little mechanical stress on the structure;
- a rather **harsh environment**:
  - **thermal** shocks;
  - very low density (**vacuum**);
  - **microgravity**;
  - **radiation**.

SOLAR SYSTEM



Outer space is not completely empty: in the Solar System in addition to

- **inner planets**: Mercury, Venus, Earth, Mars, terrestrial-rocky, smaller in size, with few natural satellites;
- **outer planets**: Jupiter, Saturn, Uranus, Neptune, less dense, larger in size, with numerous natural satellites;
- separated by the **asteroid belt** orbiting at a distance of about 2.7 AU from the central star: an asteroid is a small rocky celestial body (of three types: carbonaceous, siliceous, metallic) without an atmosphere with a **characteristic diameter**
  - less than several **hundred kilometres** (to distinguish asteroids from planets),
  - greater than about **50 m** (to distinguish asteroids from meteoroids);

INTERPLANETARY ENVIRONMENT

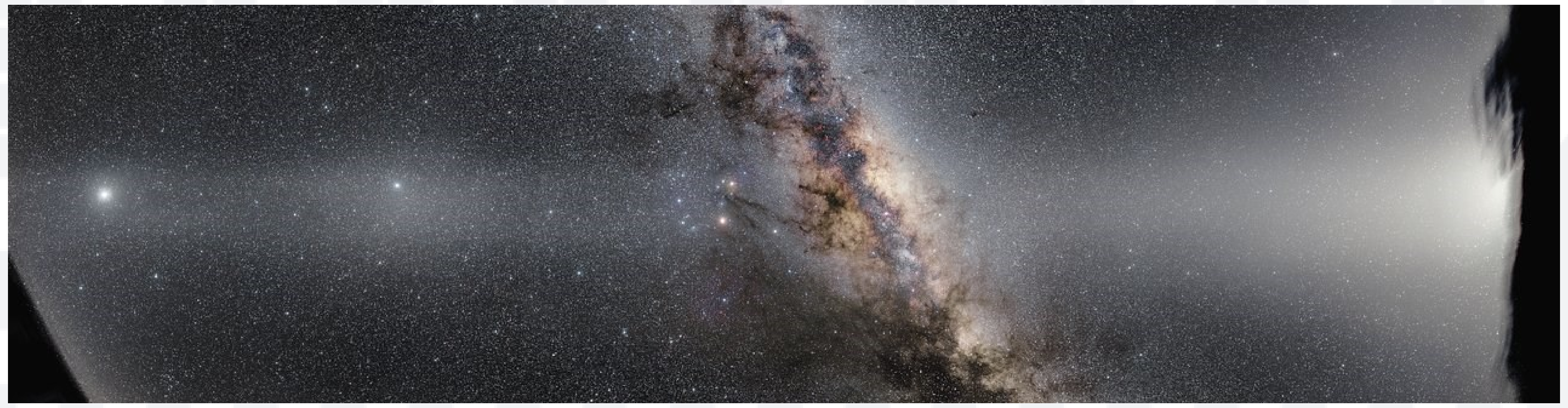
- **meteoroids** are small pieces of **debris**, ranging from the size of sand to that of a boulder less than 50 m in diameter, drifting in the Solar System: they are generated by collisions between asteroids and the dissolution of cometary nuclei near the Sun, or by impacts between asteroids and comets with the surface of telluric planets or satellites;
- **comets**, small celestial bodies in orbit around the Sun, composed of dust and an icy core of **carbon dioxide**, **methane** and **water**, with a **tail in the anti-solar direction** up to tens of millions of kilometres long: most comets travel in **highly elliptical orbits** around the Sun with orbital periods of more than a few years;
  - periodic comets with **orbital periods of a few years** have an aphelion around the orbit of Jupiter, and would originate in the **Kuiper Belt**, a disc-shaped region of small icy bodies extending from 30 to 50 AU (their motion is influenced by the outer planets);
  - **longer-period** comets would originate in the **Oort Cloud**, a collection of ice and dust surrounding the solar system and extending from about 2 000 to 100 000 AU (their motion is influenced by the transit of nearby stars);

we also find something else ...

INTERPLANETARY MEDIUM

Space contains an interplanetary medium of particles, mainly a **plasma** of hydrogen and helium, and other atoms and molecules, as well as electromagnetic **radiation**, magnetic **fields**, neutrinos, dust and cosmic rays:

- all components that can **adversely affect spacecraft**, causing performance reductions and failures.



The interplanetary medium

- has a **very low and highly variable density**: in the vicinity of the Earth it is 5 particles cm^{-3}, while it can be as high as 100 particles cm^{-3};
- is mainly **influenced by the Sun** (magnetic fields and transient phenomena): indeed, **density decreases inversely proportional to the square of the distance from the Sun**;
- **differs from the interstellar medium**: the Solar System dust consists of 99.9% dust generated within the Solar System itself and 0.1% dust from the intruding interstellar medium;
  - **sources of interplanetary dust particles** include at least: asteroid collisions, cometary activity and collisions in the inner Solar System and Kuiper belt;
  - **dust** is responsible for several **optical phenomena** that are visible from the Earth: **zodiacal light** is a wide band of faint light (so faint as to be completely invisible if the Moon is present in the sky) that can sometimes be seen after sunset and before sunrise, and which extends along the ecliptic and appears brightest near the horizon; this glow is caused by sunlight scattered by dust particles in the interplanetary medium between the Earth and the Sun.

SUN

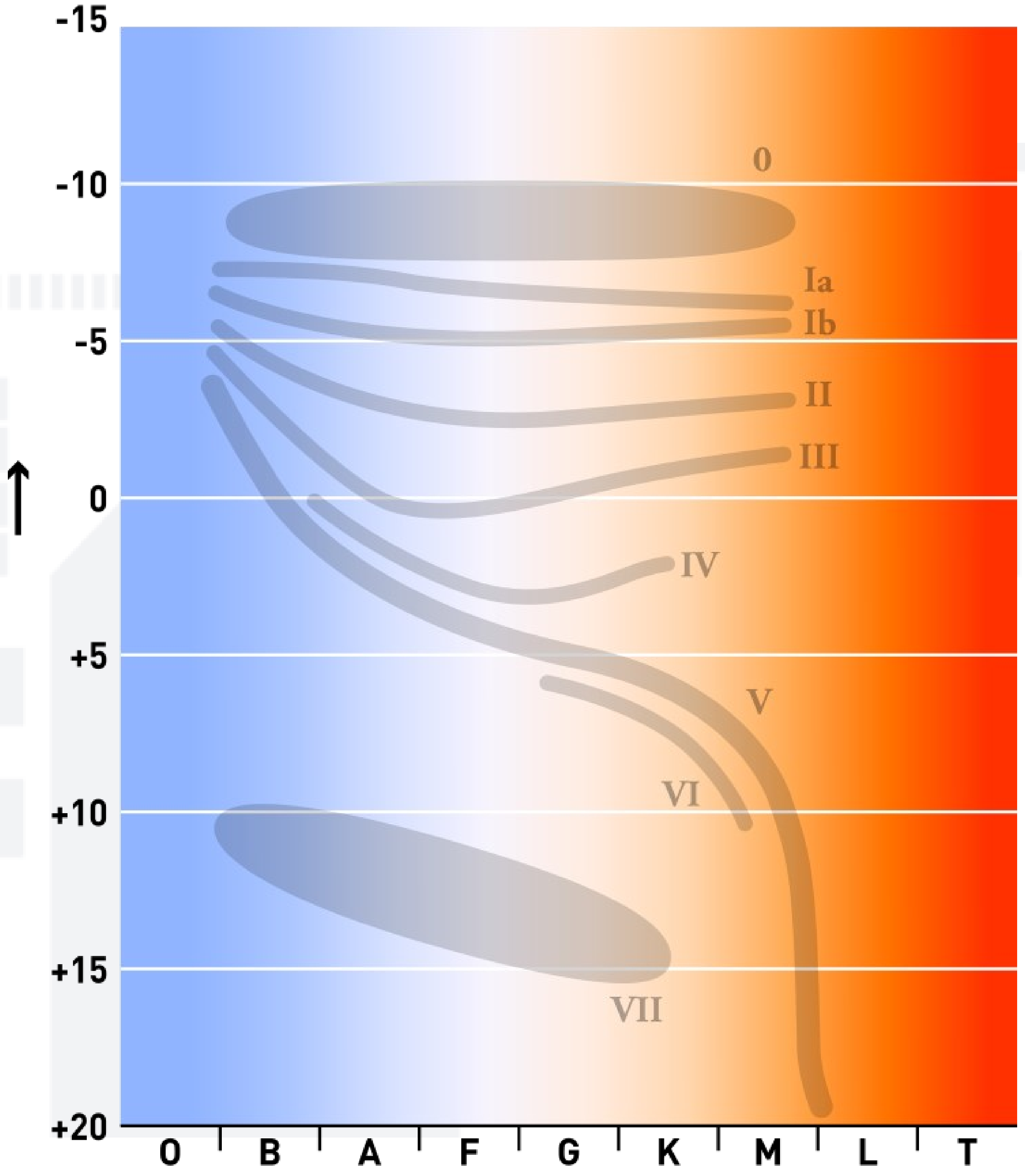
The Sun is the largest object in the solar system with a radius of $6.96 \cdot 10^8$ m and an angular extension from the Earth of 0.5 degrees;

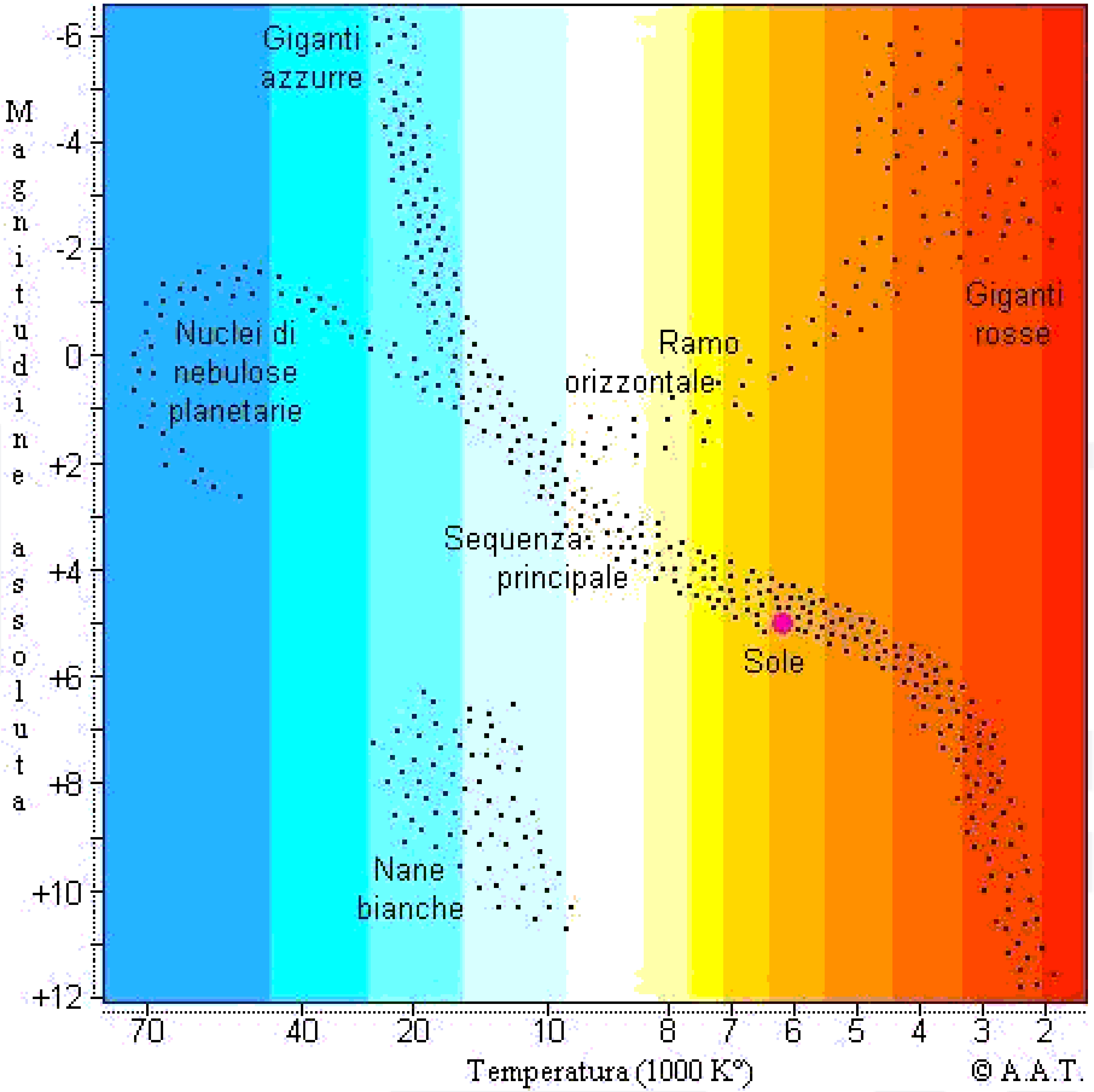
- the Sun's rotation and magnetic field make its **radial symmetry** be altered by only 9 parts per million, i.e. its polar diameter differs from its equatorial diameter by only 10 km.

In stellar terms, it is a small to medium-sized star,

as it belongs to the **G2V** class in the H-R diagram:

- G indicates the spectral class:
  - surface temperature: 5 772 K
  - solar mass $1.99 \cdot 10^{30}$ kg;
  - yellow dwarf star (between 0.8 and 1.44 solar masses);
- V indicates that it is a **Main Sequence** star.

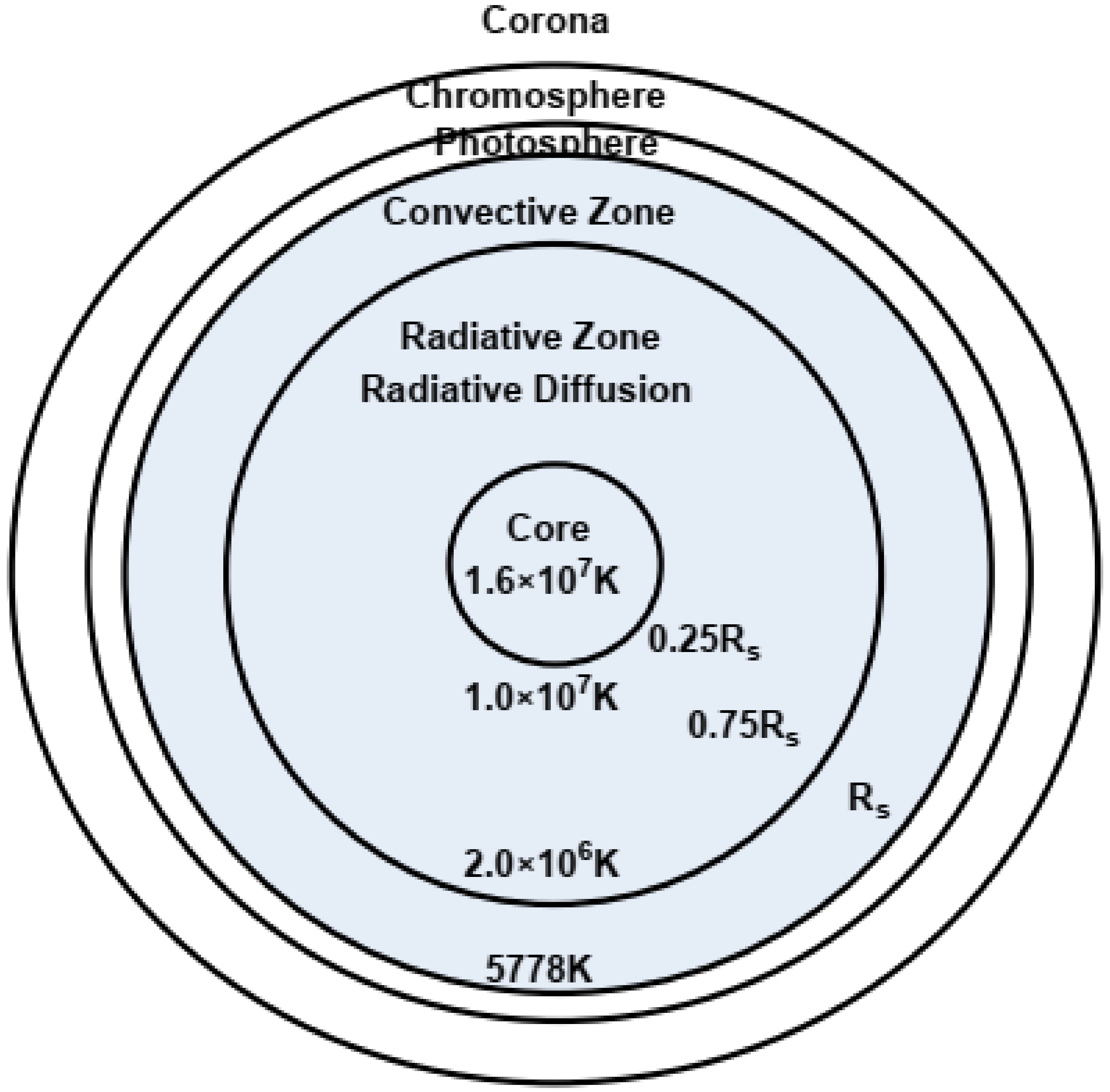


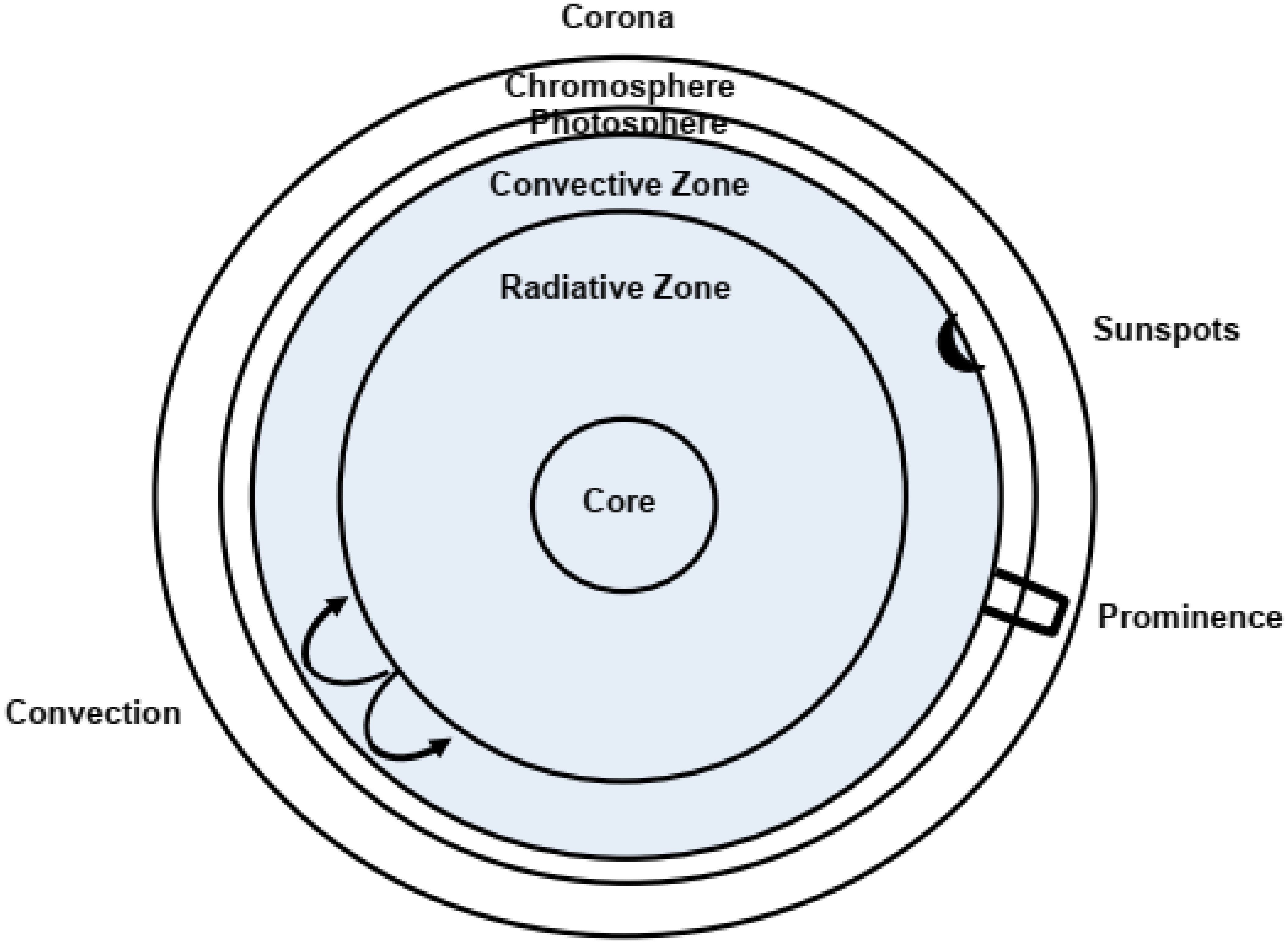


Having 1 solar mass (< 1.44 Chandrasekhar limit) in Main Sequence, its **lifetime** is about 9-10 billion years:

- now, in the middle of its journey, it **is sustained by nuclear fusion**, which **converts hydrogen into helium** in its core:
  - Sun constituents are hydrogen about 74%, helium about 24% and traces of other elements about 2%, all in varying degrees of ionisation;
- in about 4.5-5 billion years, the Sun will exhaust its nuclear fuel, at the end of which it will evolve into a **white dwarf**.

Solar structure





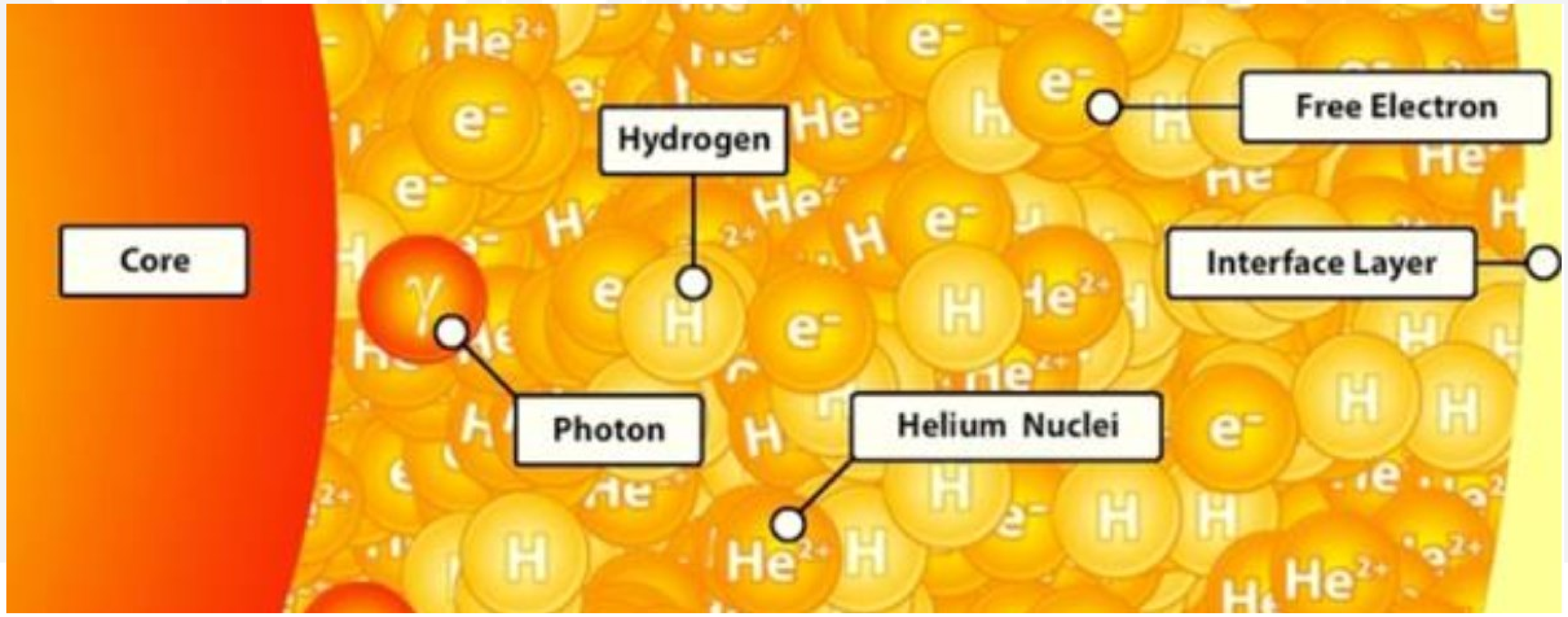
Solar structure

Core.

- The innermost region of the Sun, with a **radius** about 0.25 solar radii (174 000 km), a **density** more than 150 times the water one (150 000 kg m^{-3}), and a **temperature** about 16 000 000 K.
- High density and temperature conditions allow all constituents to be completely ionised and support energy-producing **thermonuclear fusion**.
  - Nuclear fusion converts **4 hydrogen nuclei** (protons) **into 1 helium nucleus** composed of 2 protons and 2 neutrons, through three primary processes: the **proton-proton chain**, the decay of radioactive boron and, marginally, the carbon-nitrogen-oxygen (CNO) cycle, which produces heavier elements and dominates in stars greater than 1.44 solar masses.
  - The neutron mass is lower than proton one: the **difference in mass is converted into energy**.
  - The energy created is of the order of **MeV** (gamma rays), and is **transported to the outer layers of the star**.

Radiative zone.

- Region of **highly ionised gas** from about 0.25 solar radii (174 000 km) to 0.75 solar radii (522 000 km), temperature 10^7 K to $2 \cdot 10^6$ K, density $2 \cdot 10^4$ kg m^{-3} to $2 \cdot 10^2$ kg m^{-3}.
- **Energy transport** from the core to the outer surface of the radiative zone occurs mainly by **scattering of gamma-ray photons**:
  - mean free path: $\lambda_{photons} \approx 1$ mm
  - diffusion timescale: $t_{photons} \approx 10^5$ year



Solar structure

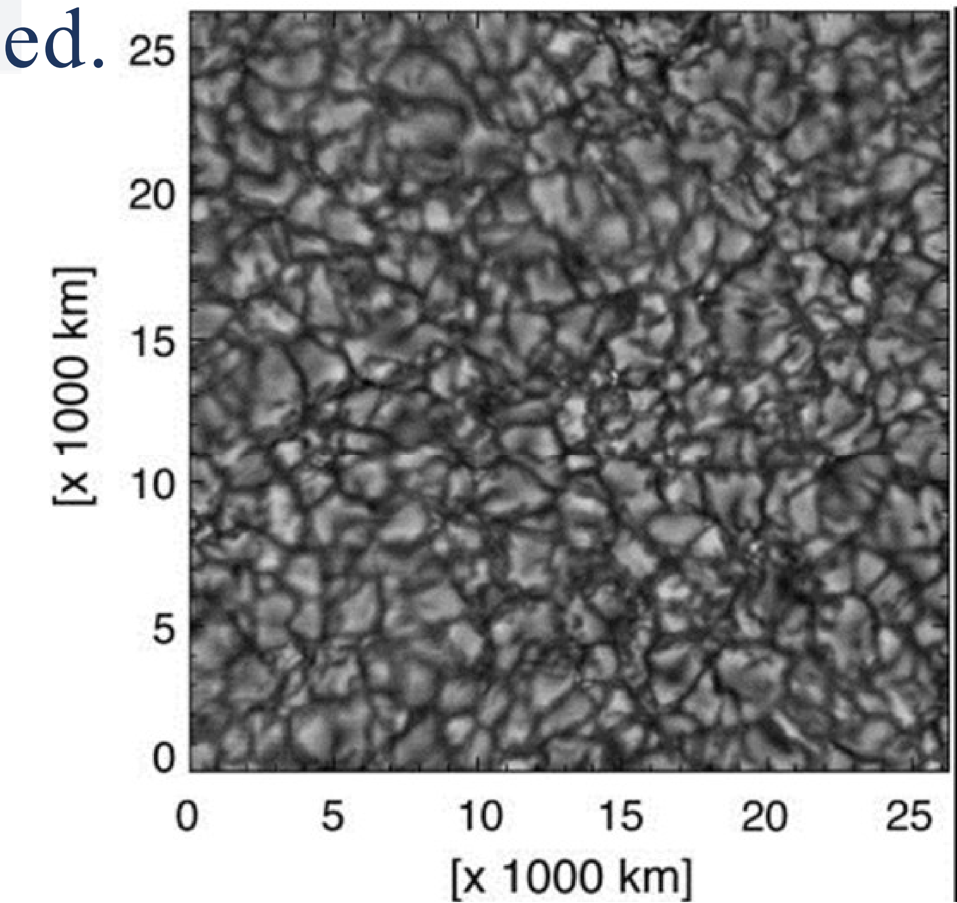
Tachocline.

- Transition between radiative region and convective region at 0.7 solar radii with a thickness of 0.05 R_{Sun}.
- It marks the **transition** between the **innermost** portion of the star, whose rotation is comparable to that of a rigid/**solid body**, and the **outer** portion, which rotates differentially, behaving like a **fluid**.
- **Solar dynamo**: this is **where the strong toroidal magnetic field is generated** as a result of the fact that in this area there are intense shear stress/forces between the different parts of the Sun rotating at different speeds, and ultimately stretching a kind of matter that is an excellent electrical conductor: therefore, currents that are responsible for the magnetic field are generated.

Solar structure

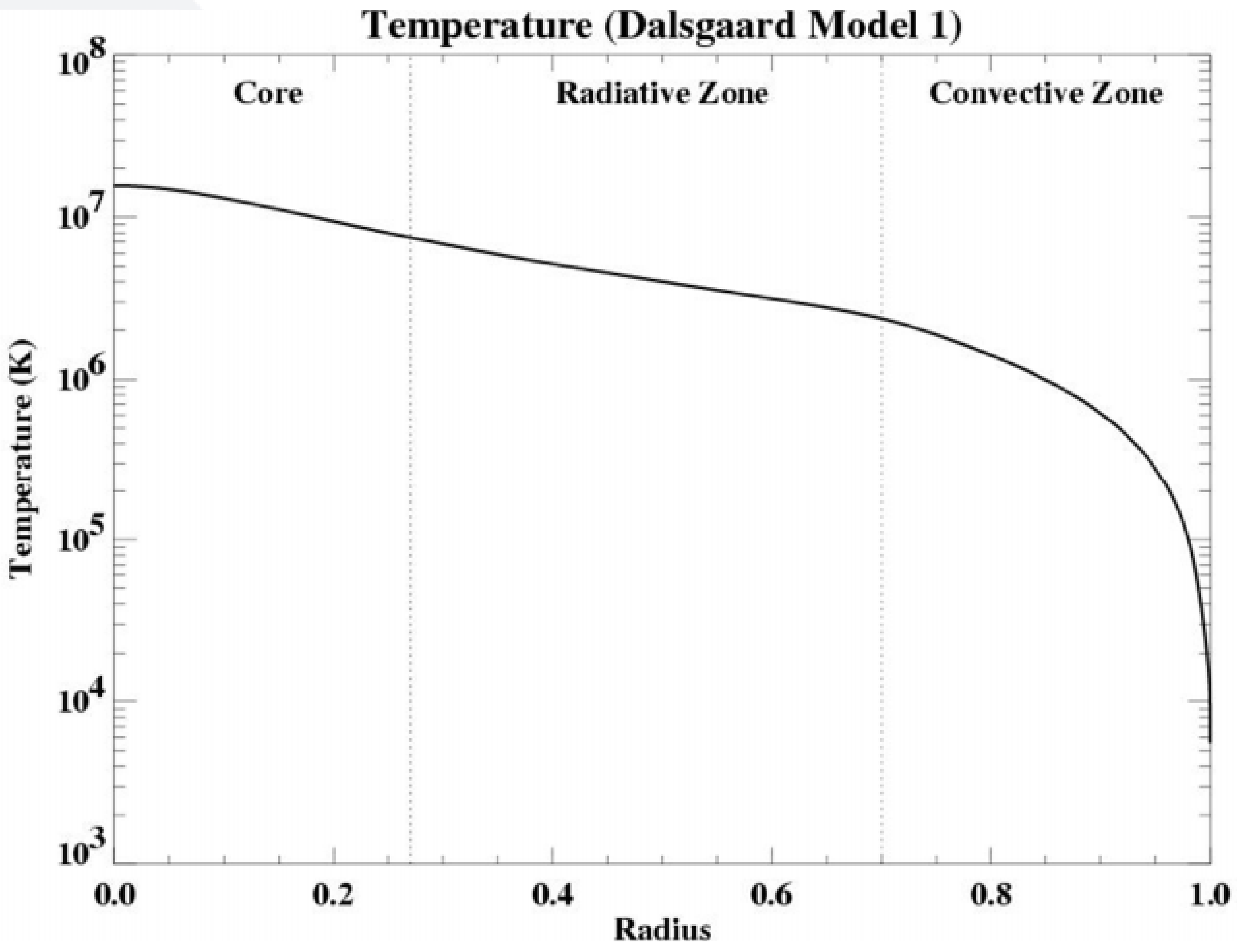
Convective zone.

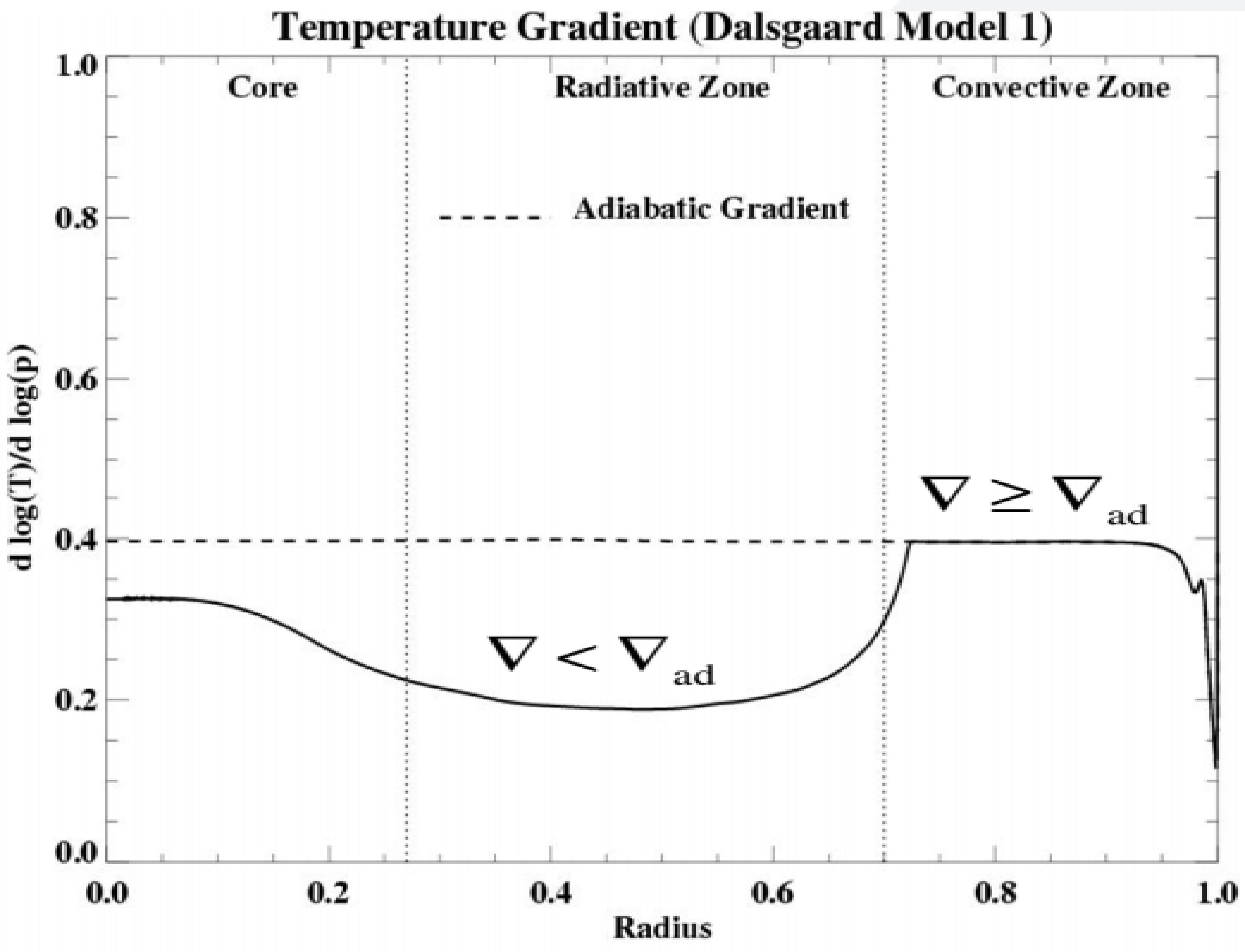
- **Outermost region** of the Sun, from about 0.75 solar radii, as thick as 200 000 km up to the visible surface; the temperature varies from about 2 000 000 K at the bottom of the convection zone, to about 5 778 K at the surface, where the density is $2 \cdot 10^{-4}$ kg m^{-3}, about $1 \cdot 10^{-4}$ with respect to the air density at sea level on Earth.
- The surface of the convection zone is **where energy is radiated from the Sun**.
  - Convective regions on the surface of the sun are **visible in the form of surface granulation** with dimensions ranging from 1 000 to 30 000 km.
  - When the plasma reaches the cooler surface of the convection zone, it cools and returns to the bottom: a pattern of bright cellular elements, the granules, surrounded by a network of dark intergranular fluff is formed.



Solar structure

- Convection occurs because the **temperature gradient becomes steeper than the adiabatic temperature gradient**. The temperature gradient becomes steeper because the **temperature is lower than the radiative core temperature, low enough not to ionise all elements**: this implies that heavier elements are not ionised, that makes **radiative transport less efficient than convective transport of fluids** in turbulent motion.

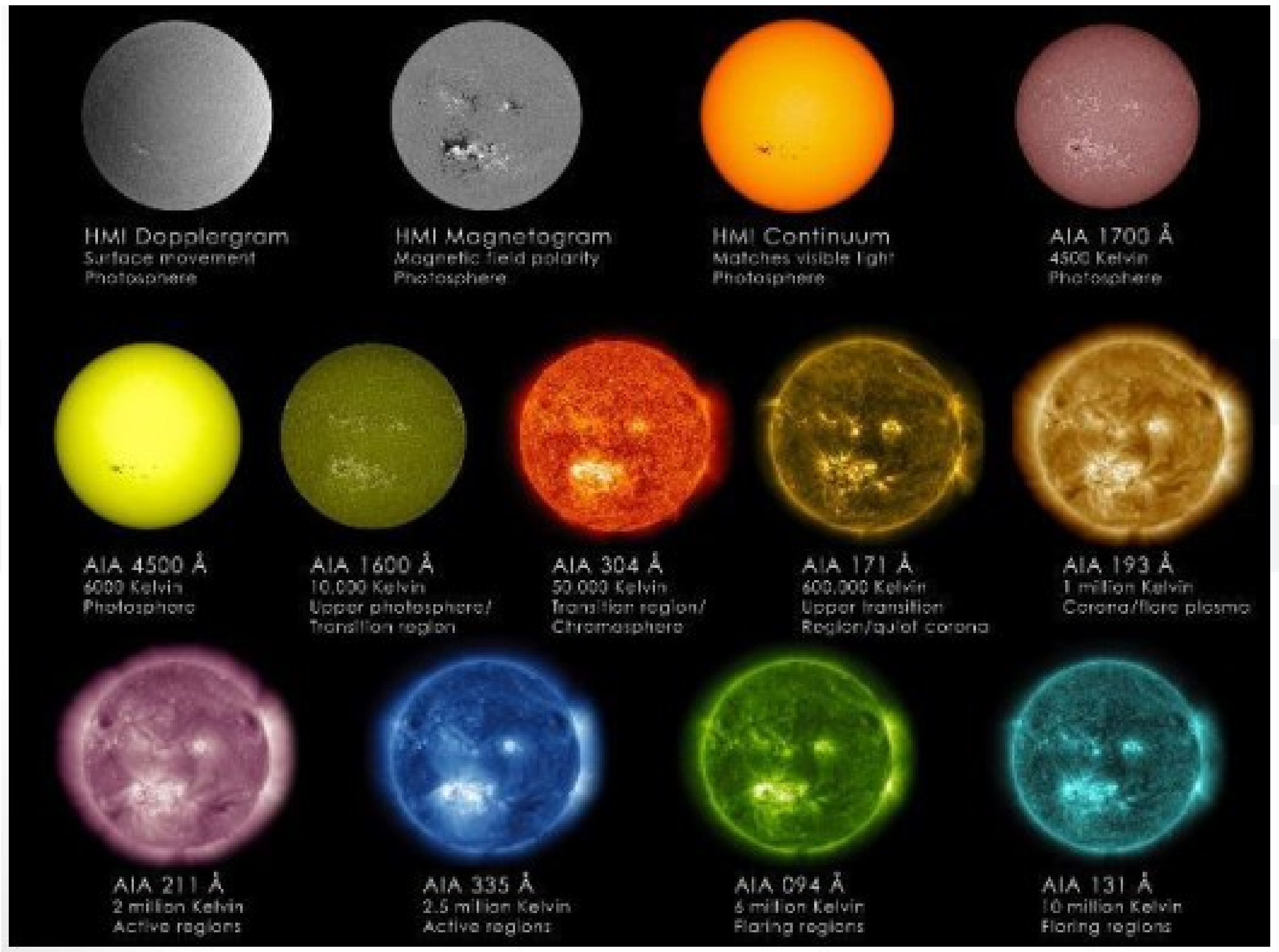




Solar atmosphere structure

Photosphere.

- The photosphere is the **visible** surface of the Sun, about 500 km thick, with a blackbody radiation temperature of about 5 778 K and a particle density of about 1 per cent of the density of the Earth's atmosphere at sea level.
- When energy in the form of gamma rays diffuses from the core towards the photosphere, **gamma rays are scattered, absorbed and re-emitted by nuclei and electrons**: as a result, high-energy gamma ray radiation is **transformed** into the **blackbody radiation spectrum**. **Neutrinos** that have weak interactions leave the nucleus and remain largely **unaffected**.



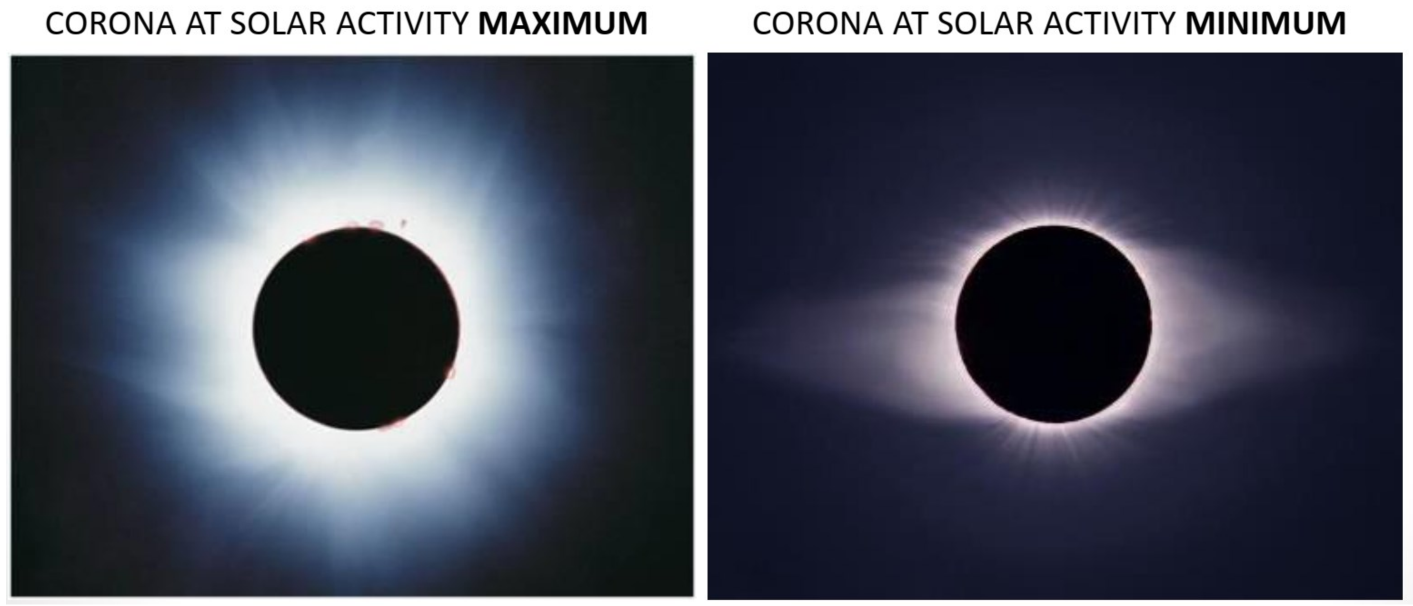
Solar atmosphere structure

Chromosphere.

- Region extending 2 000-5 000 km above the photosphere. Its density is 10^{-8} times lower than that one of air at sea level. It is considerably warmer than the photosphere, with a temperature of around 10 000-40 000 K.
- The chromosphere has a characteristic red colour due to electromagnetic emissions at the *Hα* spectral line, 656.3 nm, emitted by energy transition of atomic hydrogen.

Corona.

- The Sun's outermost plasma atmosphere, visible during a total solar eclipse, has no well-defined outer surface: its structure varies with solar activity. Plasma from the corona flows into the solar wind, which emanates from the Sun and extends into interplanetary space.
- The temperature of the solar corona varies from about $0.5 \cdot 10^6$ to $2 \cdot 10^6$ K and emits X-rays and UV radiation; the plasma particle density is 10^{15} particles m^{-3}.



RADIATIVE ENERGY TRANSFER

Solar luminosity

The solar **photosphere** has in the **blackbody** approximation, effective temperature $T = 5\ 770$ K. This temperature corresponds, via **Wien's displacement law**, to an emission peak at wavelength

$$\lambda = \text{constant} / T = 503 \text{ nm (constant} = 2.898 \cdot 10^{-3} \text{ m K)}$$

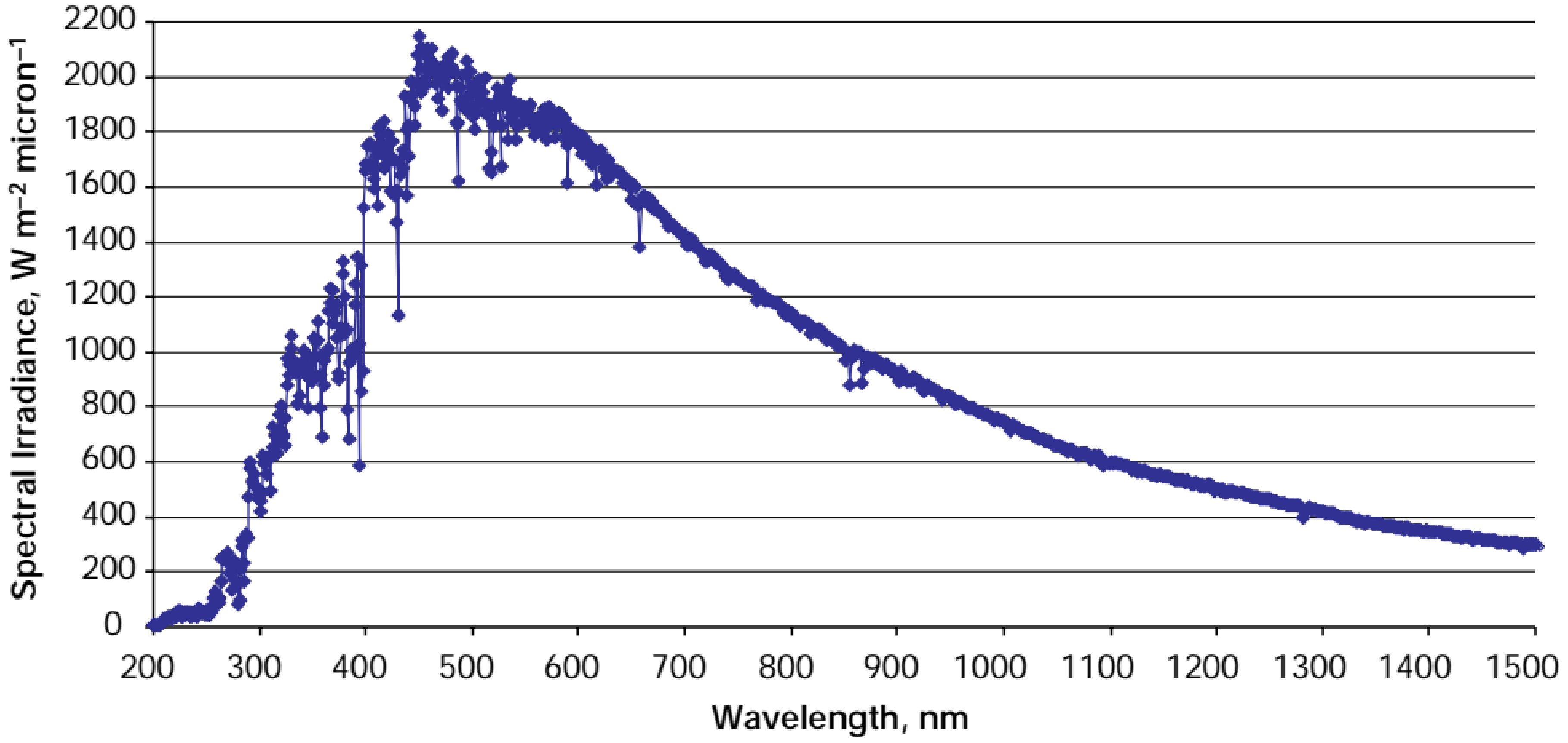
right near the centre of the **visible** spectrum; in this range the greatest amount of energy is emitted, **40-45%**, while outside this range the radiation falls rapidly, so that between 150 nm and 3 μm, 99% of the emission is found: 7-9% falls in the ultraviolet and the rest in the near infrared.

From **Stefan-Boltzmann's law** we can derive the luminosity relative to the solar sphere of radius $R = 6.955 \cdot 10^8$ m and the given temperature:

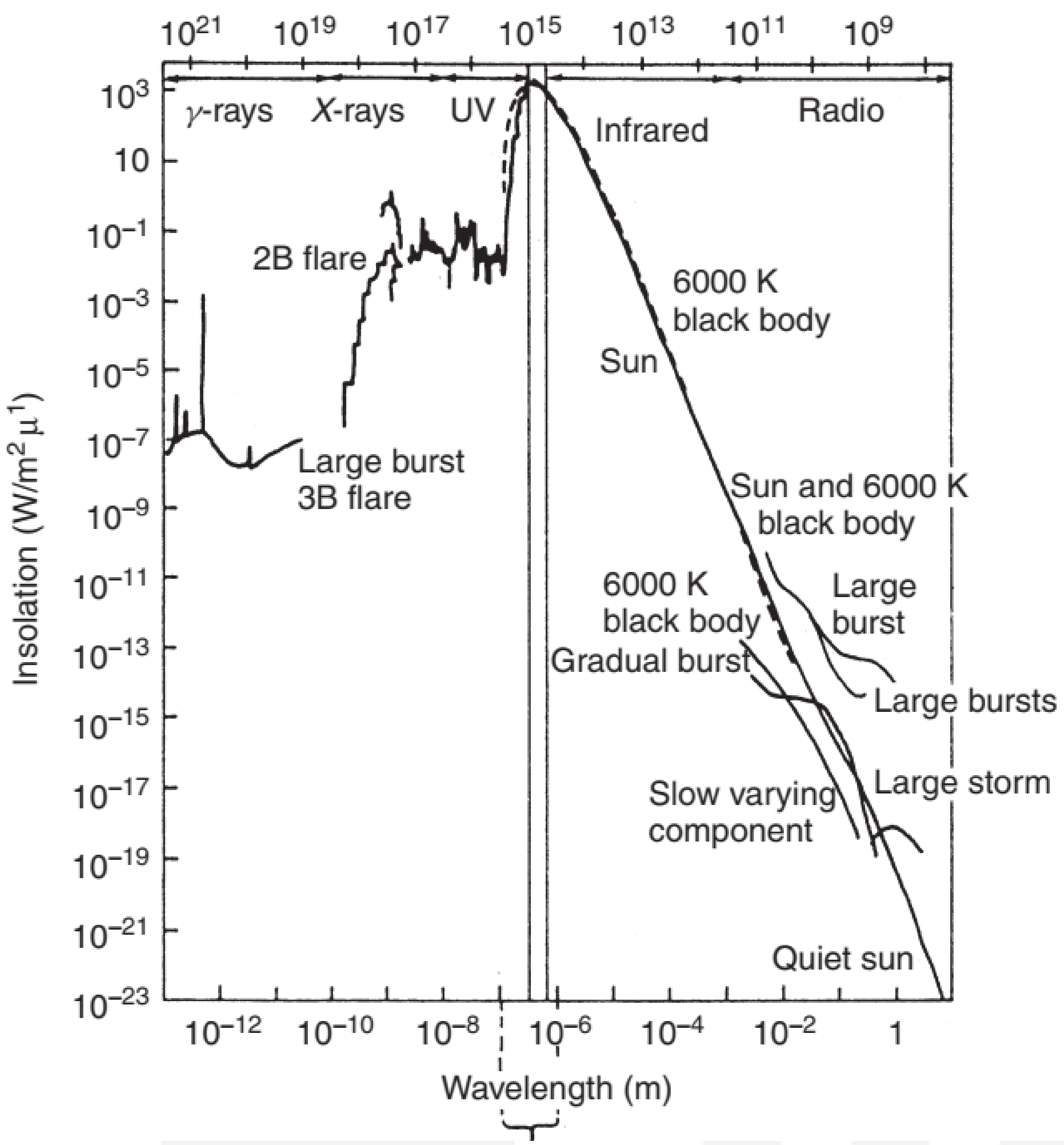
$$L = 4\pi \cdot R^2 \cdot \sigma \cdot T^4 = 3.820 \cdot 10^{26} \text{ W}$$

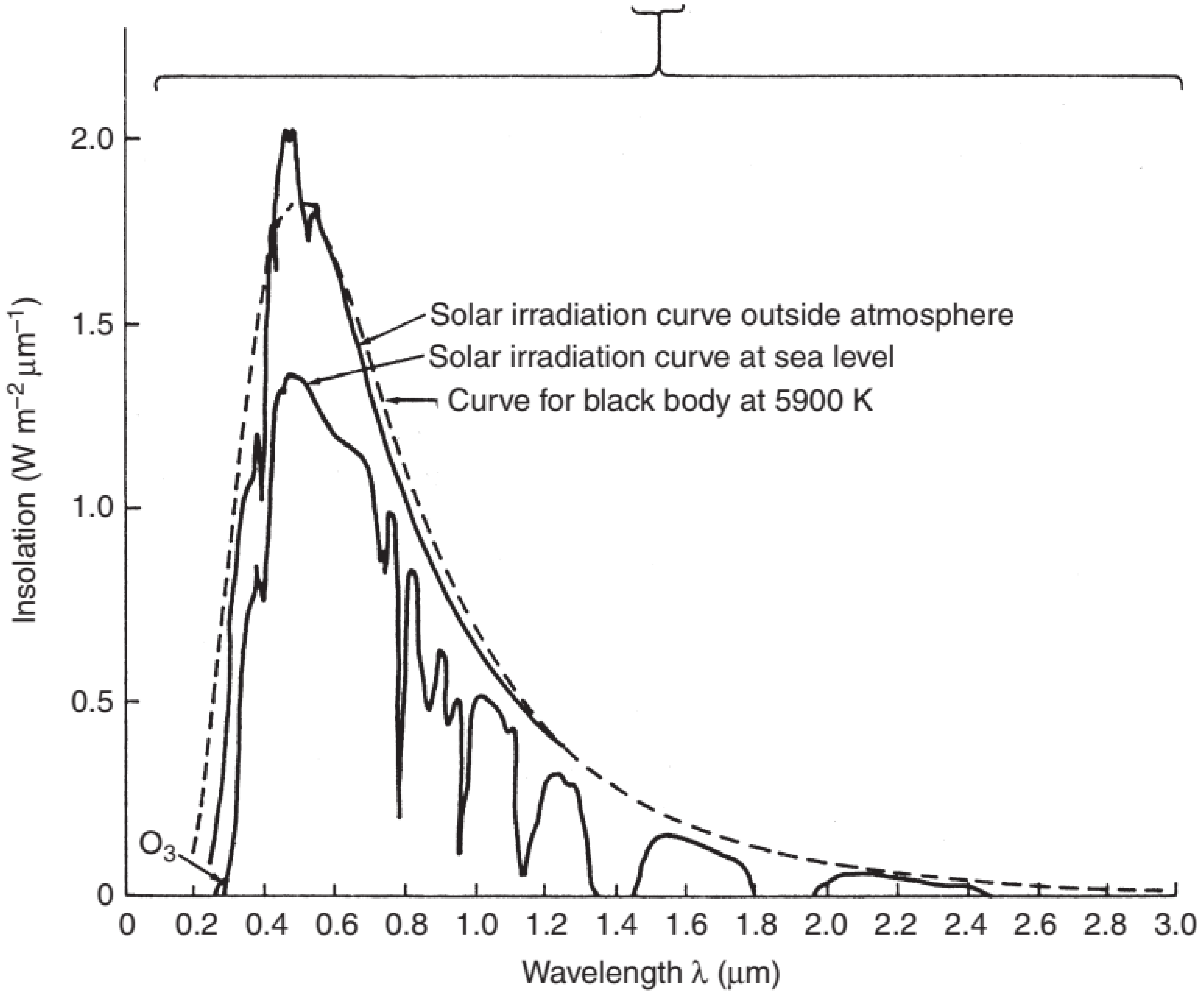
$$(\sigma = 5.670 \cdot 10^{26} \text{ W m}^{-2} \text{ K}^{-4}).$$

InfraRed	52 %
Visible	41%
NUV	<7%
EUV	0.1%
Radio	0.1%
X	<0.1%



Solar luminosity





Solar constant

Travelling the distance from the Sun to a planet, say the Earth, the solar spectrum does not change significantly. So what remains to be calculated at the threshold of a planet is the solar constant. The **solar constant** is defined as the average solar energy incident, in the unit time, a unit area perpendicular to Sun's rays at the average Earth-Sun distance outside the Earth's atmosphere:

$$S_e = L / (4\pi \cdot a^2) = 1\ 365\ \mathrm{W\ m^{-2}}.$$

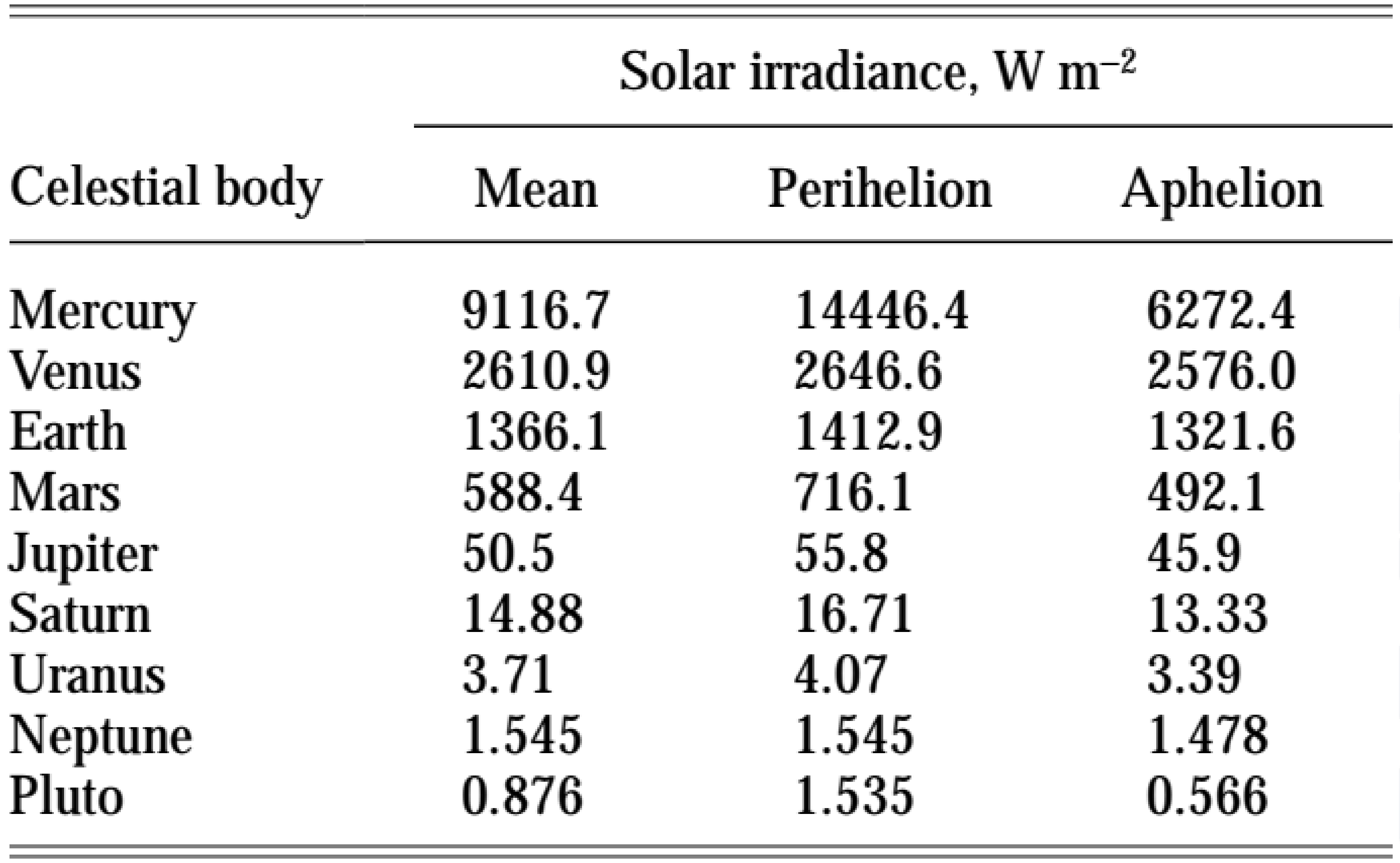
Since the average distance between the Sun and the Earth, a, is not constant over time, one can quantify this variation by measuring the solar constant every thirty degrees of true anomaly during the Earth's motion of revolution:

- solar constant oscillation during the year is limited: just observe the **difference between aphelion and perihelion limited to 92 W $\mathbf{m^{-2}}$**, a variation of about **3.5%**, which is due to the **very low ellipticity** of the orbit ($e = 0.01671$)

anomalia vera v [°] dal perielio	costante solare S [W m^{-2}]
0	1394,64
30	1388,39
60	1371,42
90	1348,40
120	1325,57
150	1308,98
180	1302,94
210	1308,98
240	1325,57
270	1348,40
310	1378,03
330	1388,39
360	1394,64

Solar constant

Solar constant at any Sun distance is $$S(r) = S_e\left(\frac{a}{r}\right)^2$$



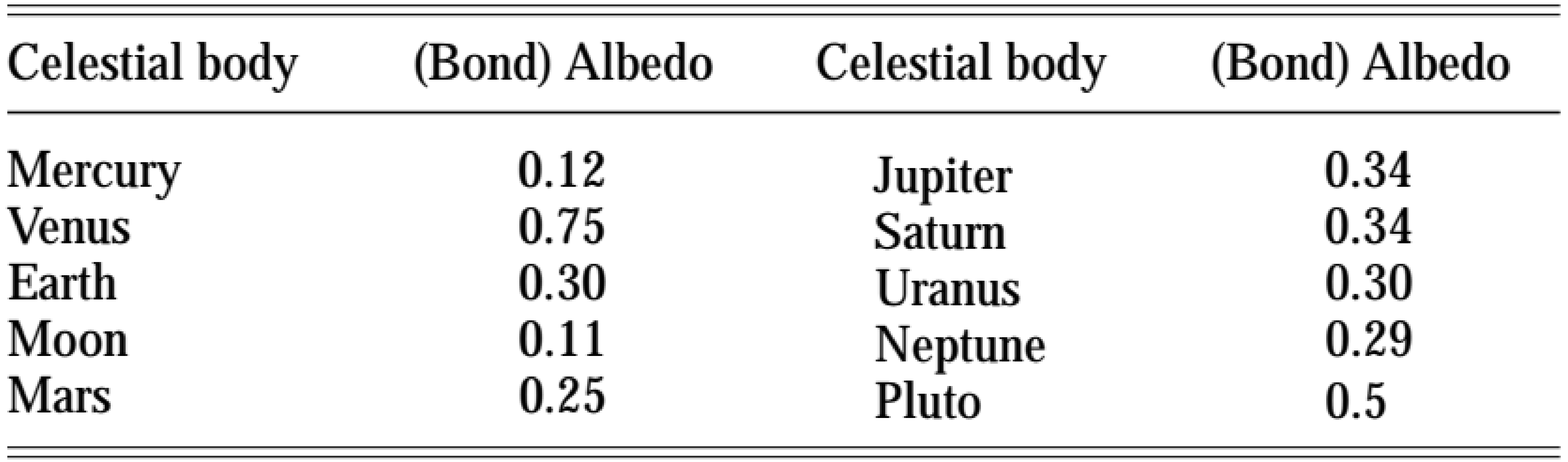
Celestial body	Solar irradiance, W m^{-2}		
	Mean	Perihelion	Aphelion
Mercury	9116.7	14446.4	6272.4
Venus	2610.9	2646.6	2576.0
Earth	1366.1	1412.9	1321.6
Mars	588.4	716.1	492.1
Jupiter	50.5	55.8	45.9
Saturn	14.88	16.71	13.33
Uranus	3.71	4.07	3.39
Neptune	1.545	1.545	1.478
Pluto	0.876	1.535	0.566

Albedo

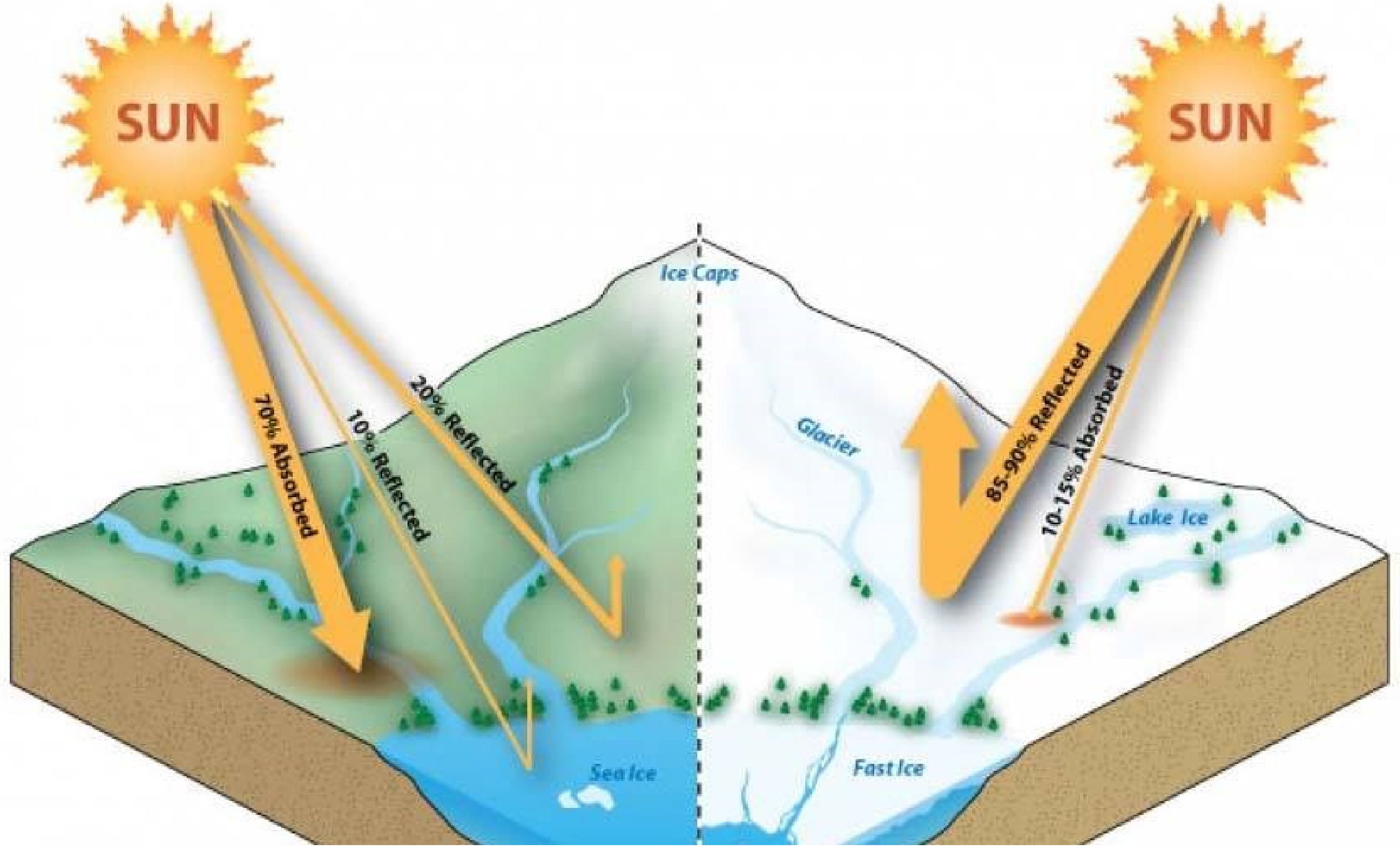
Not all radiation that arrives at a planet contributes to irradiating its surface: there are some surfaces in the planetary system that absorb less sunlight and return it to space.

Albedo is defined as the amount of **electromagnetic radiation reflected** from a surface **relative** to the amount of **energy incident** on it. There are different types of albedo. We normally refer to Bond albedo, also known as **planetary albedo** or spherical albedo, which is the fraction of total incident radiation that is reflected from the planet:

- A = reflected energy / incident energy;
- the spectral content of the Bond albedo is generally assumed to refer to solar radiation;
- the Bond albedo on a celestial body can vary significantly: this is the case for the Earth.



Celestial body	(Bond) Albedo	Celestial body	(Bond) Albedo
Mercury	0.12	Jupiter	0.34
Venus	0.75	Saturn	0.34
Earth	0.30	Uranus	0.30
Moon	0.11	Neptune	0.29
Mars	0.25	Pluto	0.5



Albedo

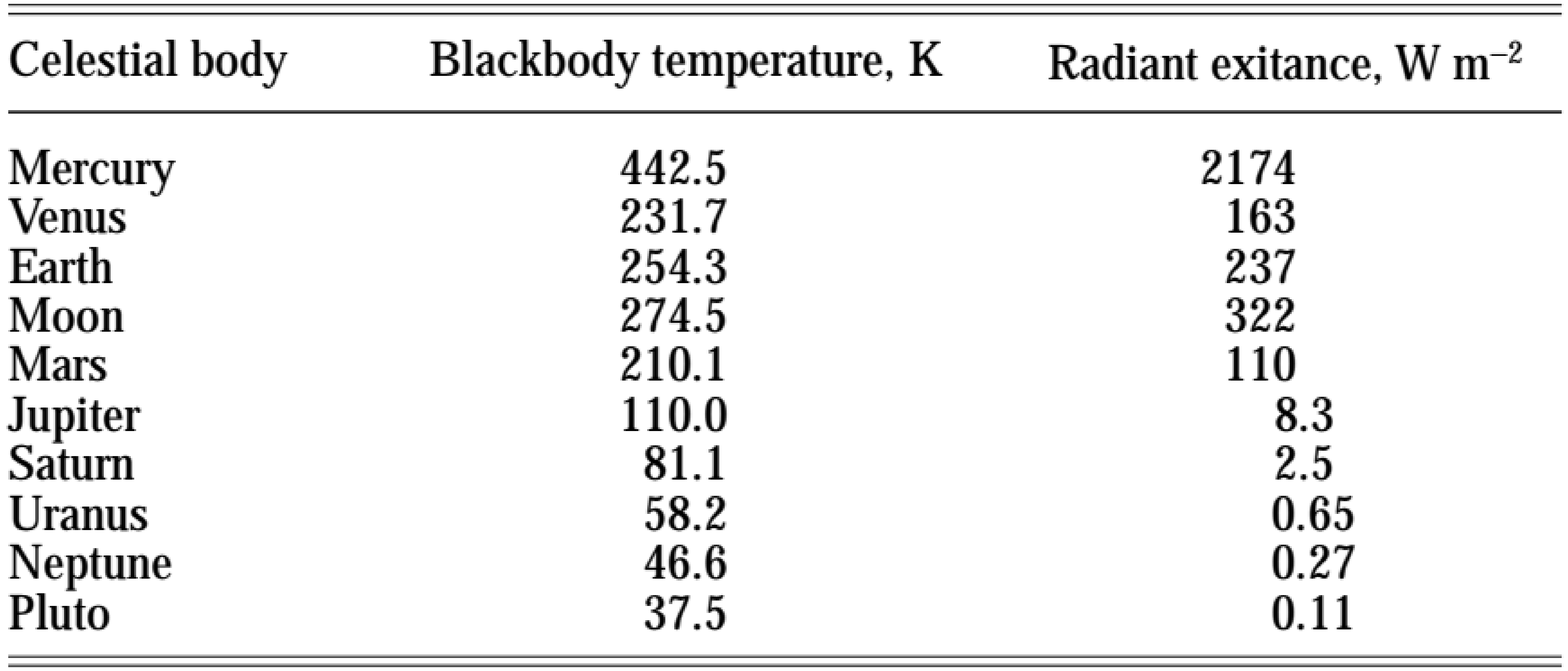
Total planetary albedo is a **difficult** quantity **to determine** because reflective **surfaces change over time**.

- The **darker areas** of the planet, such as **forests**, woodlands, cultivated areas absorb almost all the energy, have **low albedo** (0.05-0.45), and are, over time, **constant**.
- On the other hand, **snow and ice**, which tend to reflect light more, have a **high albedo** (0.75-0.85), are more **variable over time**, just think of the **seasons**, and **affect the northern hemisphere more**, where there is a greater surface area of land;
- Another case of high albedo is the presence of **deserts**, which reaches 40%.
- A parameter that increases albedo, but in an inconstant manner (0.10-0.80), is **cloud formations**: first of all, the response to solar radiation is consistently linked to the **type of cloud**, with rather considerable **albedo range**.
- Attention must be paid to the development of the study of **aerosols in the air**, both because they themselves **reflect** the wavelengths of **solar radiation, and** because **clouds form around them**: they therefore have a dual function. The presence of **dark dust**, the result of human pollution, **deposited on ice and snow** in the northern hemisphere would have covered the surface layer responsible for the high albedo.
- **Liquid water** surfaces are a case in point: at **low temperatures** they almost completely **absorb light** (0.03-0.20); conversely they have an **albedo equal to even 1 when approaching 360 K**.

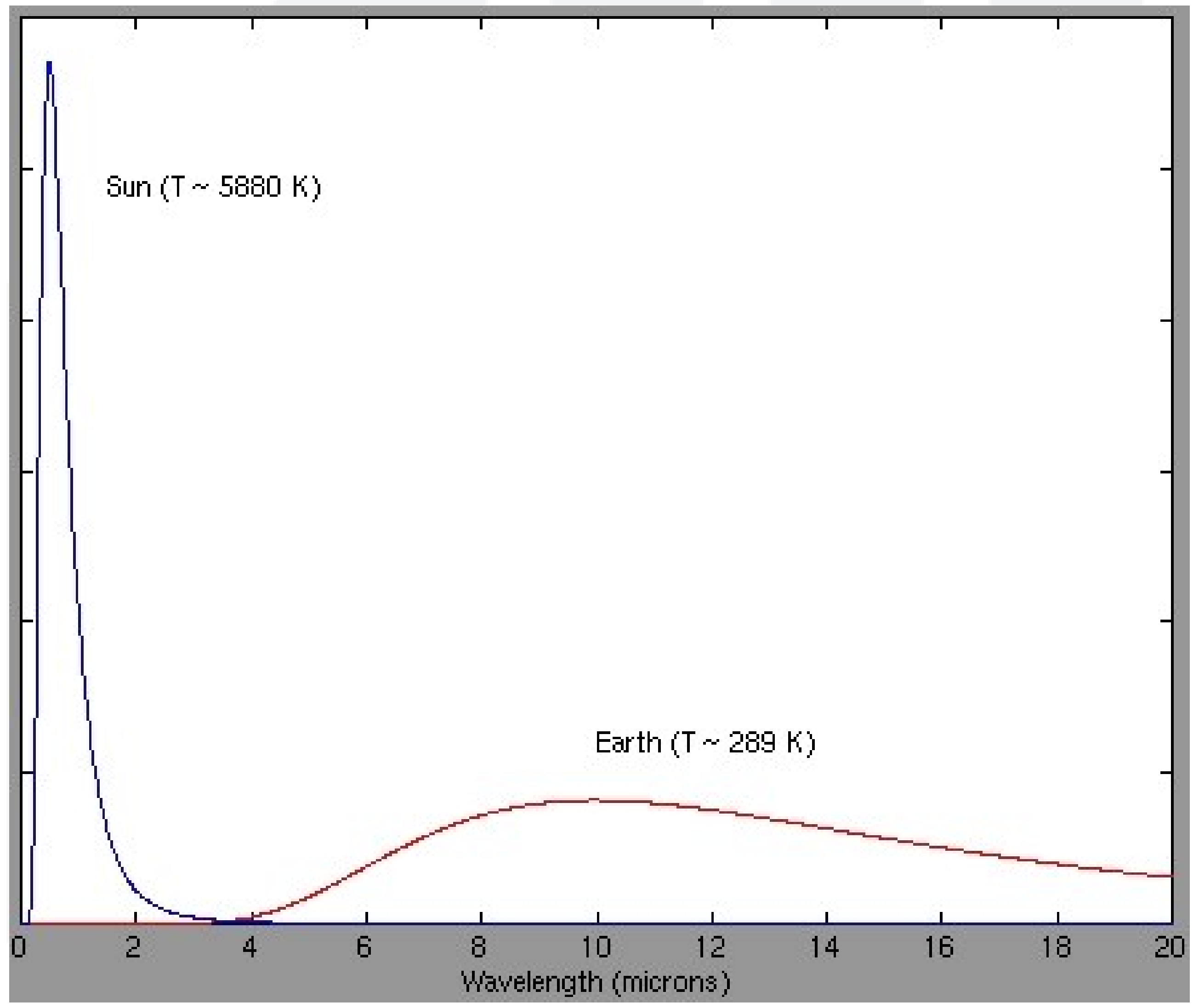
Planetary irradiation

A celestial body, which is not at absolute zero, has a specific T_{eff} **effective temperature** at which it radiates F_e energy, in modulus equal to that absorbed one F_a: $F_a = F_e$.

- The thermal energy radiated by planetary bodies is expressed in terms of blackbody temperature: then, the **radiated thermal power** is determined by $L(T) = 4\pi \cdot R_E^2 \cdot \sigma \cdot T_{eff}^4$.
- Since the **Earth** has a surface temperature of 288 K lower than the sun's, Wien's law requires it to emit in the **mid-infrared** between 4 μm and 15 μm with a peak of λ_E = 10 μm.



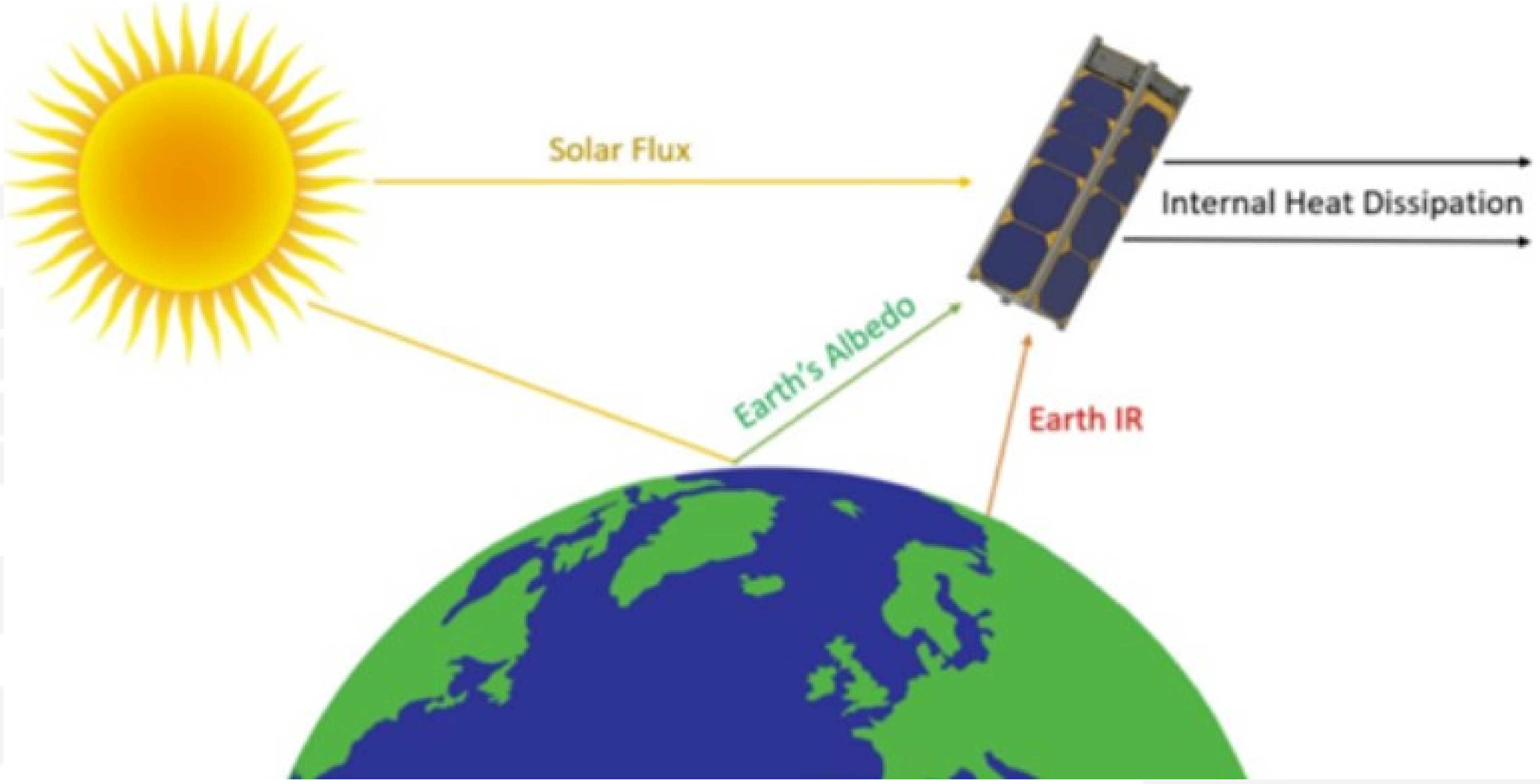
Celestial body	Blackbody temperature, K	Radiant exitance, W m^{-2}
Mercury	442.5	2174
Venus	231.7	163
Earth	254.3	237
Moon	274.5	322
Mars	210.1	110
Jupiter	110.0	8.3
Saturn	81.1	2.5
Uranus	58.2	0.65
Neptune	46.6	0.27
Pluto	37.5	0.11



SPACE MISSION ISSUES

The same reasoning which was used for calculating a celestial body temperature can be employed also to set:

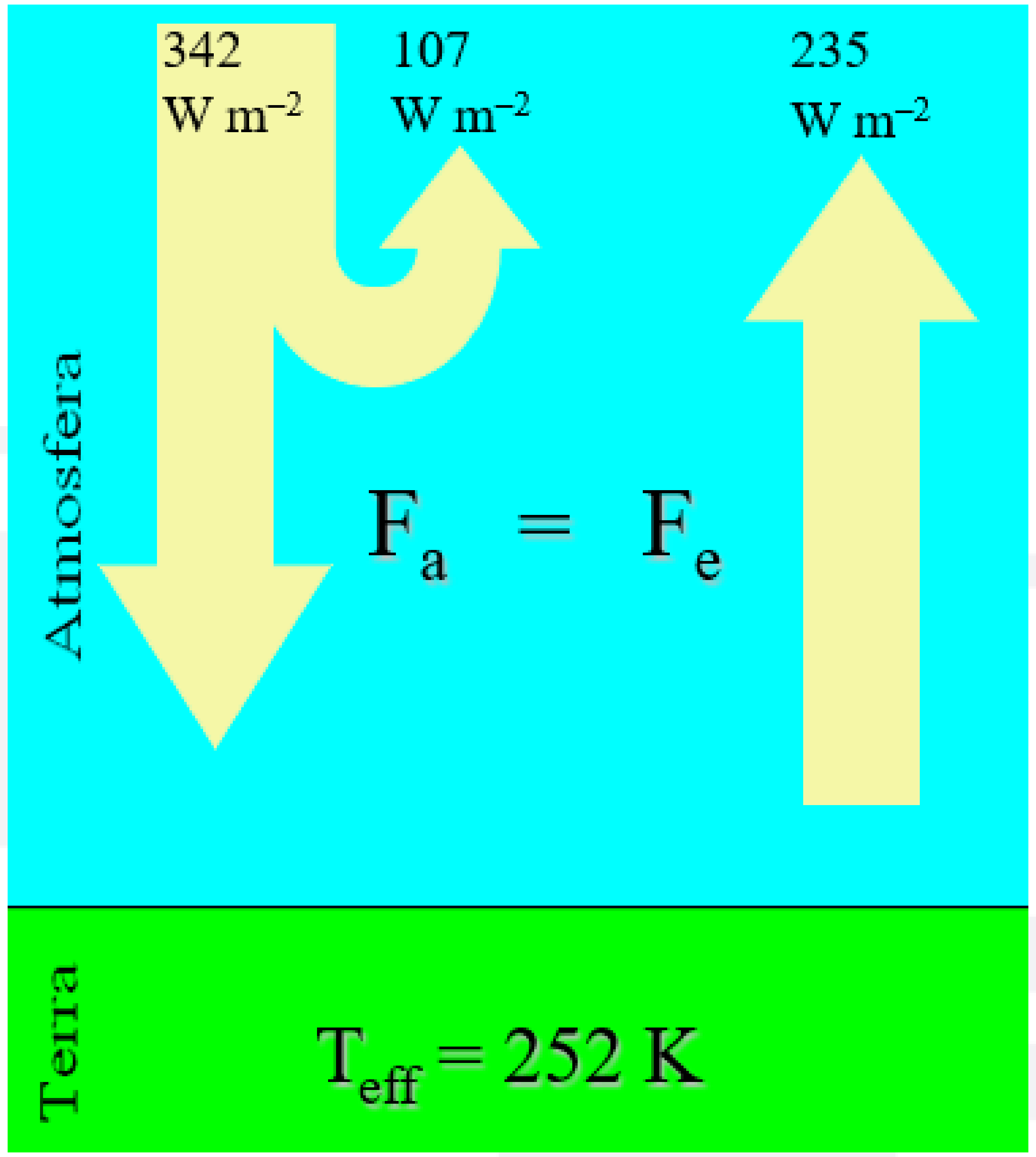
- **thermal** analysis / **subsystem**
- **power** supply **subsystem**

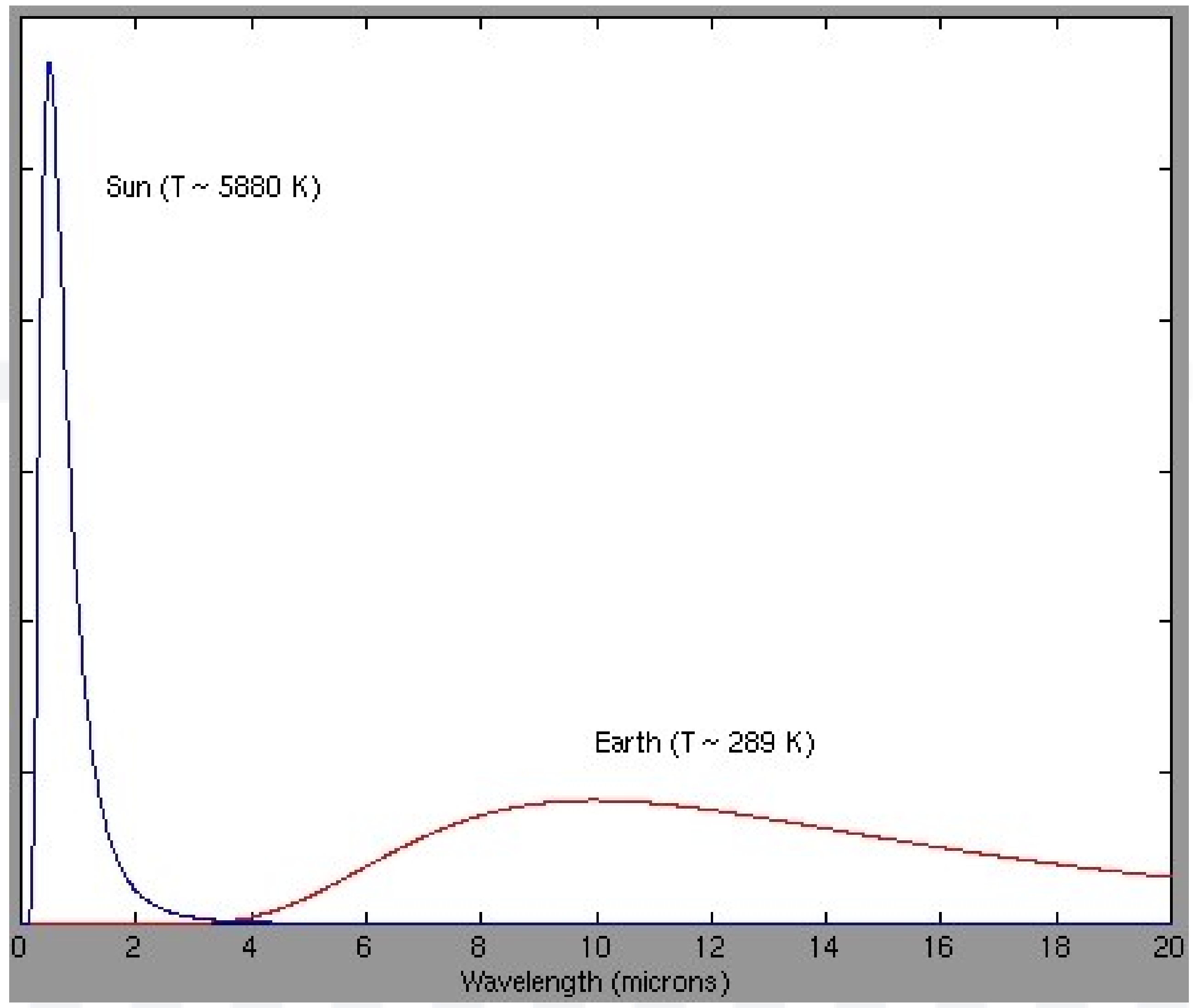


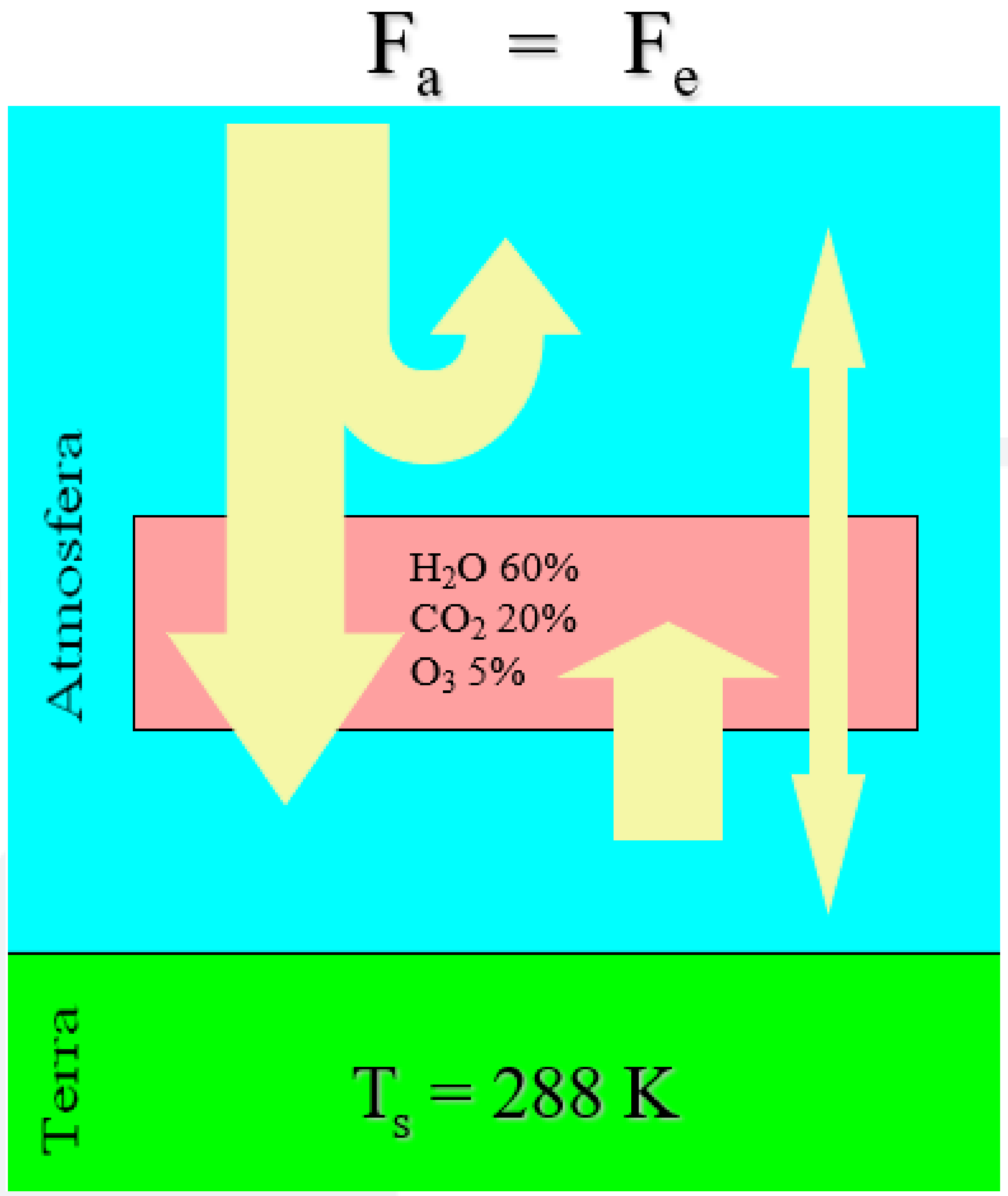
The spacecraft temperature is determined by the balance between heat received by radiation from Sun, Earth, and Moon, heat radiated out by the spacecraft.

ATMOSPHERE

Energy balance and greenhouse effect





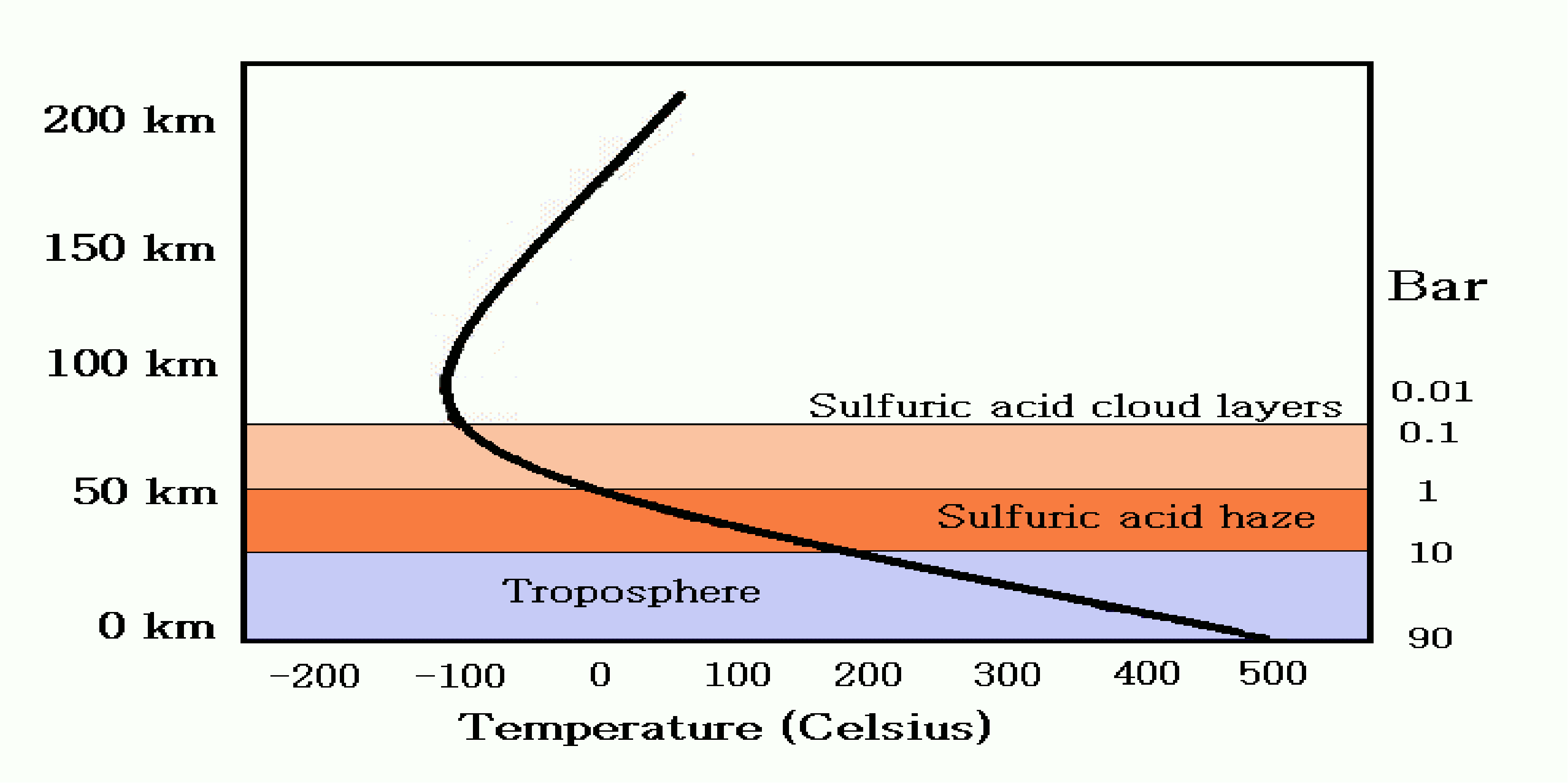


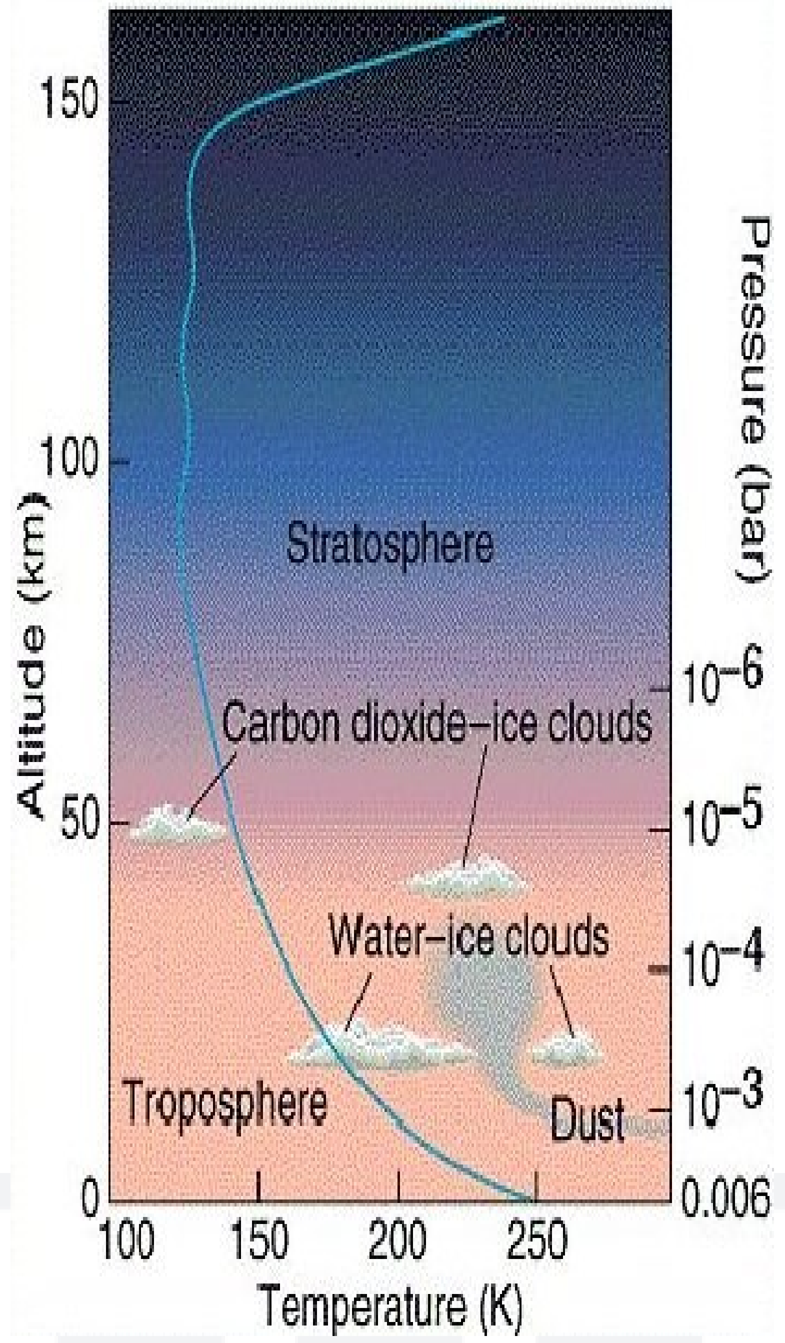
$$\pi \cdot R_E^2 \cdot S \cdot (1-A) = 4\pi \cdot R_E^2 \cdot \sigma \cdot T_{eff}^4$$

$$\pi \cdot R_E^2 \cdot S \cdot (1-A) = 4\pi \cdot R_E^2 \cdot \varepsilon \cdot \sigma \cdot T_s^4$$

Greenhouse effect is determined by the chemical composition of the atmosphere.

Energy balance and greenhouse effect





See more cases of greenhouse effect.

Venus

- $T_{eff,V} = [S_V \cdot (1 - A_V) / 4\sigma]^{1/4} = 252$ K
  - rather high albedo: $A_V = 0.65$
- greenhouse effect estimated at around 480 K: in fact, the surface temperature is 735 K;
- the absence of a temperature inversion may have been the reason that made it impossible for water to be retained: the lack of an ozone layer, due to a shortage of molecular oxygen in the atmosphere, allowed gaseous water to rise up the atmosphere and be decomposed; the hydrogen and oxygen so obtained were released into outer space.

Mars

- $T_{eff,M} = [S_M \cdot (1 - A_M) / 4\sigma]^{1/4} = 217$ K
- greenhouse effect estimated at around 5 K: in fact, the surface temperature is 222 K;
- the planet small size has not developed enough gravity to limit the escape of atmospheric gases, and the weak temperature inversion has prevented the atmosphere from blocking this escape.

To have or not to have

The atmosphere is the layer of gas surrounding a celestial body. It appears as a mixture of permanent and concentration-varying gases, and aerosols, i.e. microscopic particles in suspension (both liquid and solid).

The **capability of holding an atmosphere** reflects the competition between **escape velocity** and **thermal velocity** acting on a chemical species

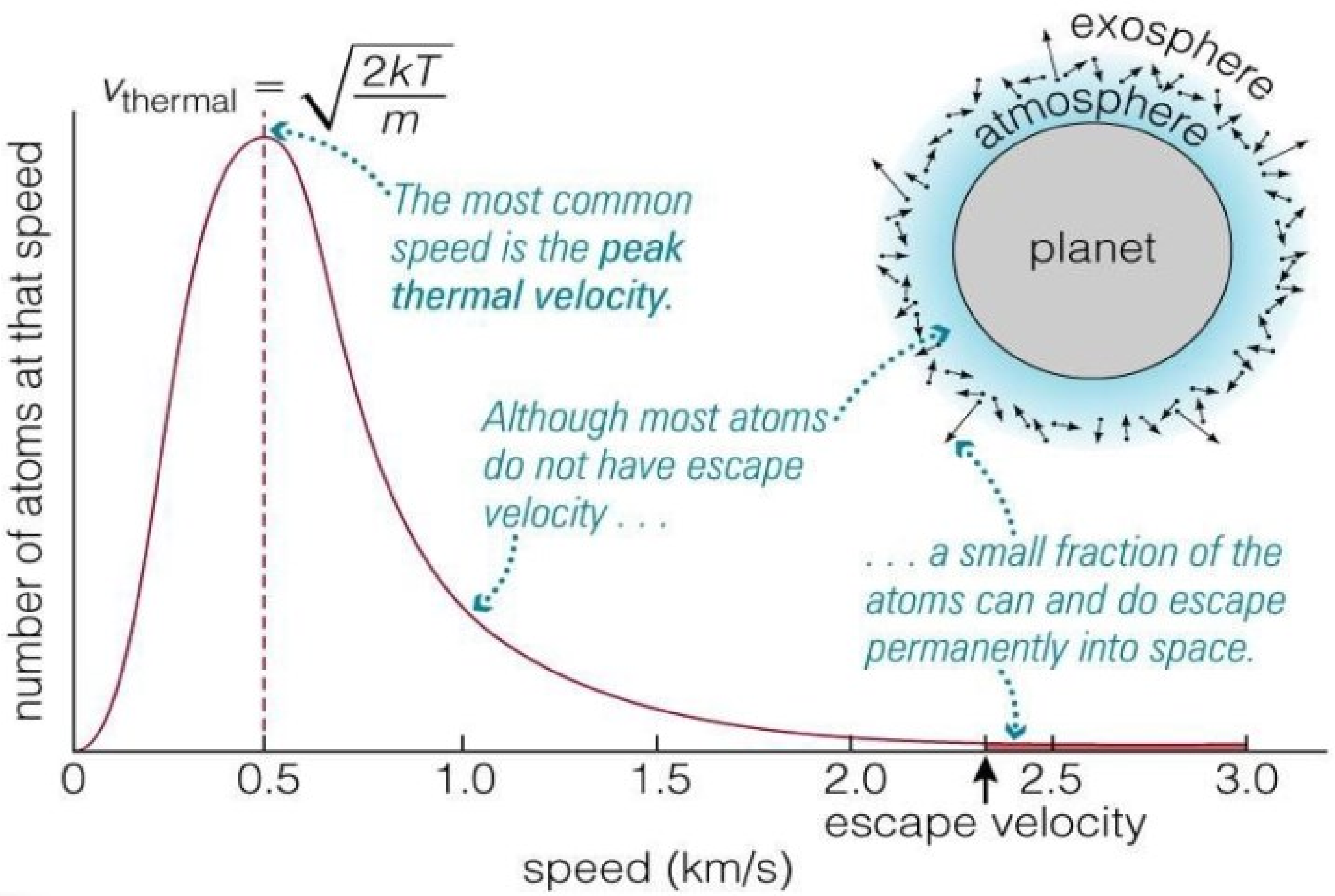
$$E_{total} = E_k + E_p = 1/2mv^2 - \frac{GMm}{r} = 0 \longrightarrow \boxed{v_{esc} = \sqrt{\frac{2GM}{R}}}$$

$$1/2mv_{therm}^2 = 3/2kT \longrightarrow \boxed{v_{therm} = \sqrt{\frac{3kT}{m}}}$$

$$\sqrt{\frac{3kT}{m}} = \sqrt{\frac{2GM}{R}} \Rightarrow T_{esc} = \frac{2GMm}{3kR}$$

Condition to keep an atmosphere: $T_{atm} < T_{esc}$

To have or not to have



Pianeta	Raggio eq. $[R_\oplus]$	Massa $[M_\oplus]$	ρ $[\text{g cm}^{-3}]$	v_{fuga} $[\text{km/s}]$
Mercurio	0.383	0.055	5.43	4.3
Venere	0.949	0.815	5.24	10.4
Terra	1.000	1.000	5.52	11.2
Marte	0.533	0.107	3.94	5.0
Giove	11.209	317.820	1.33	59.5
Saturno	9.449	95.161	0.70	35.5
Urano	4.007	14.371	1.30	21.3
Nettuno	3.883	17.147	1.76	23.7

$$R_\oplus = 6378 \text{ km} \quad ; \quad M_\oplus = 5.974 \times 10^{27} \text{ g}$$

Composition

When planets formed, atmospheres were mainly composed of **hydrogen** and **helium**.

In the **inner or terrestrial planets**, such as Mercury, Venus, Earth and Mars, the increase in the **thermal velocity** of the atmosphere due to the solar wind **was greater than the escape velocity** from the gravitational field: thus the **lighter constituents were depleted**.

- Mercury has essentially no atmosphere.
- The other terrestrial planets show some similarities, having retained various amounts of the heavier molecular constituents.

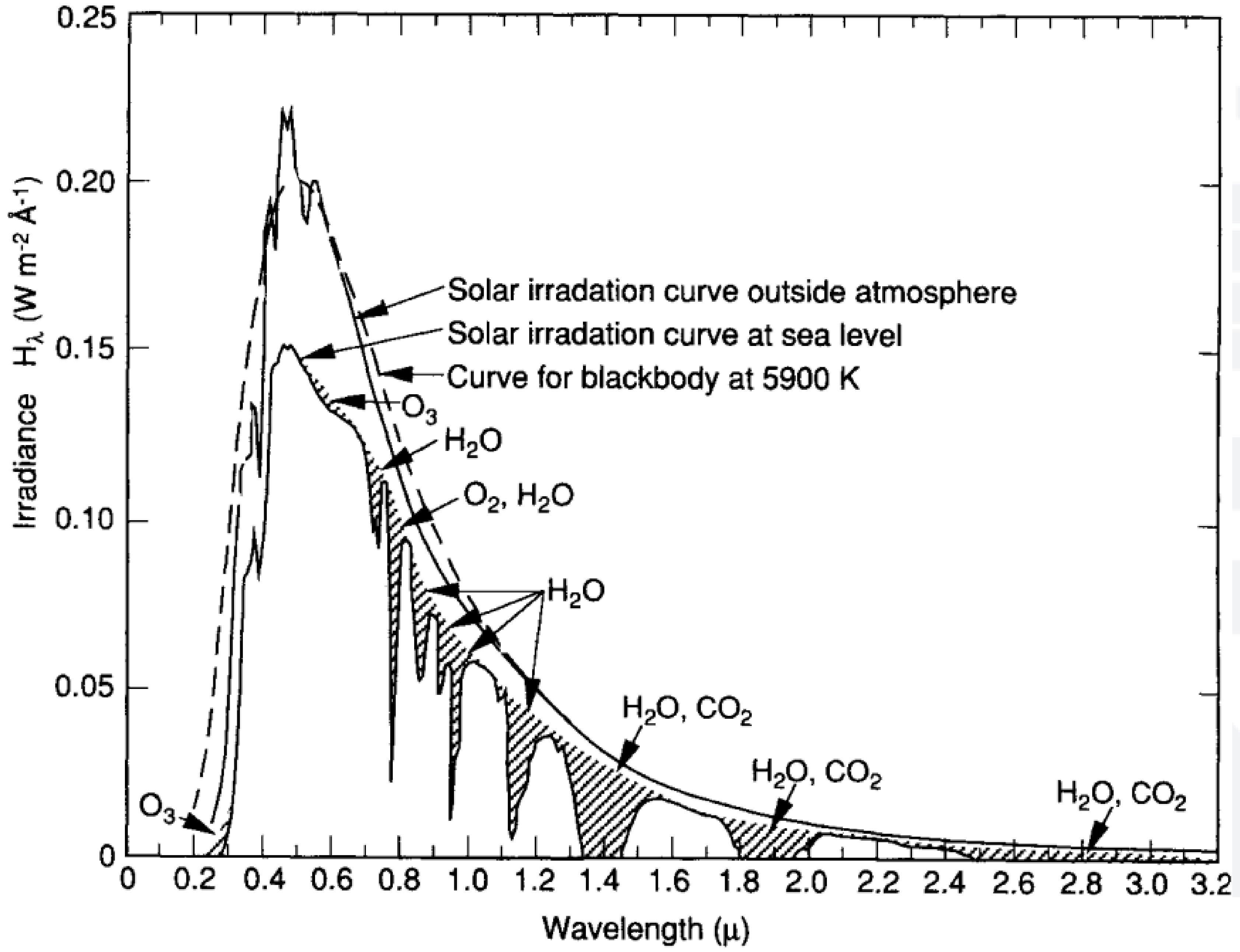
Further away from the Sun, the **outer or gaseous planets** of Jupiter, Saturn, Uranus and Neptune have been able to retain much of their hydrogen and helium.

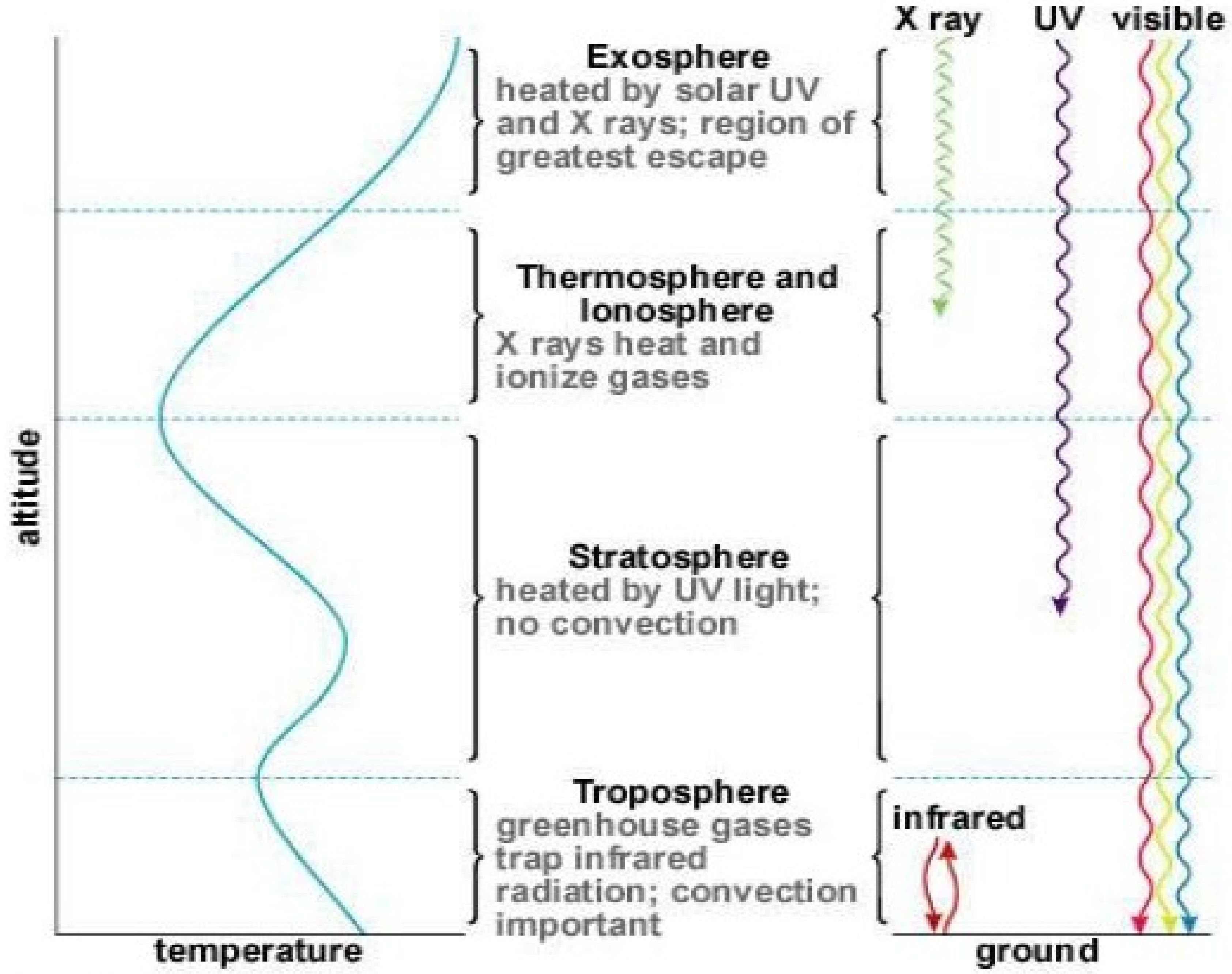
Composition

Composition alters certain atmospheric properties, in particular it has an **effect on solar radiation**.

Molecular absorptions due to the various atmospheric components alter the profile of the Sun's spectrum, which, having remained unchanged up to the top of the atmosphere, becomes distorted on the ground.

- **Absorption occurs in dependence with altitude**.

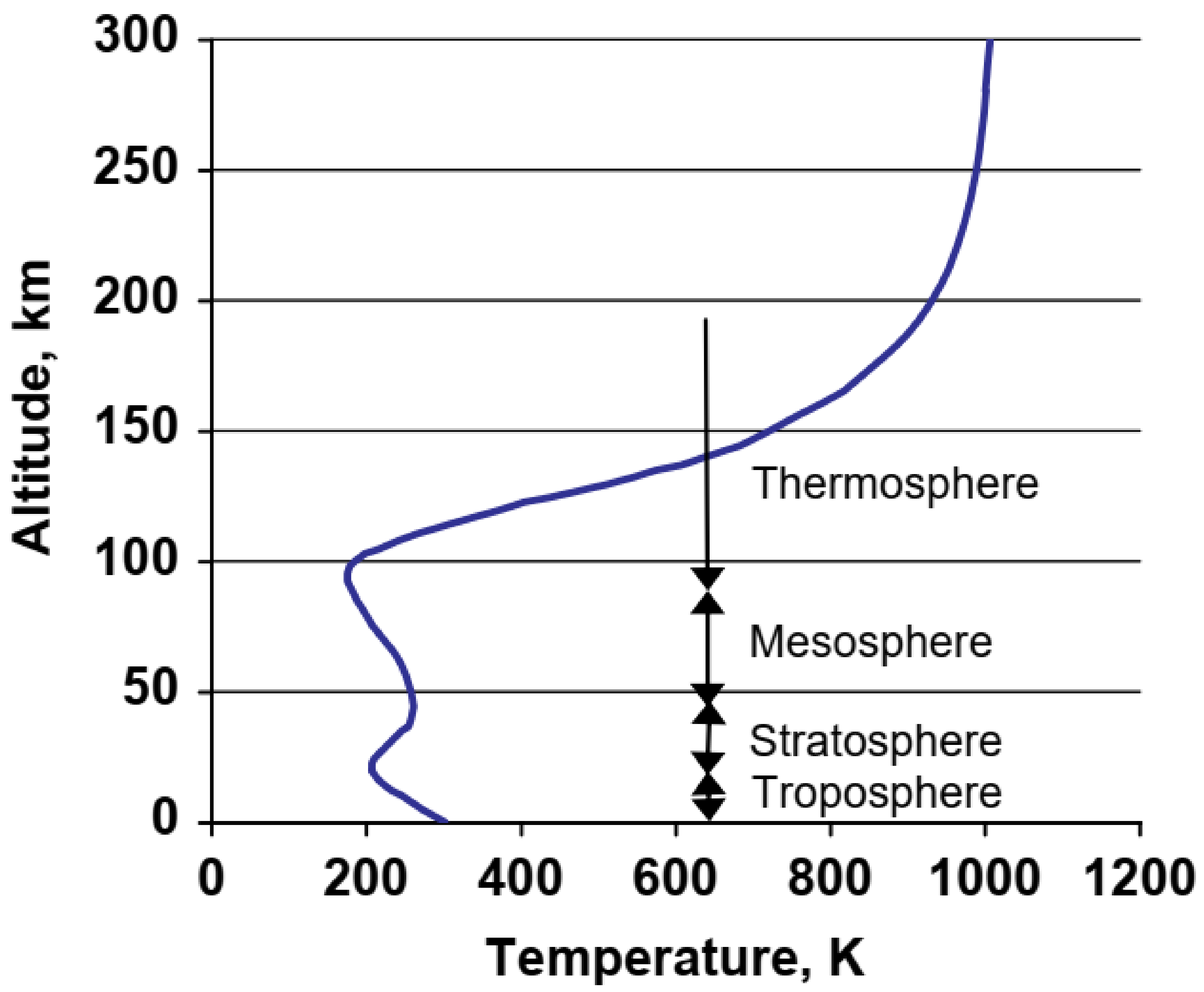


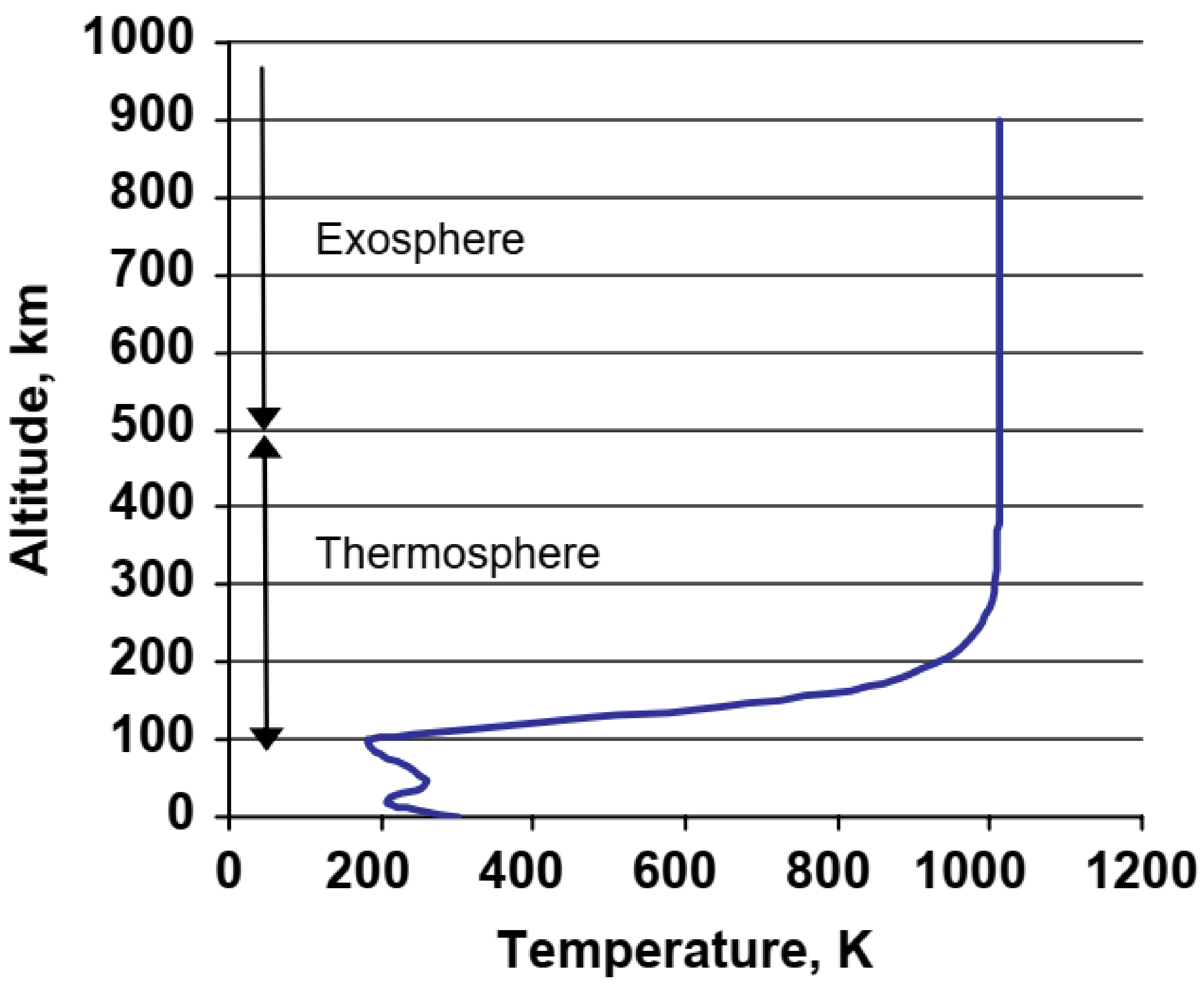


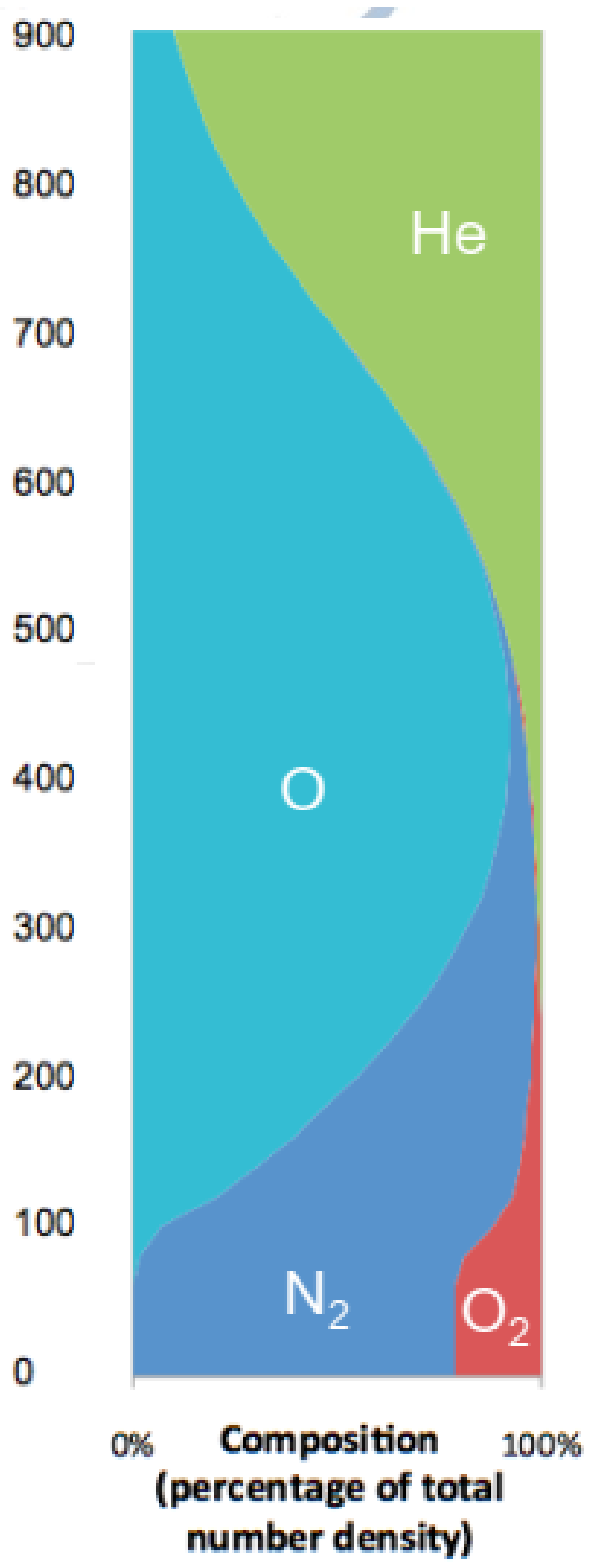
Altitude role

The characteristics of the gas surrounding a planet, and especially the **Earth**, change as a **function of altitude**.

- The variation **according to temperature** leads to the identification of **five distinct layers**.

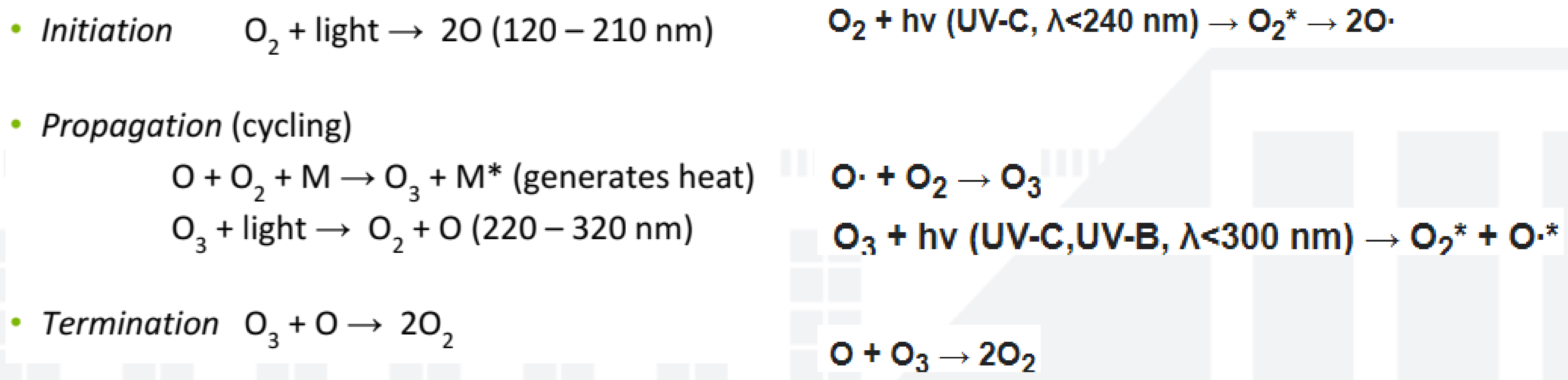






Altitude role

- **Troposphere** (8-14 km), contains 99% of the water, 50% of the mass of the atmosphere within 5 km altitude and 75% below 11 km; and temperature decreases with altitude down to 0.1 atm with the tropopause.
- **Stratosphere** (up to 50 km): **temperature inversion** (temperature increase with altitude) is **due to absorption of UV radiation by the ozone** layer through the **Chapman cycle**; it ends with the stratopause.



- *Initiation* O_2 + light $\rightarrow$ 2O (120 – 210 nm)
- *Propagation* (cycling)
  - $O + O_2 + M \rightarrow O_3 + M^*$ (generates heat)
  - O_3 + light $\rightarrow$ $O_2 + O$ (220 – 320 nm)
- *Termination* $O_3 + O \rightarrow 2O_2$

O_2 + hν (UV-C, λ<240 nm) $\rightarrow O_2^* \rightarrow 2O\cdot$

$O\cdot + O_2 \rightarrow O_3$

O_3 + hν (UV-C,UV-B, λ<300 nm) $\rightarrow O_2^* + O\cdot^*$

$O + O_3 \rightarrow 2O_2$

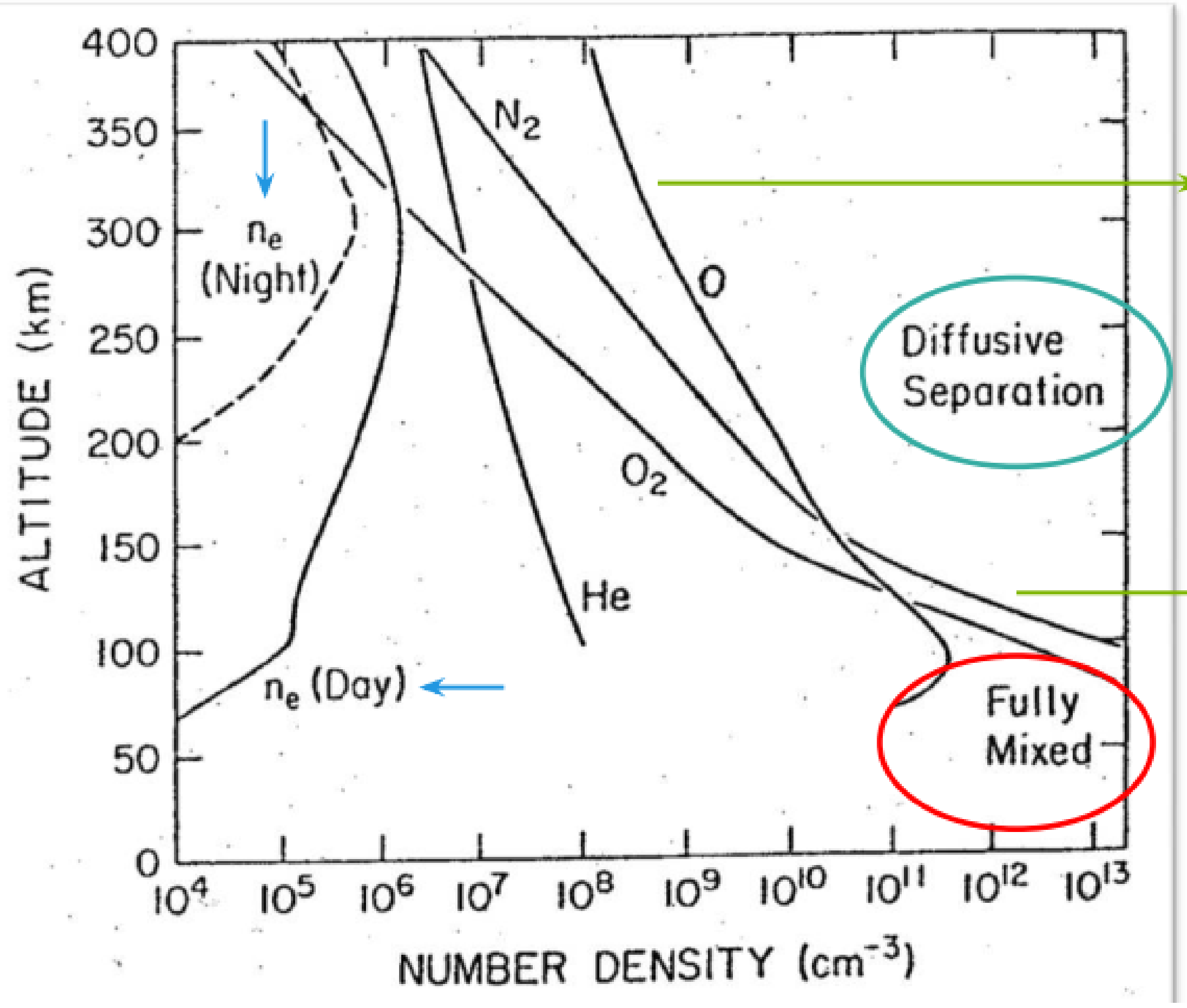
- **Mesosphere** (up to 80-90 km): **temperature decreases with altitude** due to low ozone or other absorbers; ends with the mesopause.
- **Thermosphere** (up to 300-800 km): **temperature returns to increase with altitude**; gas in excited state **due to absorption of solar radiation**; solar activity determines how **ionosphere** layers are arranged; ends with thermopause.
- **Exosphere** (extends to interplanetary space, around 10 000 km): **hydrogen** and **helium** at a temperature almost constant with altitude.

Altitude role

The **mesopause coincides** with the turbopause or **homopause** that separates:

- below, the **homosphere**, in which the **composition** of gases is almost **uniform** due to gas **convention**;
- above, the **heterosphere**, in which the **composition varies with altitude**: **density** of each constituent **falls exponentially with altitude** at a rate that **depends on the molecular mass**.

composition



H, He dominate at highest altitude

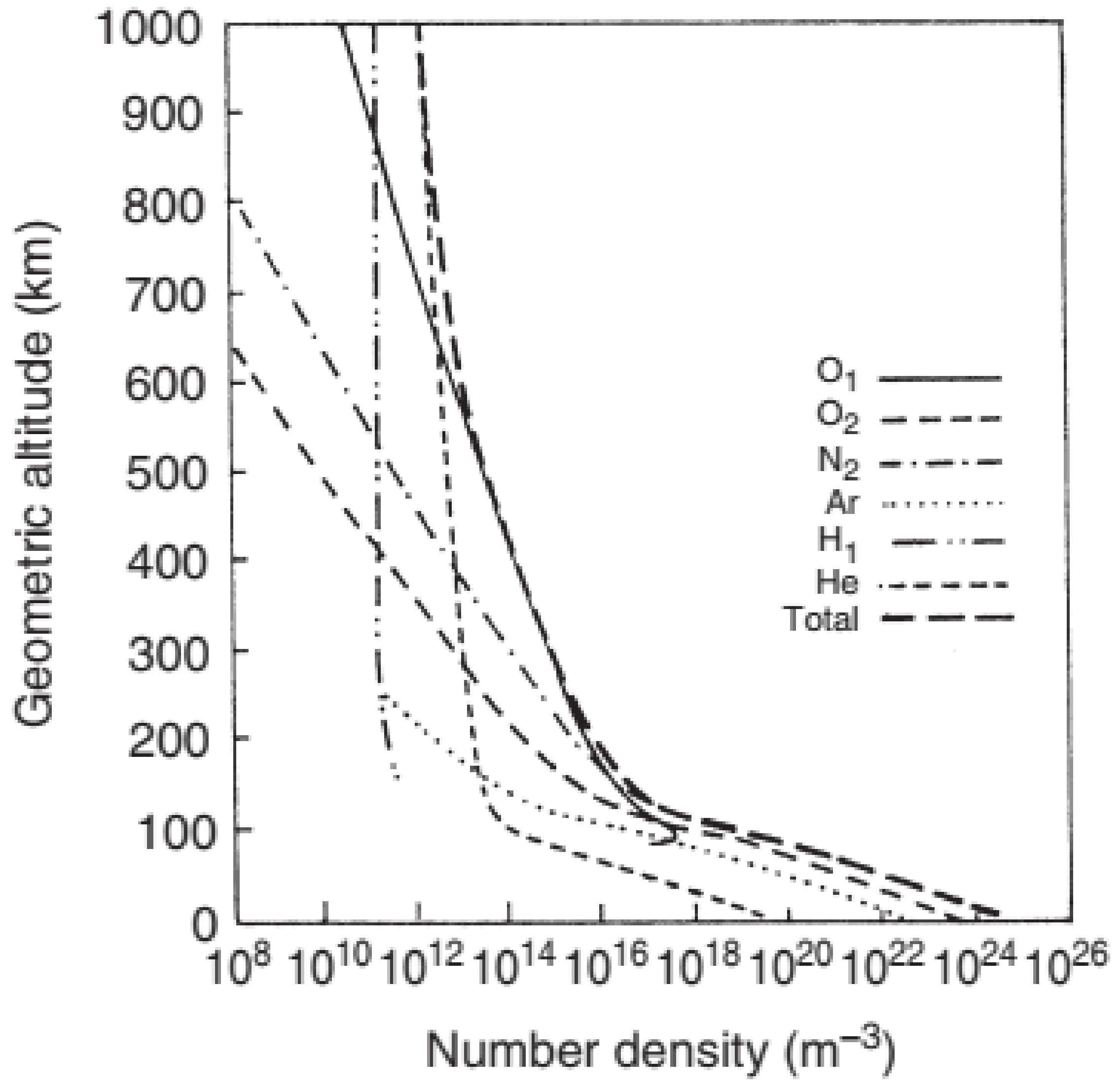
O, O_2 dominate at higher altitude where its low weight is important

N_2 dominates at low altitude

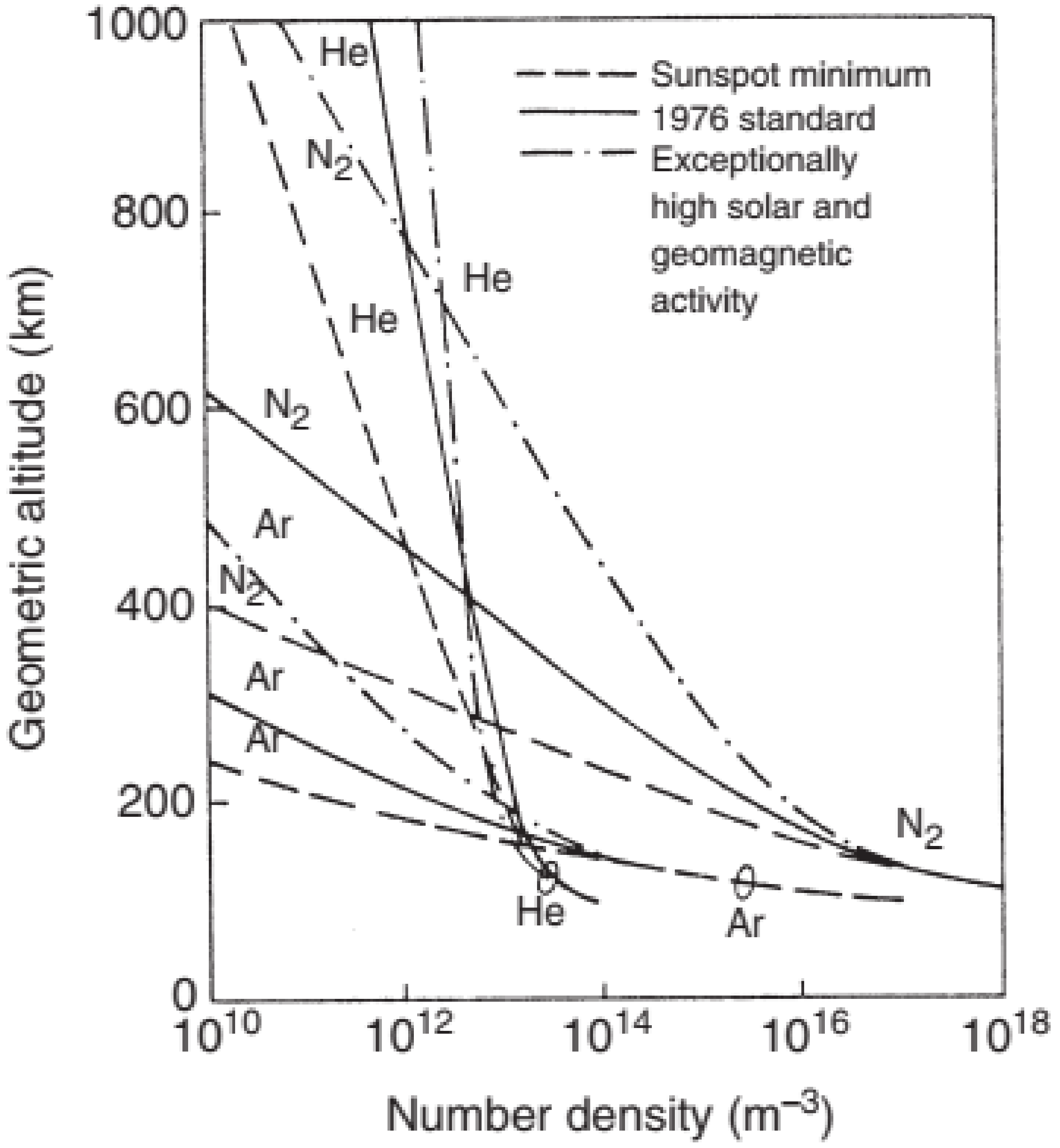
Altitude role

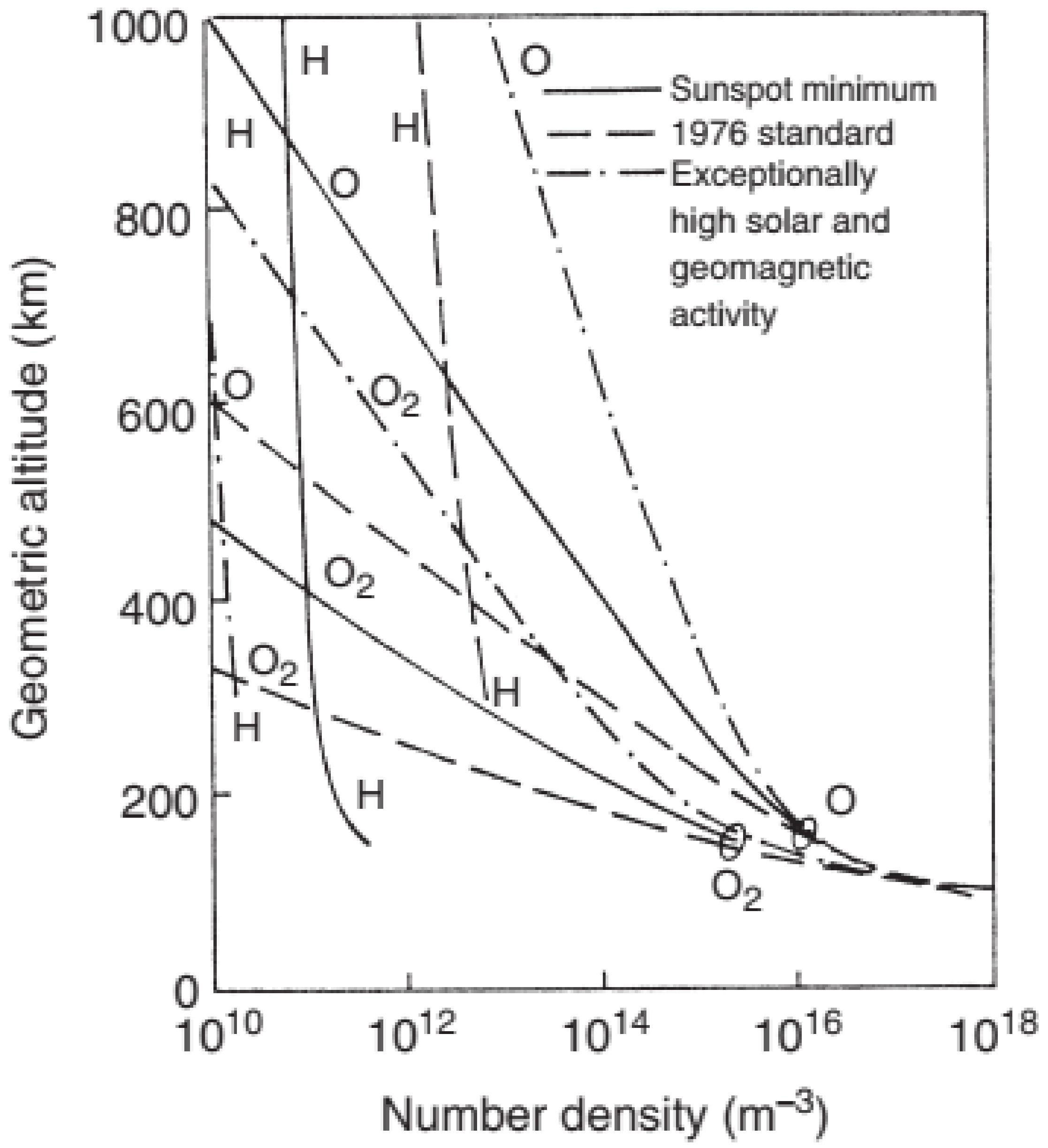
In the heterosphere, the constituent **species are decoupled** from each other.

If **thermal diffusion and vertical transport are negligible**, we can treat the situation through a **hydrostatic equilibrium equation** in which the density profile depends on atmospheric temperature.



(a)





Altitude role

Let us start under **isothermal conditions** and assuming ideal gases: according to the **hydrostatic equilibrium**, density ρ varies with pressure p, i.e. with altitude

$$\rho = \frac{pM}{RT} = \frac{p_0 M}{RT} \exp\left(-\frac{Mg}{RT}h\right) = \rho_0 \exp\left(-\frac{h}{H}\right)$$

where **scale height** is defined as $H \equiv \frac{RT}{Mg}$

g = gravitational acceleration

M = molecular weight

R = universal gas constant

T = temperature

At **ground level**,

- the temperature is on average about 288 K;
- the mean molecular weight of air at sea level is 29 (i.e., the molecular weight of a gas made up of 78% Nitrogen, 21% Oxygen, and 1% Argon);
- the acceleration due to gravity is 9.81 m s^{-1}; the ideal gas constant is 8.314 J K^{-1} mol^{-1} ;

the isothermal scale-height of the atmosphere comes out to be about **8.4 km** (~M. Everest).

- This trend, which depends on the molecular mass of the chemical species, is **valid for the heterosphere** and for most **planets** that do **not exhibit thermal inversion**.
- In the **homosphere**, the **atmosphere is not actually isothermal**: this model gives good results if one does not stray too far from the reference altitude, so that the hypothesis of T = cost at least in that altitude range can be considered verified.

Altitude role

So let us now consider an **adiabatic atmosphere**, the temperature variation with altitude is $T = T_0 + Lh$

- T_0 is the **temperature at the reference altitude** h_0, where we also have pressure p_0 and density ρ_0;
- $L = \mathrm{d}T\,/\,\mathrm{d}h$ is the **temperature gradient**.

Then,

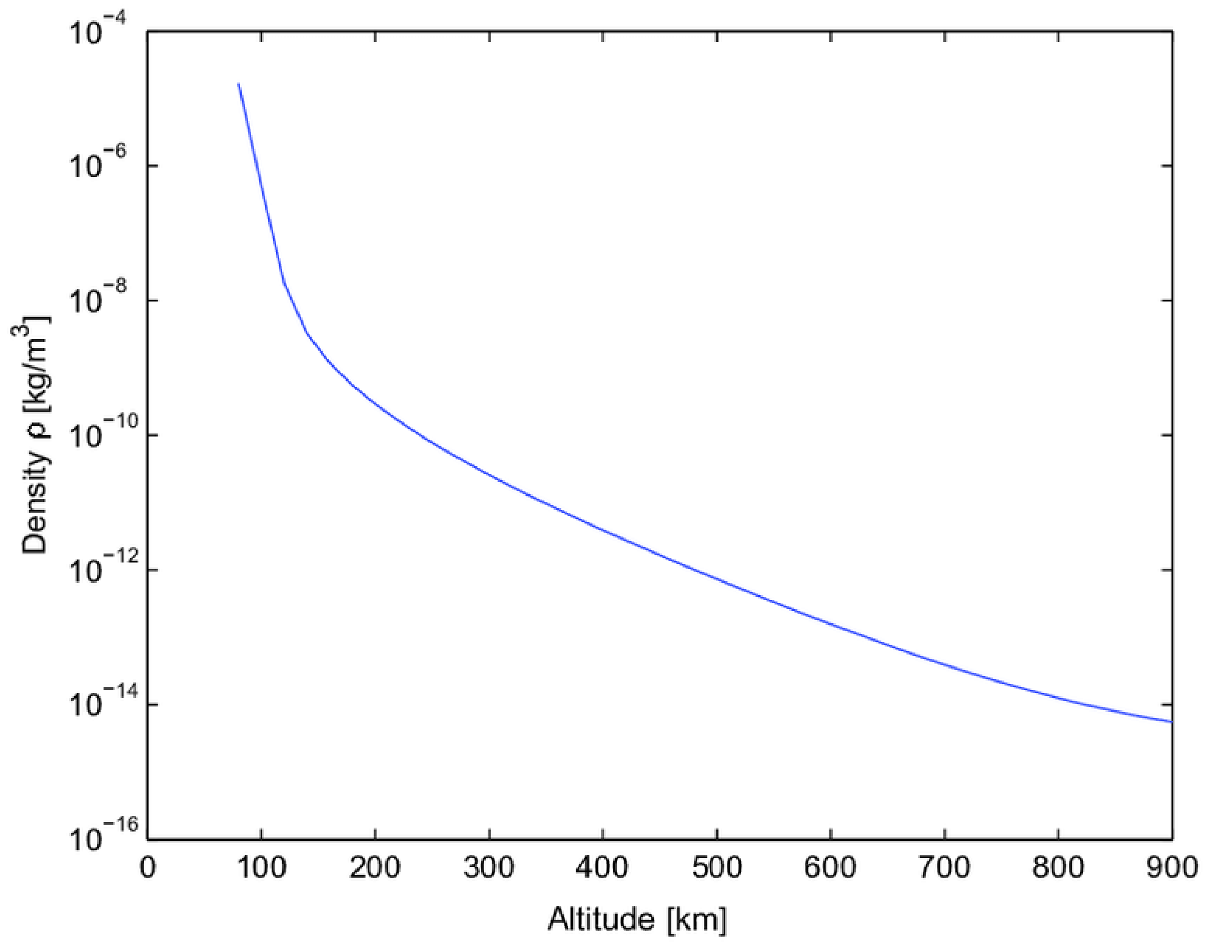
- the variation of H with the temperature gradient is $\dfrac{\mathrm{d}H}{\mathrm{d}h} = \dfrac{R}{Mg}\dfrac{\mathrm{d}T}{\mathrm{d}h} = \dfrac{H}{T}\dfrac{\mathrm{d}T}{\mathrm{d}h}$
  - in the troposphere $\mathrm{d}T/\mathrm{d}h = -6.5\ \mathrm{K\ km^{-1}}$, $H = 8.72\ \mathrm{km}$

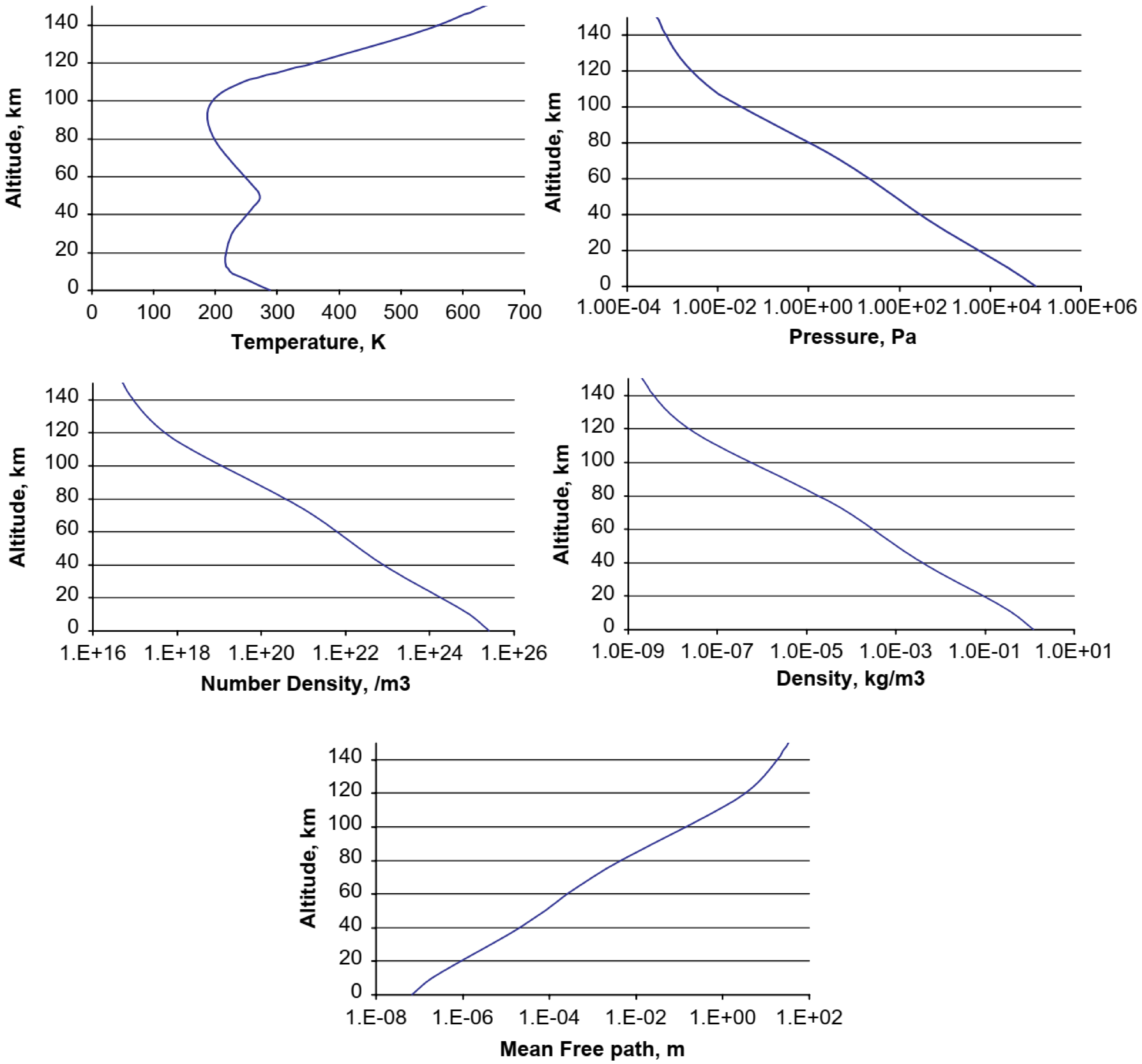
    hence $\mathrm{d}H/\mathrm{d}h = \dfrac{H}{T}\dfrac{\mathrm{d}T}{\mathrm{d}h} = -\dfrac{8.72}{298.15}\,6.5 = -0.19 \approx -0.2$
  - the pressure variation is $p = p_0\left(\dfrac{1+\dfrac{L}{T_0}h}{1+\dfrac{L}{T_0}h_0}\right)^{-\frac{Mg}{RL}}$; the density variation is $\rho = \rho_0\dfrac{\left(1+\dfrac{L}{T_0}h\right)^{-\left(\frac{Mg}{RL}+1\right)}}{\left(1+\dfrac{L}{T_0}h_0\right)^{-\frac{Mg}{RL}}}$

Altitude role

As the distance from the centre of a planet increases, atmospheric **pressure and density decrease**, approaching the interplanetary environment without a clear discontinuity.

- At LEO altitudes (300-900 km) the density is low, but not insignificant.
- At **GEO altitude**, ~36 000 km, the density of the atmosphere is approximately the same as in the **interplanetary medium**, i.e. 10^{-20} kg m^{-3}, and the pressure is ~10^{-15} Pa.





SPACE MISSION ISSUES

The characteristics and composition of the neutral atmosphere play a role on spacecraft design

- mechanical **structure subsystem**, in particular on the material selection

Outgassing

It is the release of gases from a material over time. In other words, outgassing or sublimation refers to the vaporisation of the surface atoms of a material when it is subjected to an **ambient pressure comparable to its vapour pressure**. This pressure, 10^{-11}-10^{-15} Pa, occurs at spacecraft altitudes.

- The rate of outgassing is generally exacerbated by exposure to the **near vacuum of space**, and this process occurs at an increasing rate with **increasing temperature**.
- While structural problems due to outgassing are unlikely to occur, the subsequent deposition of other material is **hazardous to** both **optical** and **electrically** sensitive surfaces (especially if they are used for their thermal properties).
  - Many COTS integrated electronic circuits contain plastic materials that could release gases under vacuum.
- A summary of **mass loss rates** for different metals at various temperatures is given in the table: appreciable loss of
  - cadmium and zinc (used in plating) and selenium (used in photocells)

  occur at temperatures likely to be encountered by these materials in spacecraft.

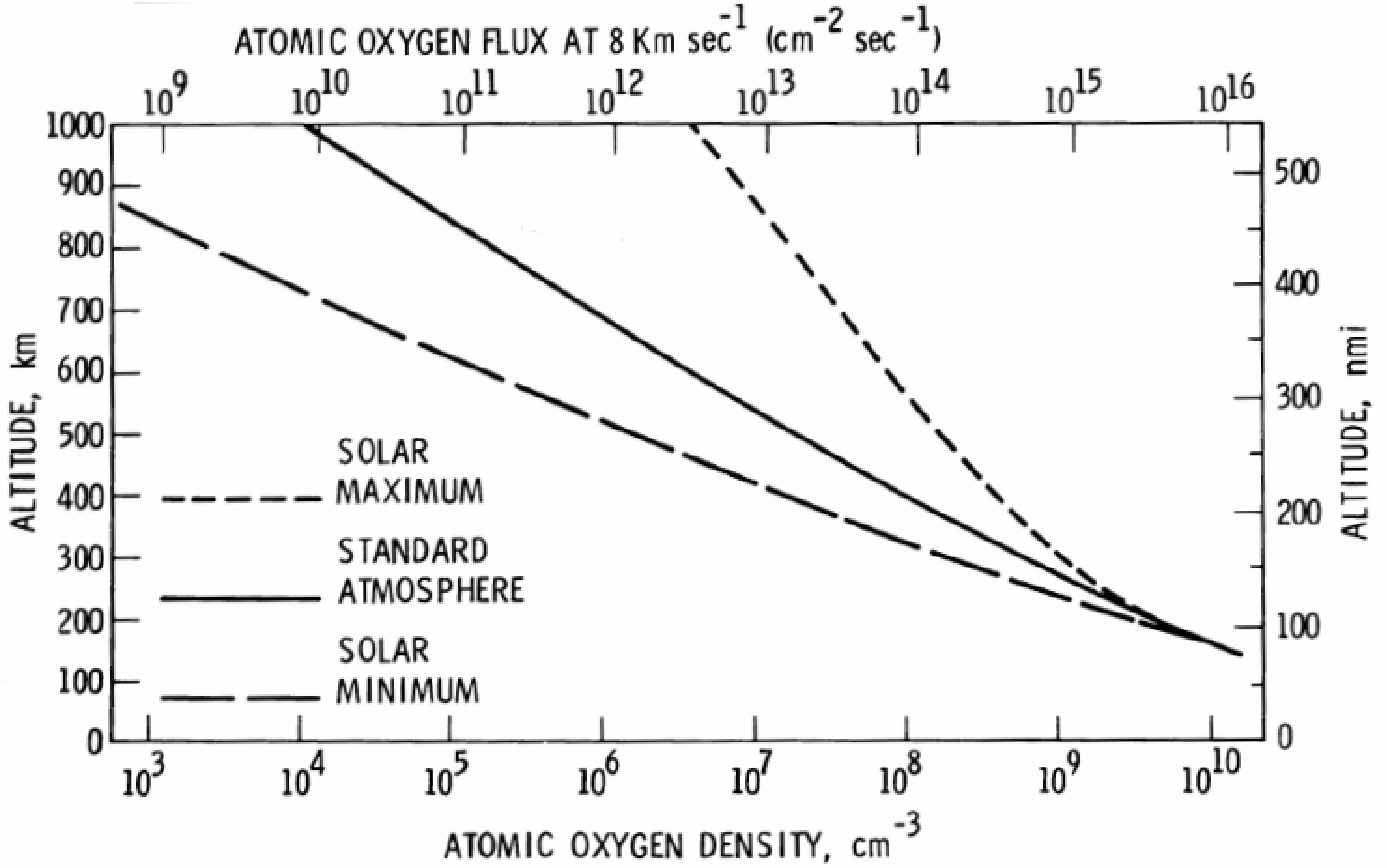
Temperature for a given sublimation rate (°C)

Element	0.1 µm/yr	10 µm/yr	1 mm/yr
Cd	38	77	122
Zn	71	127	177
Mg	110	171	233
Au	660	800	950
Ti	920	1070	1250
Mo	1380	1630	1900
W	1870	2150	2480

Atomic oxygen

Atomic oxygen O is the **main constituent** of the residual atmosphere in LEO orbits:

- it is formed by **photo-dissociation** due to solar ray energy:
  - therefore its concentration **depends on the solar activity**.



Atomic oxygen

Atomic oxygen O, other atomic and molecular elements and radiation, can react with the system and lead to degradation of the system.

- Atomic oxygen constitutes an **aggressive** environment for **materials** used on spacecraft in LEO. This results not only from its **chemical activity**, but mainly from the fact that its atoms **travel at ~8 km s** $^{-1}$ relative to the vehicle (due to the orbital motion of the vehicle).
- The interactions between oxygen atoms and spacecraft surfaces are erosive, stable oxide formation, diffusion or reflection and chemo-luminescence; as a consequence, **different scenarios** appear:
  - elastic diffusion in the surrounding environment of oxygen;
  - oxygen can stick to the surface of a material and react with other chemical species present in the space environment;
  - oxygen can react with the material on which it is deposited, oxidising it and degrading its physical structure:
    - when **erosion** occurs, volatile products are formed that cause the **surface to recede**:
      - erosion E (in cm) of a material is proportional to the fluence Φ_{yr} of particles impacting on the material by a proportionality constant R (in 10^{-24} cm^3) representing the reactivity of that material: $E = \Phi_{yr} \cdot R$

Atomic oxygen

The probability of reaction depends on the material with which the oxidation takes place:

- for instance, the carbon probability of reaction is 13%;
- while the **silver** probability of reaction is 63% ($R = 10$): the degradation of silver by the following **oxidation** reaction

$$2Ag + \frac{1}{2}O_2 \rightarrow Ag_2O$$

  silver oxide is very brittle and porous: after the formation of a 0.5 µm thickness of silver oxide, this layer disintegrates, increasing the contact surface between pure silver and oxygen;

- **gold** is preferred to silver as coating conductive parts (copper $R = 0.0007$);

The **NRLMSISE-00 model** is an empirical model developed by the United States Naval Research Laboratory in collaboration with NASA, which makes it possible to describe the densities of atomic and molecular particles in a given orbit:

- the model calculates the **fluence of oxygen atoms** on an arbitrary surface oriented with respect to the velocity vector of the spacecraft;
- the particle density is estimated by setting the orbit characteristics (mission time, mission start date, type of orbit...) and some characteristics related to the space environment, such as the solar flux *F10.7* (daily and averaged over the last 81 days) and the magnetic index A_p.

Charging

Spacecraft charging is the process by which a spacecraft or selected components **accumulate an electrical charge** from its environment. Spacecraft charging is the storing of electrical charges on the surface (surface charging) or into the structure (internal charging) of a spacecraft. In-space charging effects are caused by **interactions between** the in-flight **plasma environment and spacecraft materials and electronic subsystems**.

This charging, if crosses a threshold value, could lead to an **electrical discharge** and to a consequent failure of the entire mission. When a **dielectric** or an **ungrounded conductor** collect enough charge to induce a local electric field which exceed the dielectric strength of the material. **Breakdown voltage level** depend on the basic dielectric strength and on the thickness of the material.

- Differences in potentials between surfaces in the spacecraft can produce **arc-discharges** when the electric field generated from charging exceeds breakdown threshold voltages.

- As a result of charging, molecules outgassing from the spacecraft can be ionized while nearby and attracted to negatively charged surfaces, causing contamination to the surfaces.

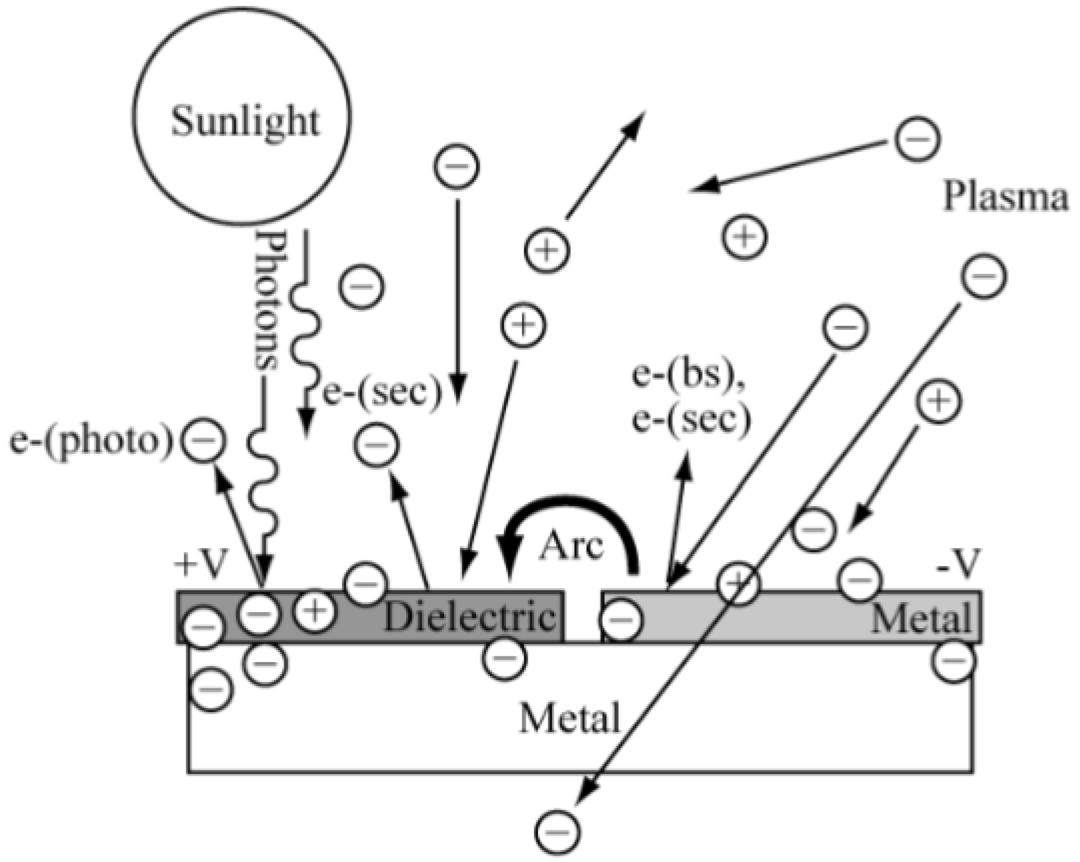


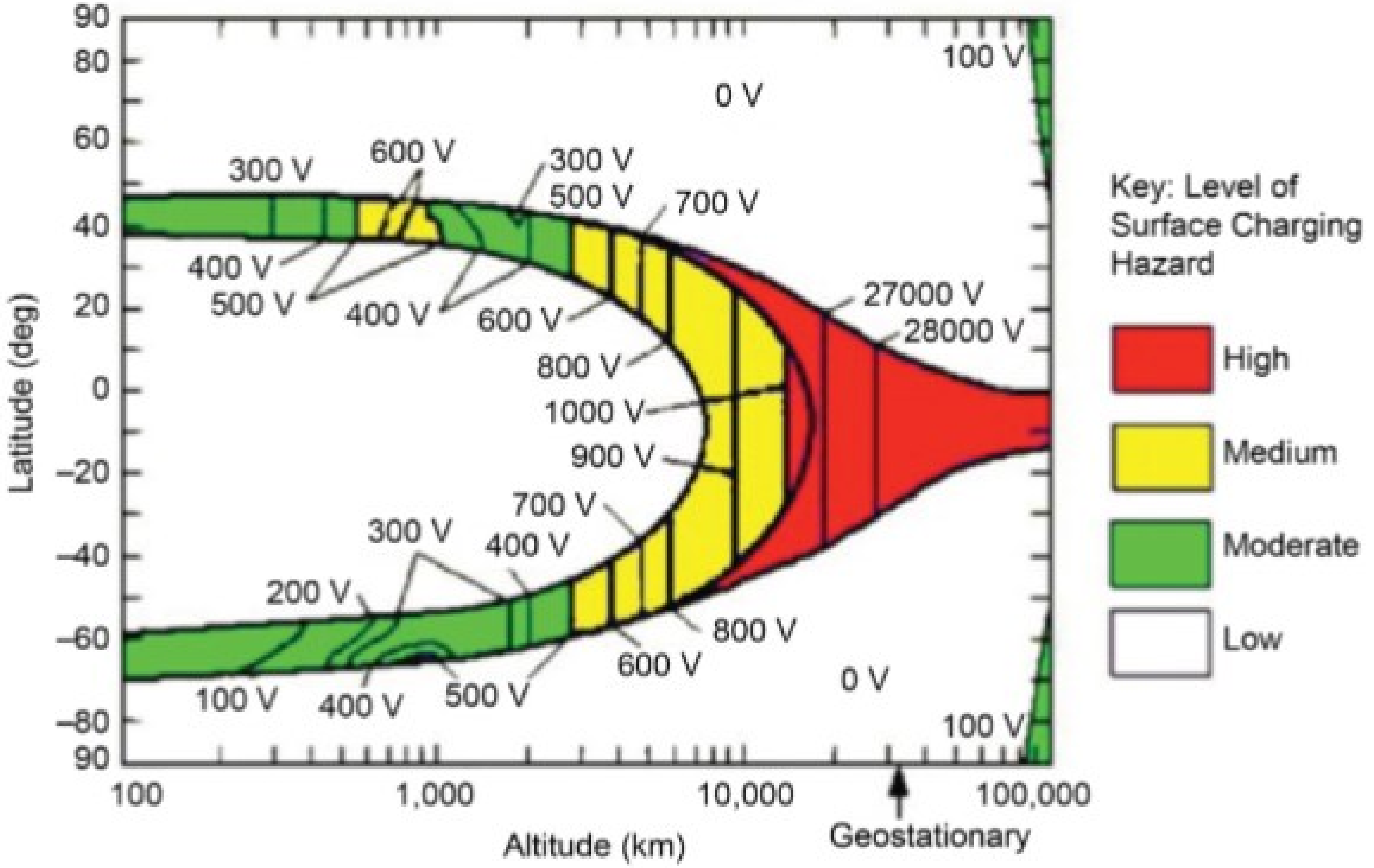
Fig. 2-2. Plasma interactions with spacecraft surfaces.

Charging

Spacecraft charging is dependent on the characteristics of the space environment, including where the spacecraft is exposed to the Sun or the eclipse, solar activity, geomagnetic activity, and the solar electron flux density.

The hazardousness of this environment varies with the position in orbit as shown in Figure (Potential were calculated for an aluminium sphere in shadow).

- For this reason different standard for mitigation were realized, according to the specific orbit.



Space plasma physics

PLASMA

Plasma represents a state of matter characterized by **gases** wherein the **constituent particles possess electrical charge**.

- In a gas composed of **neutral particles**, interactions between these particles are postulated to occur **exclusively** upon **collision**, implying that they maintain **linear trajectories** when not in close proximity.
- Conversely, in a **plasma**, the particles continuously engage in interactions mediated by **long-range electromagnetic forces**, resulting in **intricate trajectories** for individual particles.

A plasma can be defined as a region in which the charged particles, namely **ions** and **electrons**, achieve a **balance**.

- When examining a sufficiently **large volume of plasma** containing numerous charged particles, it is expected that this volume will exhibit **near-neutrality**:
  - **any significant charge** imbalance would invoke substantial **electrostatic forces** aimed at **reestablishing charge neutrality**;
  - **such imbalances** are typically **transient** – with short **duration** constrained by the **inverse of the plasma frequency** – or **spatially limited** – corresponding to the characteristic length known as the **Debye length**.

Plasma frequency

Let us **assume** a completely ionized, infinite, and uniform plasma at a temperature wherein the thermal motion of ions and electrons is negligible, devoid of any magnetic field, and considering that the ion mass exceeds the electron mass, so that the ion motion is neglected.

Along an axis X, let us consider a sheet of **electrons** (density n, charge e, mass m_e) normal to X-axis and located at position x, which is displaced by its quasi-neutral position by an infinitesimal distance of amount $x + \xi$:

- the resulting charge density that develops on the leading face of the slab is $\sigma = ne\xi$;
    - an equal and opposite charge density develops on the opposite face;
- the electric field generated by the electrons is expressed as $E = \frac{ne\xi}{\varepsilon_0} = 4\pi\, ne\xi$ (in SI and cgs units, respectively);
- the equation of motion for each electron within the sheet can be articulated as follows: $m_e \frac{d^2\xi}{dt^2} = -eE.$

Plasma frequency

So we can write $\frac{d^2\xi}{dt^2} + \omega_{p,e}{}^2 \xi = 0$

- the **electronic plasma angular frequency** is defined as $\omega_{pe} = \sqrt{\frac{n_e e^2}{m\ \varepsilon_0}} = \sqrt{\frac{4\pi n_e e^2}{m}}, \ [\mathrm{rad/s}]$
- the plasma frequency $f_p = \omega_p / 2\pi$ → $f_{pe} = \frac{1}{2\pi}\sqrt{\frac{n_e e^2}{\varepsilon_0 m_e}} = 8.979\sqrt{n_e}$ or $f_p \approx 10^4 \sqrt{n}$ Hz (n_0 in cm^{-1})

representing the **natural frequency of collective oscillation of the electrons within the plasma**.

By analogy, the **ion plasma frequency** of the ions is represented as $\omega_{pi} = \left(\frac{4\pi n_i Z^2 e^2}{m_i}\right)^{\frac{1}{2}}$ $f_{pi} = \frac{1}{2\pi}\sqrt{\frac{e^2}{\varepsilon_0}\sum_{i,j} j_i^2 \frac{n_i}{m_i}}$

Plasma frequency

For **effective electromagnetic wave propagation in plasma**, the incident **electromagnetic wave frequency must exceed the plasma frequency**: $\omega > \omega_p$

If an electromagnetic wave of frequency ω is incident on a plasma volume possessing electron plasma frequency ω_p greater than ω (i.e., $\boldsymbol{\omega < \omega_p}$), then the electromagnetic wave is unable to penetrate/propagate through the plasma and is consequently **reflected by the plasma**.

- This phenomenon accounts for the reflection of radio waves by the **ionosphere**, which plays a critical role in facilitating **long-distance radio communications**:
  - enabling transmission **beyond the horizon** and leading to **communication blackout during re-entry** from space when the surrounding electron density increases due to atmospheric heating;
  - **solar emissions of ionized particles** during active periods can significantly **alter the composition of the ionosphere**, thereby impacting transmission efficacy.

Debye length

In a plasma maintained at **uniform temperature**, let us consider a **charge Q** and the **electric field** it generates, characterized by a **potential $\phi = \phi(r)$** that exhibits **spherical symmetry** around the central charge.

This scenario is described by the **Poisson equation** $\nabla^2\phi = -4\pi(n_i - n_e)e = -\frac{(n_p - n_e)e}{\epsilon_0}$ (in cgs and SI units, respectively) in which the numerical densities of electrons (n_e) and ions (n_i) follow **Maxwell-Boltzmann distribution**:

$$n_i = n\exp\left(-\frac{e\phi}{\kappa_B T}\right), \qquad n_e = n\exp\left(\frac{e\phi}{\kappa_B T}\right)$$

$$\rightarrow \qquad \nabla^2\phi = 4\pi n e\left[\exp\left(\frac{e\phi}{\kappa_B T}\right) - \exp\left(-\frac{e\phi}{\kappa_B T}\right)\right]$$

This relationship can be expanded into a Taylor series, where nonlinear terms in ϕ (starting from quadratic order and above) are neglected, resulting in a simplified expression:

$$\nabla^2\phi = \frac{2\phi}{\lambda_D^2},$$

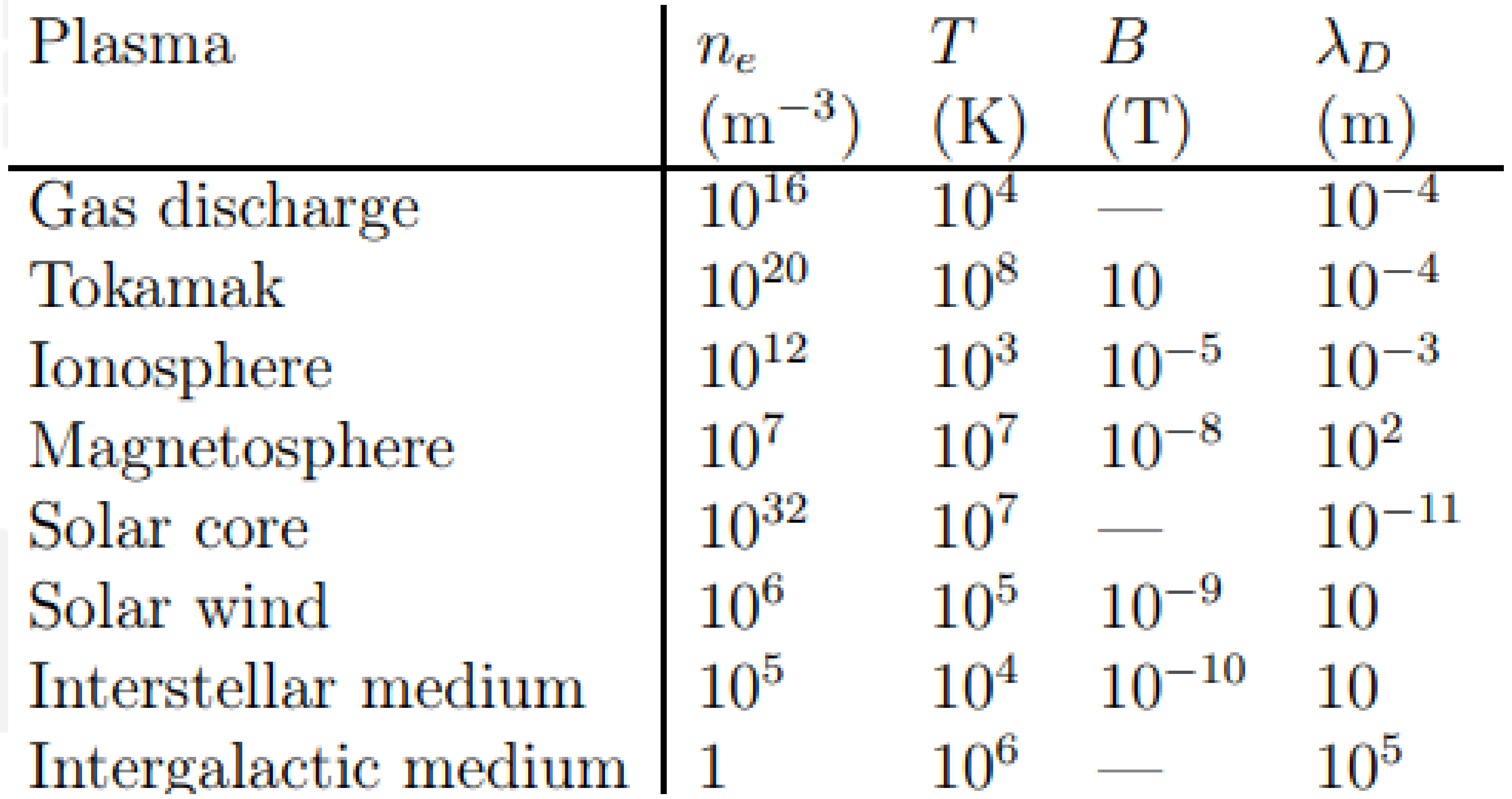
The **Debye length** is defined as $\lambda_D = \left(\frac{\kappa_B T}{4\pi n e^2}\right)^{1/2} = \sqrt{\frac{\varepsilon_0 k_B T}{n\ e^2}}$ (in cgs and SI units, respectively)

Debye length

The potential surrounding the charge is $\phi = Q\frac{\exp(-r/\lambda_D)}{r} = \frac{Q}{4\pi\varepsilon r}e^{-r/\lambda_D}$ (in cgs and SI units, respectively)

- the **charge influence is screened beyond a distance λ_D**:
  - for $r > \lambda_D$, the electric field generated by the charge is attenuated by an exponential factor, resulting in the **plasma** being effectively **charge neutral**;
  - for $r < \lambda_D$, conversely, the electric field remains **unaffected** by the plasma presence, which begins to shield at the distance λ_D.

In **space plasmas** where the **electron density** is relatively **low**, the **Debye length** may reach **macroscopic values**, such as in the magnetosphere, solar wind, interstellar medium and intergalactic medium.



Plasma	n_e (m^{-3})	T (K)	B (T)	λ_D (m)
Gas discharge	10^{16}	10^4	—	10^{-4}
Tokamak	10^{20}	10^8	10	10^{-4}
Ionosphere	10^{12}	10^3	10^{-5}	10^{-3}
Magnetosphere	10^7	10^7	10^{-8}	10^2
Solar core	10^{32}	10^7	—	10^{-11}
Solar wind	10^6	10^5	10^{-9}	10
Interstellar medium	10^5	10^4	10^{-10}	10
Intergalactic medium	1	10^6	—	10^5

Debye length

The **number of particles influenced** by the charge within the **Debye volume** $\lambda_D{}^3$ is approximately of the order $\left(\frac{4\pi}{3}\right) n\lambda_D^3$

The **plasma parameter** quantifies the number of collective interactions within the plasma $g = \frac{1}{n\lambda_\mathrm{D}^3} = \frac{(8\pi)^{3/2} e^3 n^{1/2}}{(\kappa_\mathrm{B} T)^{3/2}}$

- in scenarios where **g is small**, indicative of **low density plasma**, a **greater number of collective interactions** among particles occurs:
    - **less effective Debye shielding**, therefore the **Debye volume increases**: although the particle density is lower, the **total number of particles** within the Debye volume becomes **larger**;
    - however, these **particles interact weakly** since the kinetic energy surpasses the potential energy of interaction;
- in scenarios where **g is large**, conversely, **fewer particles** engage in collective interactions, albeit with **greater intensity**.

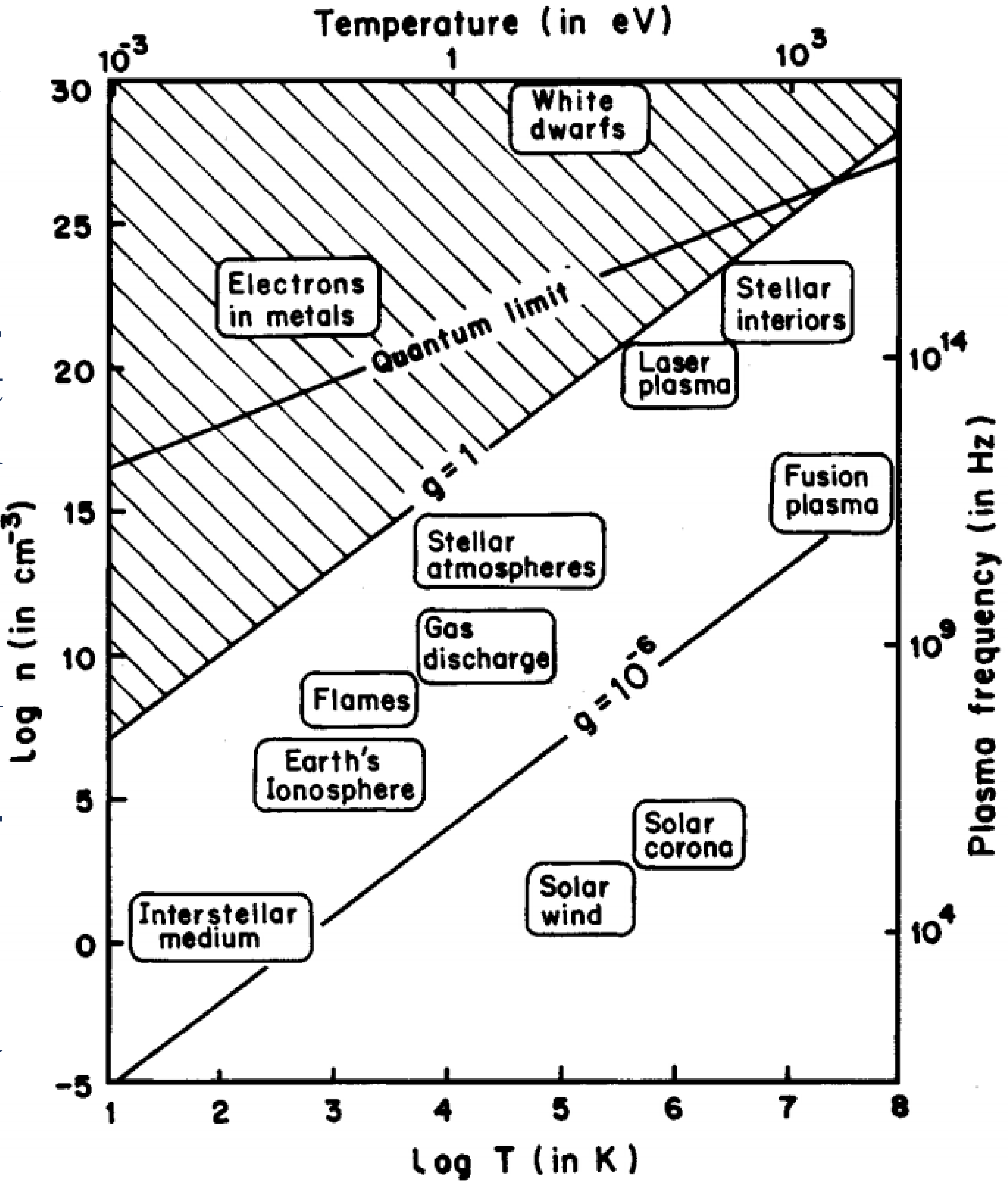
Plasma types

The **plasma characteristics** are predominantly governed by the number density ***n*** of charged particles and the temperature ***T***.

- In the shaded region above the "quantum limit" line, particle wave packets overlap, indicating that electrons within **metals or white dwarf stars cannot be regarded as classical particles**, necessitating consideration of quantum Fermi-Dirac distributions.

- For low values of g (**$g \ll 1$**), the potential energy of interactions between neighbouring particles is negligible in comparison to the kinetic energy, permitting the treatment of plasma as an ideal gas comprised of **non-interacting particles**.

- The **Earth's ionosphere** is situated around 10^7 Hz, within the **radio frequency range**.



IONOSPHERE

The ionosphere of a planetary body represents the **upper atmospheric portion** where charged particles—electrons and ions—constitute a plasma.

Such a plasma primarily results from the **photoionization** of the remaining constituents of the so-called **neutral atmosphere** by solar electromagnetic radiation, particularly in the ultraviolet spectrum and shorter wavelengths, alongside solar and cosmic particles.

- The **upper boundary** of the ionosphere is typically defined by its **interaction with the solar wind**:
  - in celestial bodies with a **weak** or virtually non-existent global **magnetic field**, this boundary is termed the **ionopause**;
  - in celestial bodies possessing a global **magnetic field**, the **ionosphere** or plasmasphere is encompassed **within the magnetosphere**.
- The **lower boundary** is determined by the altitude accessible to the most intense radiation.

Ionisation

The **time rate of change of electron density** at a site is the **difference between the rate of electron production** and the **rate of electron recombination**, where the latter depends on the **density of the neutral atmosphere**.

- Since **atmospheric density decreases with increasing altitude**, at **low altitudes** the **density is so high** that **recombination occurs**, making the **electron density essentially zero**.
- As **altitude increases**, the **recombination of free electrons decreases**, causing the **electron density to increase** until, at even **higher altitudes**, the **electron density starts to decrease** because there is **less atmosphere to ionize**. For singly charged ions, the rate of change of electron density can be represented by

$$\frac{\mathrm{d}n_e}{\mathrm{d}t} = q - n_e \sum_i \alpha_i n_i$$

q = rate of electron production [electrons m^{-3} s^{-1}]

α_i = recombination coefficient for ions i [m^{-3} s^{-1}]

- When **equilibrium** is reached, the rate of electron production equals the rate of recombination, so

$$n_e = \frac{q}{\sum_i \alpha_i n_i}$$

Ionisation

In the case of a **single gas** where the **energy absorption** is the **same for all wavelengths** of solar radiation, the **electron density** as a function of altitude defines the **Chapman layer**, that is given by

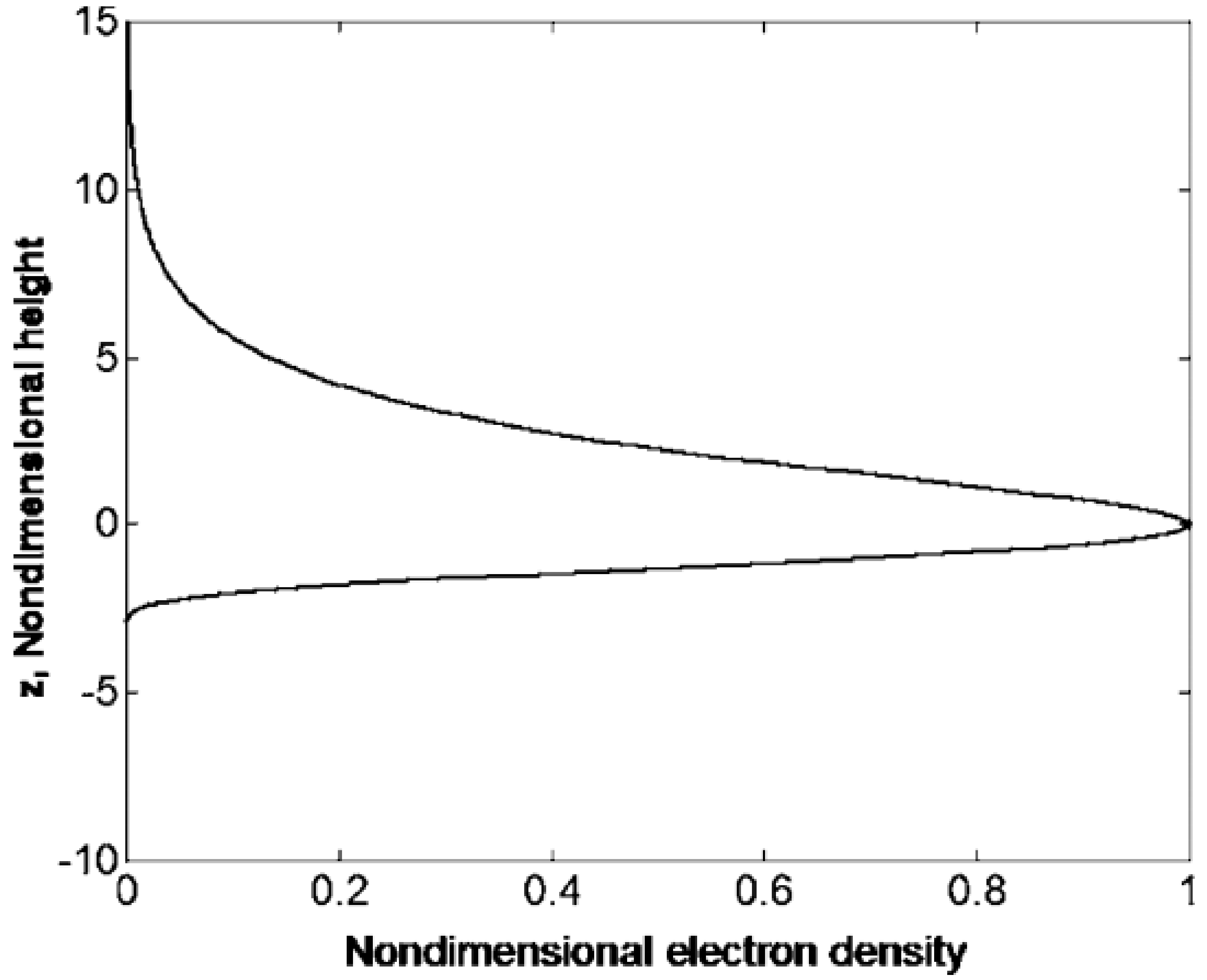
$$q = q_m \exp[1 - z - \exp(-z)]$$

q_m = maximum rate of electron production [electrons $m^{-3}\ s^{-1}$]

$z = (h - h_m) / H$, reduced altitude parameter

h = altitude [m]

h_m = altitude above the surface of maximum electron production [m]



Chapman layer.

It follows that, for a **fully ionized medium**, where $n_e = n_i$,

the electron density as a function of altitude is

$$n_e = \left(\frac{q_m}{\alpha_i}\right)^{1/2} \exp\left\{\frac{1}{2}\left[1 - z - \exp(-z)\right]\right\}$$

Earth ionosphere

The Earth's ionosphere, which extends from about **50 km altitude**, constitutes the inner boundary of the magnetosphere.

- From an altitude of about 50 km, the atmosphere **density is low** enough to allow **electrons to remain free for short periods**.
- As atmospheric **density decreases with altitude**, the **recombination of free electrons diminishes**, causing the electron density to increase with altitude **up to about 300-350 km**, where it reaches a maximum and starts to decrease.

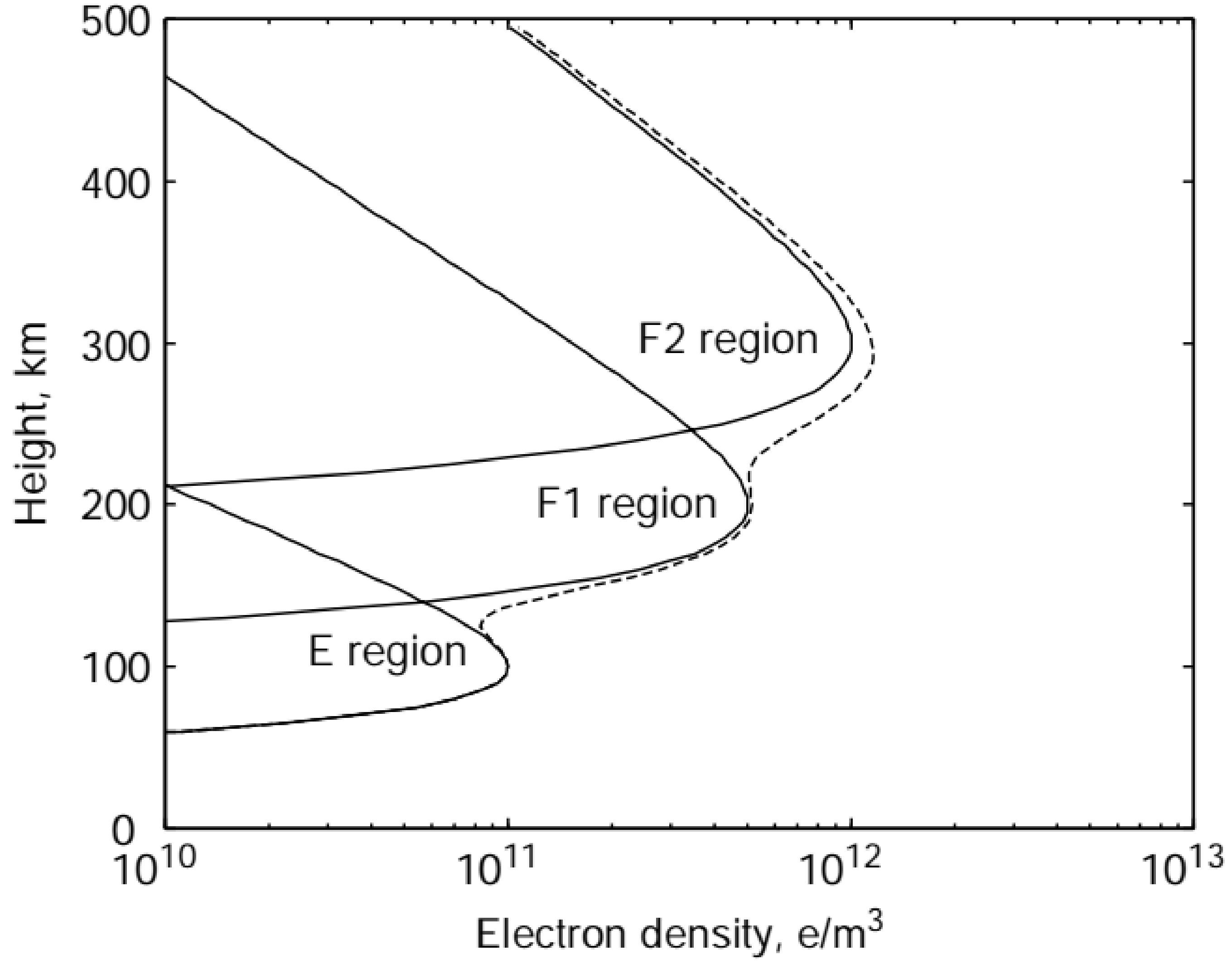
However, **increasing in electron density with altitude is not monotonic**.

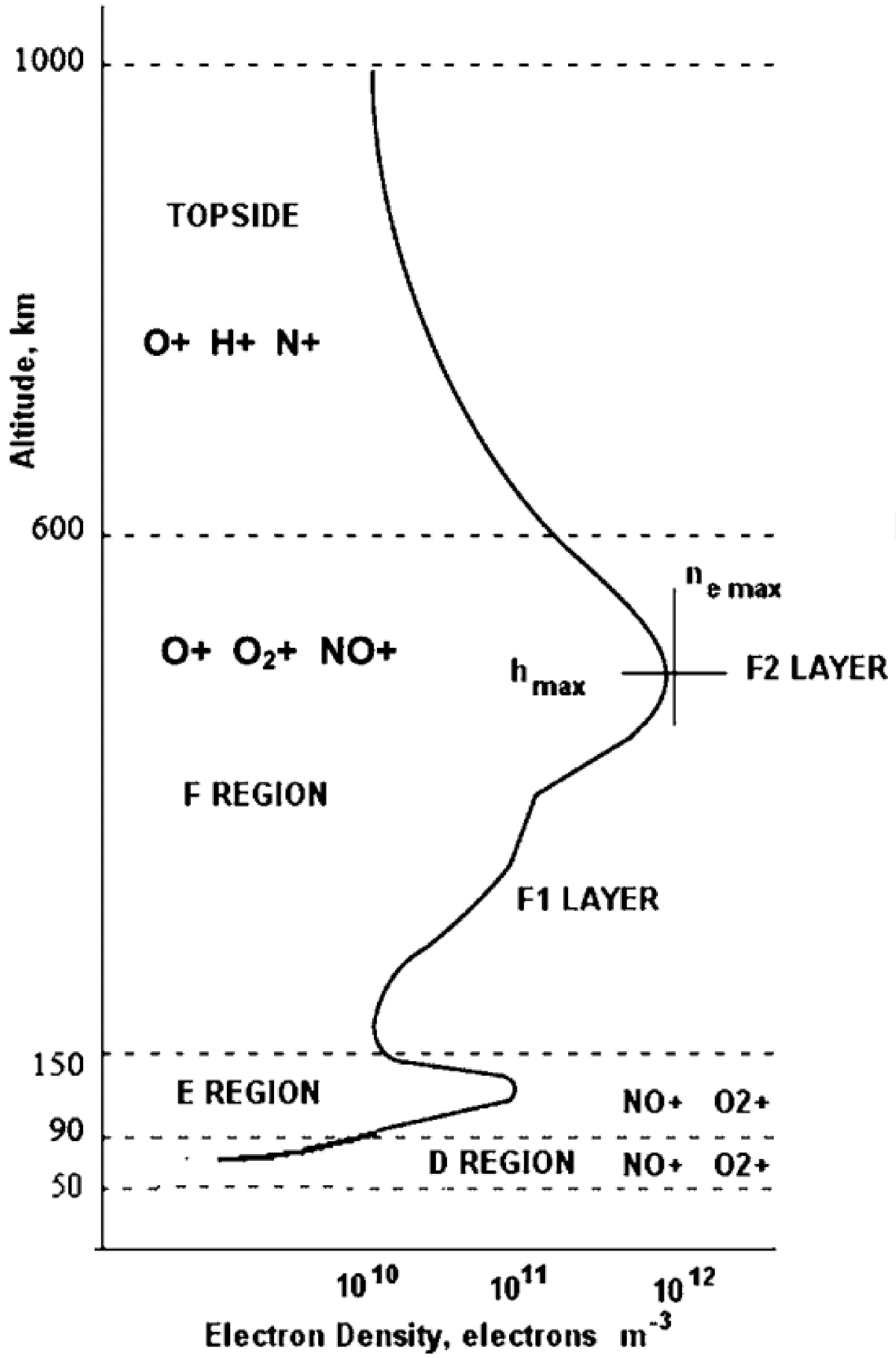
- The degree of ionization **depends on the atmospheric constituents** and **the solar radiation intensity**, and as such depends on solar activity, the time of day, longitude, and latitude:
  - **variations can be extreme** by one or more orders of magnitude over time, from day to night, from one location to another, and in cases of significant changes in solar or magnetic activity.

Earth ionosphere

The Earth ionosphere is generally characterized by a series of **layers** or regions.

- The typical Earth ionosphere can be modelled as a sum of **Chapman models** for the E, F1, and F2 regions.





Daytime ionospheric layers.

Earth ionosphere

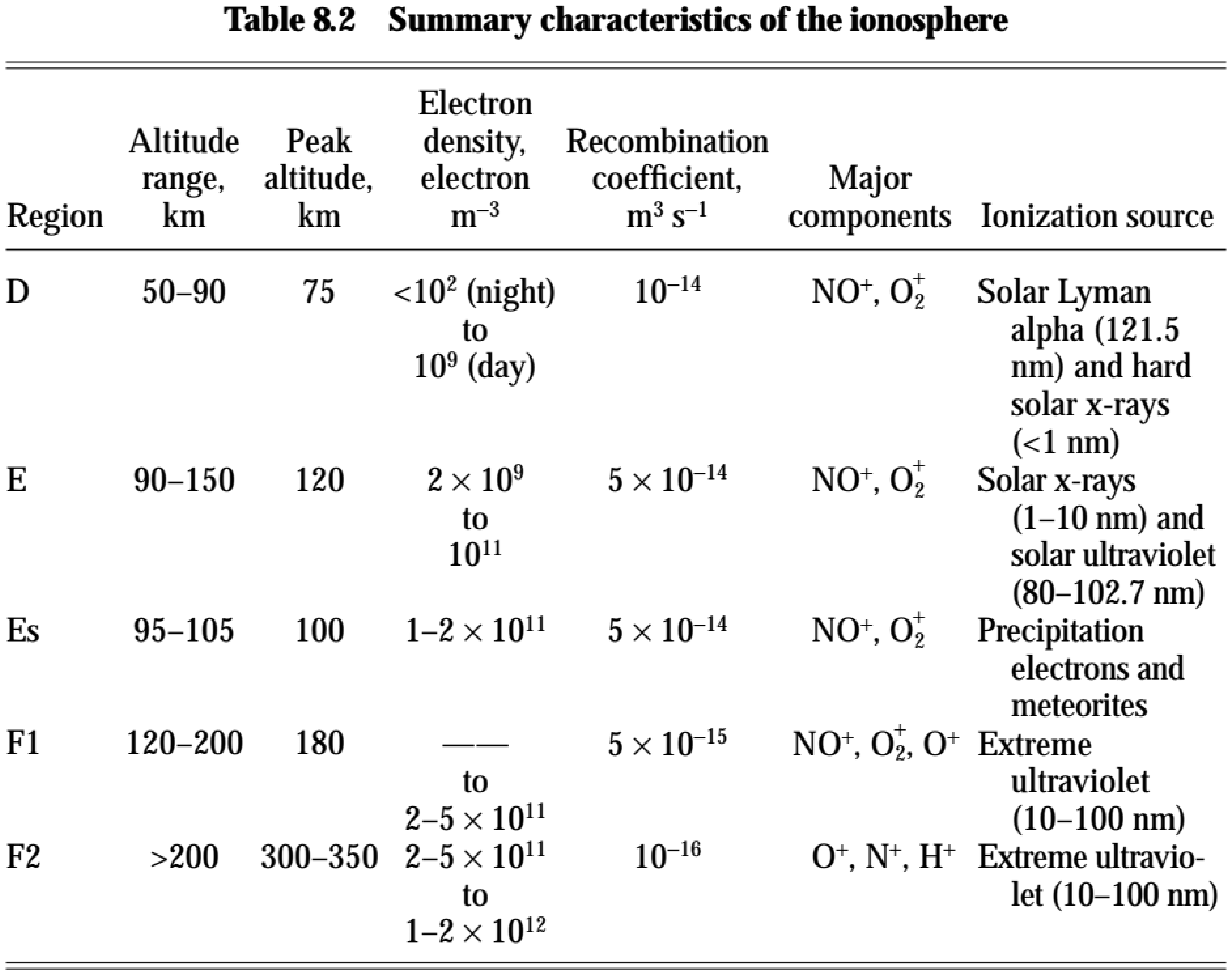


Table 8.2 Summary characteristics of the ionosphere

Region	Altitude range, km	Peak altitude, km	Electron density, electron m^{-3}	Recombination coefficient, $m^3\ s^{-1}$	Major components	Ionization source
D	50–90	75	$<10^2$ (night) to 10^9 (day)	10^{-14}	NO^+, O_2^+	Solar Lyman alpha (121.5 nm) and hard solar x-rays (<1 nm)
E	90–150	120	2×10^9 to 10^{11}	5×10^{-14}	NO^+, O_2^+	Solar x-rays (1–10 nm) and solar ultraviolet (80–102.7 nm)
Es	95–105	100	$1–2 \times 10^{11}$	5×10^{-14}	NO^+, O_2^+	Precipitation electrons and meteorites
F1	120–200	180	—— to $2–5 \times 10^{11}$	5×10^{-15}	NO^+, O_2^+, O^+	Extreme ultraviolet (10–100 nm)
F2	>200	300–350	$2–5 \times 10^{11}$ to $1–2 \times 10^{12}$	10^{-16}	O^+, N^+, H^+	Extreme ultraviolet (10–100 nm)

D region

The D region is the lowest layer extending from about **50 to 90 km** above the sea surface.

- Electrons are produced by the **molecular ionization of nitric oxide** (NO) and **oxygen**: NO^+ and O_2^+.
- Since a significant amount of atmosphere remains at these altitudes, the **recombination rate is high**.
  - The typical peak of **maximum electron density** in the D region is on the order of 10 electrons m^{-3} during the day, and several orders of magnitude lower at night, up to disappearing.
- In the **evening**, cosmic radiation maintains a **low level of electron production**.
  - D differs from the other ionospheric regions (denoted E and F) in that its free electrons almost totally **disappear during the night** because they recombine with oxygen ions to form oxygen molecules.

D region

The **critical frequencies** during the **day** and **night** are respectively:

$$f_{\mathrm{pe},D}\Big|_{\mathrm{day}} = \frac{1}{2\pi}\sqrt{\frac{n_e e^2}{\varepsilon_0 m_e}} = 8.979\sqrt{n_e} = 8.979\sqrt{10^9} \approx 0.3\ \mathrm{MHz}$$

$$f_{\mathrm{pe},D}\Big|_{\mathrm{night}} = \frac{1}{2\pi}\sqrt{\frac{n_e e^2}{\varepsilon_0 m_e}} = 8.979\sqrt{n_e} = 8.979\sqrt{10^2} \approx 90\ \mathrm{Hz}$$

As a result, radio transmissions with

- frequencies much lower than the critical frequency will be reflected from the lower boundary,
- frequencies closer to the critical frequency will penetrate the D region and be absorbed,
- frequencies much higher than the critical frequency will pass through the D region.

D region absorbing transmissions with frequencies above MHz during disturbed periods and by the **AM broadcast bands (535–1605 kHz)** transmitting over the horizon by **reflection from higher altitude ionospheric regions at night** when the D region ionization is **reduced significantly**.

E region

The E region, also known as the Kennelly-Heaviside layer, is at an altitude about **90 to 150 km** above the sea surface.

- The competing effects of ionization and recombination primarily determine the electron density as a function of altitude and cause **a peak in electron density** at about **120 km altitude**.
- Ionization in this region is primarily due
  - to **soft solar X-rays** (wavelength ≈ 1-10 nm) that **ionize N_2, O_2, O, and NO** and
  - to **ultraviolet solar radiation** (wavelength ≈ 80-102.7 nm) that **ionizes molecular oxygen** (O_2) which combines with N to form NO^+ and O_2^+.

IONOSPHERE

E region

After sunset, the **electron density decreases** because the **primary ionization source is no longer present**, while the **peak altitude increases** because recombination is greater at lower altitudes.

The typical electron density of the peak has a maximum of the order of 10^{11} electrons m^{-3} during the day, and is about two orders of magnitude lower at night, so that the critical frequencies during the day and night are, respectively, of the order

$$f_{\text{pe},E}\Big|_{\text{day}} = \frac{1}{2\pi}\sqrt{\frac{n_e e^2}{\varepsilon_0 m_e}} = 8.979\sqrt{n_e} = 8.979\sqrt{10^{11}} \approx 3\ \text{MHz}$$

$$f_{\text{pe},E}\Big|_{\text{night}} = \frac{1}{2\pi}\sqrt{\frac{n_e e^2}{\varepsilon_0 m_e}} = 8.979\sqrt{n_e} = 8.979\sqrt{2\times 10^{9}} \approx 0.4\ \text{MHz}$$

At night, the near disappearance of the D region and the **increased altitude of the E layer peak increase the distance** that **radio waves can travel by reflection**.

F region

Regions F, also known as the Appleton region, has an altitude of approximately **120 to 1000 km**.

- The electron density in this region is produced by the interaction of **solar extreme ultraviolet** (EUV) radiation (10-100 nm wavelength) with **atomic oxygen** (O) to produce O^+ and, at higher altitudes, with H to produce H^+. Some of the O^+ ions transfer charge to form O_2^+ and NO^+.

When the F region is exposed to sunlight during the **day**, it has **two distinct layers**, known as the **F1** layer and the **F2** layer, with an electron density of F2 higher than that of F1.

- At **night**, when **EUV radiation is not present**, the **two peaks merge into one**, known as the **F** layer.

F region

The differentiation into regions is due to the decrease of the recombination coefficient with increasing altitude.

- The typical altitude of the **F1 peak** is about **180 km** and has a density of about 2-5 · 10^{11} electrons m^{-3} during the day; at night, it has an electron density about an order of magnitude lower and often disappears.
- The typical altitude of the **F2 peak** is about **300-350 km** and it has a density of about 1-2 · 10^{12} electrons m^{-3} during the day and about an order of magnitude lower at night: consequently, it has **the maximum density of electrons in the ionosphere**.

The critical frequencies during the day and night are:

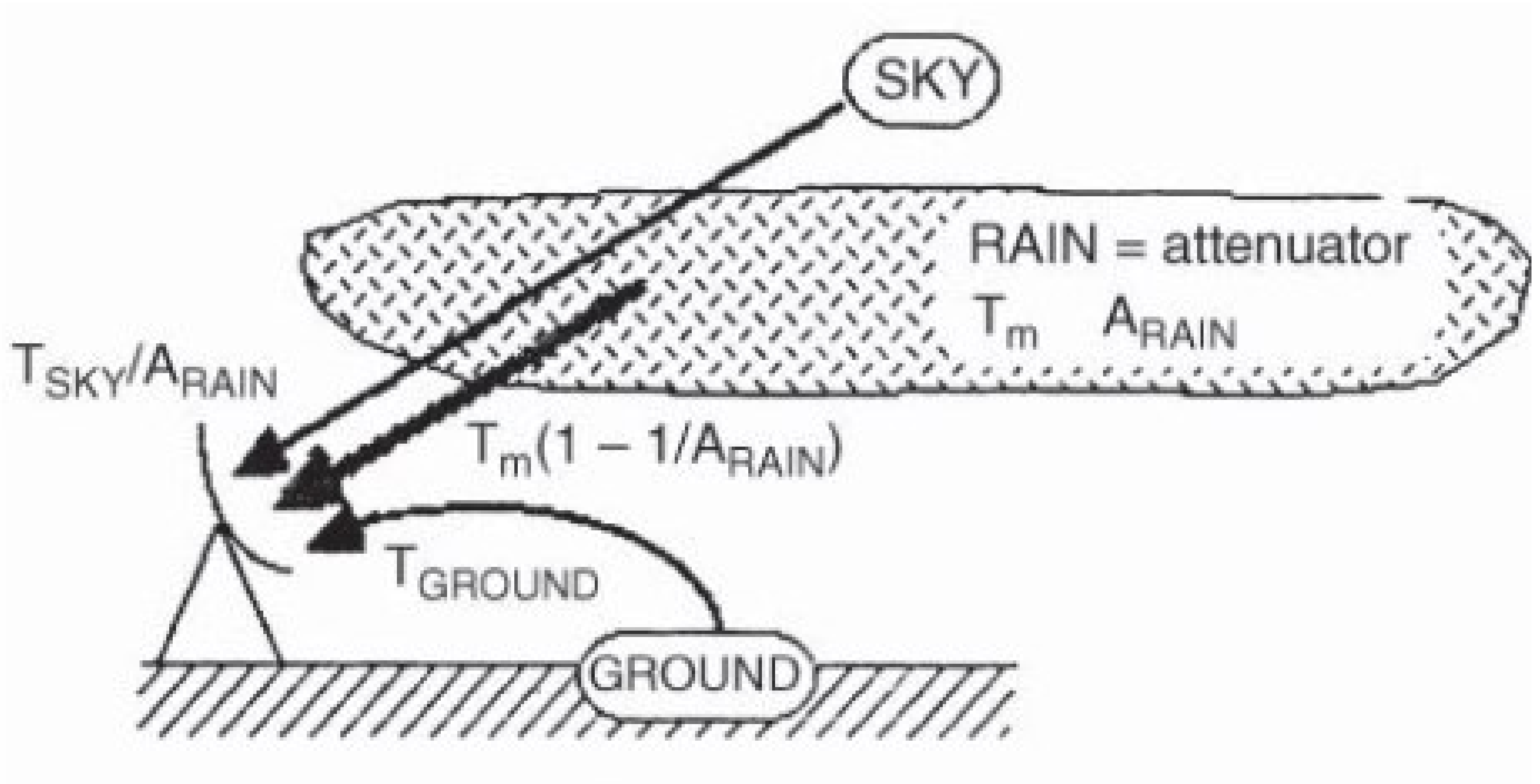
$$f_{\mathrm{pe,F2}}\Big|_{\mathrm{day}} = \frac{1}{2\pi}\sqrt{\frac{n_e e^2}{\varepsilon_0 m_e}} = 8.979\sqrt{n_e} = 8.979\sqrt{1.5\times 10^{12}} \approx 11\ \mathrm{MHz}$$

$$f_{\mathrm{pe,F2}}\Big|_{\mathrm{night}} = \frac{1}{2\pi}\sqrt{\frac{n_e e^2}{\varepsilon_0 m_e}} = 8.979\sqrt{n_e} = 8.979\sqrt{2.5\times 10^{11}} \approx 4.5\ \mathrm{MHz}$$

SPACE MISSION ISSUES

The way the atmosphere affects electromagnetic transmission constraints

- **telecommunication subsystem**



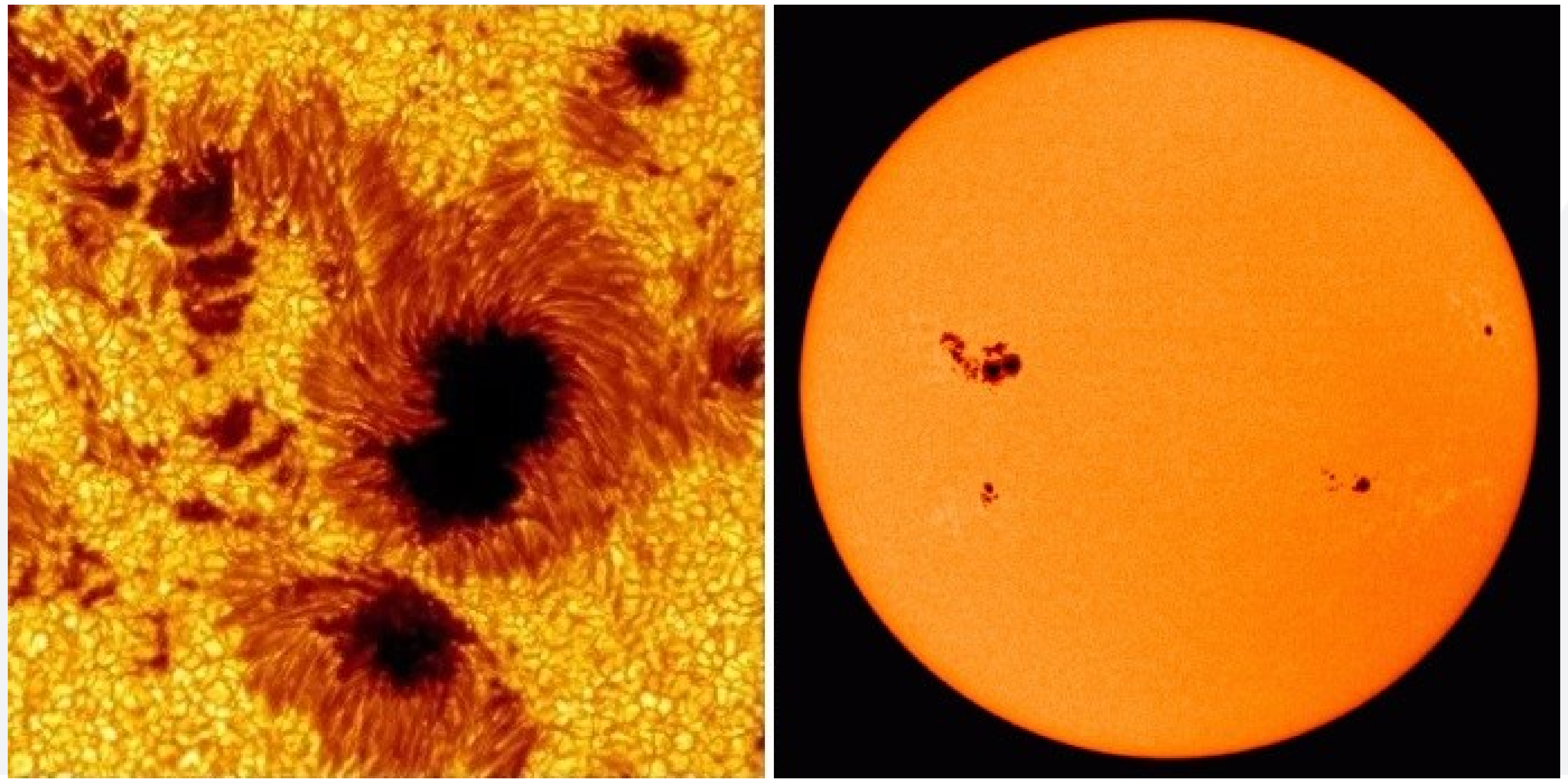
SOLAR ACTIVITY

Sunspots

Solar activity consists of various **transient phenomena** – the ones of most relevance for space activity follow.

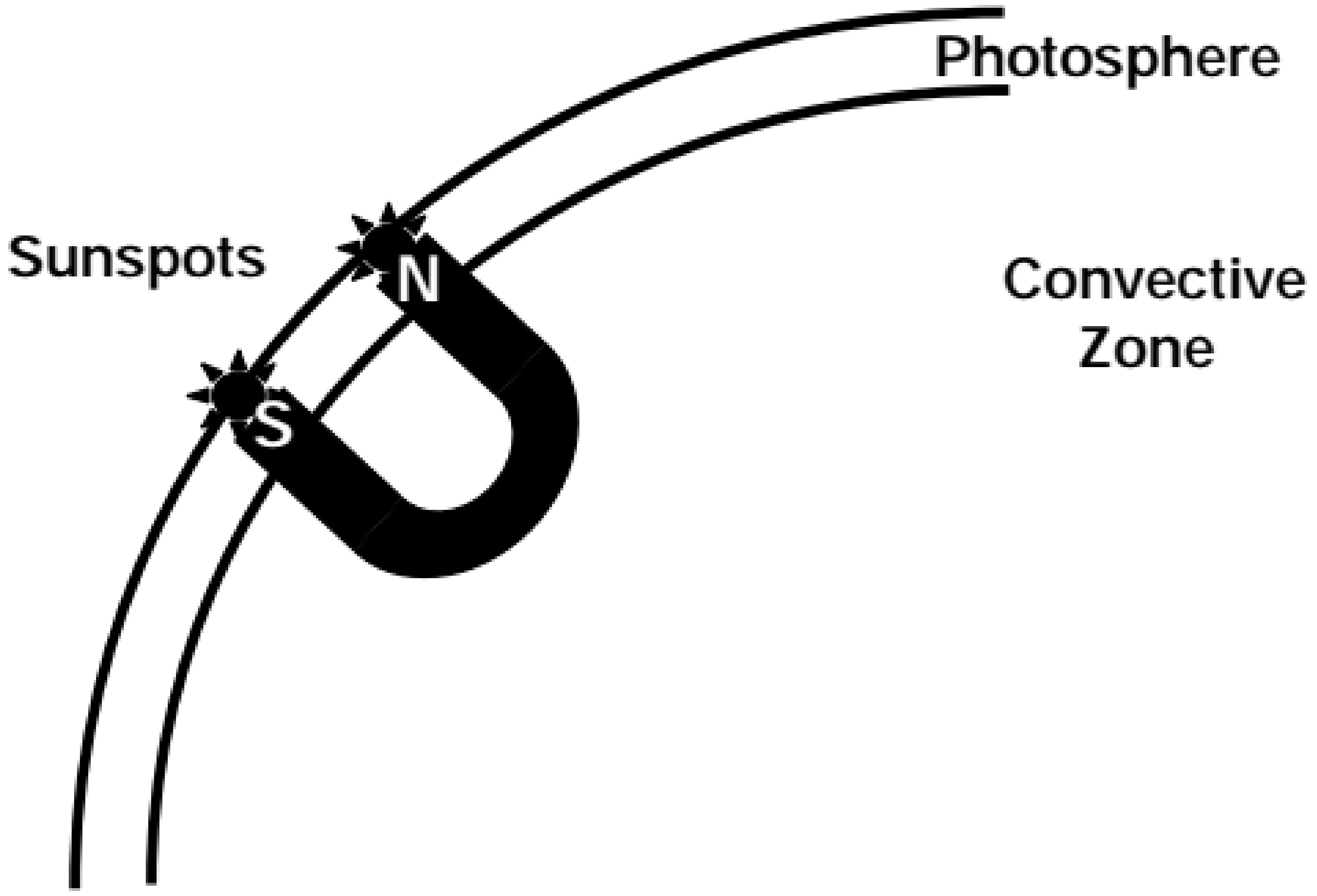
Sunspots are concentrations on the photosphere that appear **darker** than their surroundings.

- They have a temperature of about **3 700 K**, significantly **lower than the surrounding** regions of about 5 778 K, which is why they appear dark on the photosphere.
- Their **diameter** is typically less than about **50 000 km** and their **lifetime** is on the order of a **few days to weeks**.



Sunspots

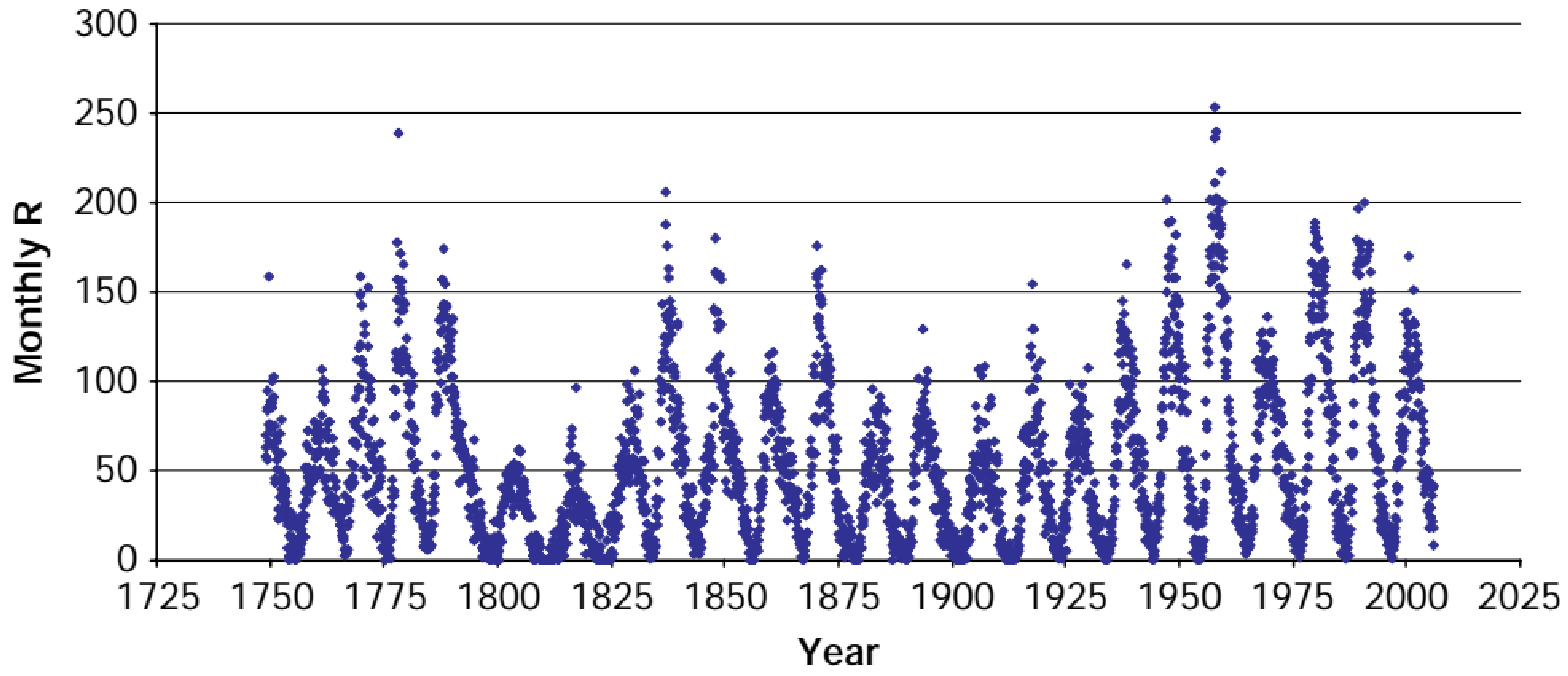
In these regions, the **magnetic field is very intense** with flux densities of 0.1-0.4 T, compared to the average flux density of the solar magnetic field of 0.0001 T. They are produced by **plasma flows** deep in the **convective zone** that **spill onto the photosphere** due to the differential rotation of the Sun. They **appear in pairs** with **opposite magnetic polarity**, as if a magnet were present. Magnetic polarity is that can influence the behaviour of the Sun. Magnetic polarity is determined by a number of factors and **measured by the Zeeman effect** on emitted electromagnetic radiation, whose spectral lines are split in the presence of a magnetic field.



Sunspots

A **sunspot cycle** consists of changes in number, size, relative positions, and polarity.

- During a sunspot cycle, the leading **sunspot pairs** in the **Northern Hemisphere all have the same polarity**, which is the **opposite polarity** of the leading sunspot pairs in the **Southern Hemisphere**. During the **next sunspot cycle**, the **polarities reverse**.
- Every **11 years or so, the number of sunspots reaches a maximum**, and the next maximum occurs with sunspots of reversed magnetic polarity. As a result, the **magnetic cycle averages about 22-25 years**.
- Periods of **high solar activity** occur when there are **large numbers of sunspots** and **increased radiation** emission occurs, particularly at radium wavelengths and **X-ray** and **γ-ray** energies. This increased emission is generally associated with **solar flares**, which occur near sunspots.



F10.7 flux

The intensity of **radio emissions from the chromosphere and the corona** at **wavelength 10.7 cm**, or 2 800 MHz, has been found to **correlate with solar activity**:

- **F10.7 flux** measurements are given in **solar flux units**: 1 *sfu* = 10^{-22} J s^{-1} m^{-2} Hz^{-1};
- as a result, this measurement is often **used to quantify solar activity** in place of sunspot number.

Solar flares

Sunspots are sometimes accompanied by sudden, **intense explosions in the corona**, called solar flares:

- the solar flare temperature can reach **10-50 million K**, while the corona has a temperature of a few million degrees K;
- the typical solar flare lifetime is 1-2 hours;
- they extend outward and emit **high-energy particles and radiation** across a broad spectrum, from **radio waves to gamma rays**.

When this flow of radiation and particles arrives on Earth, **two components** can be distinguished:

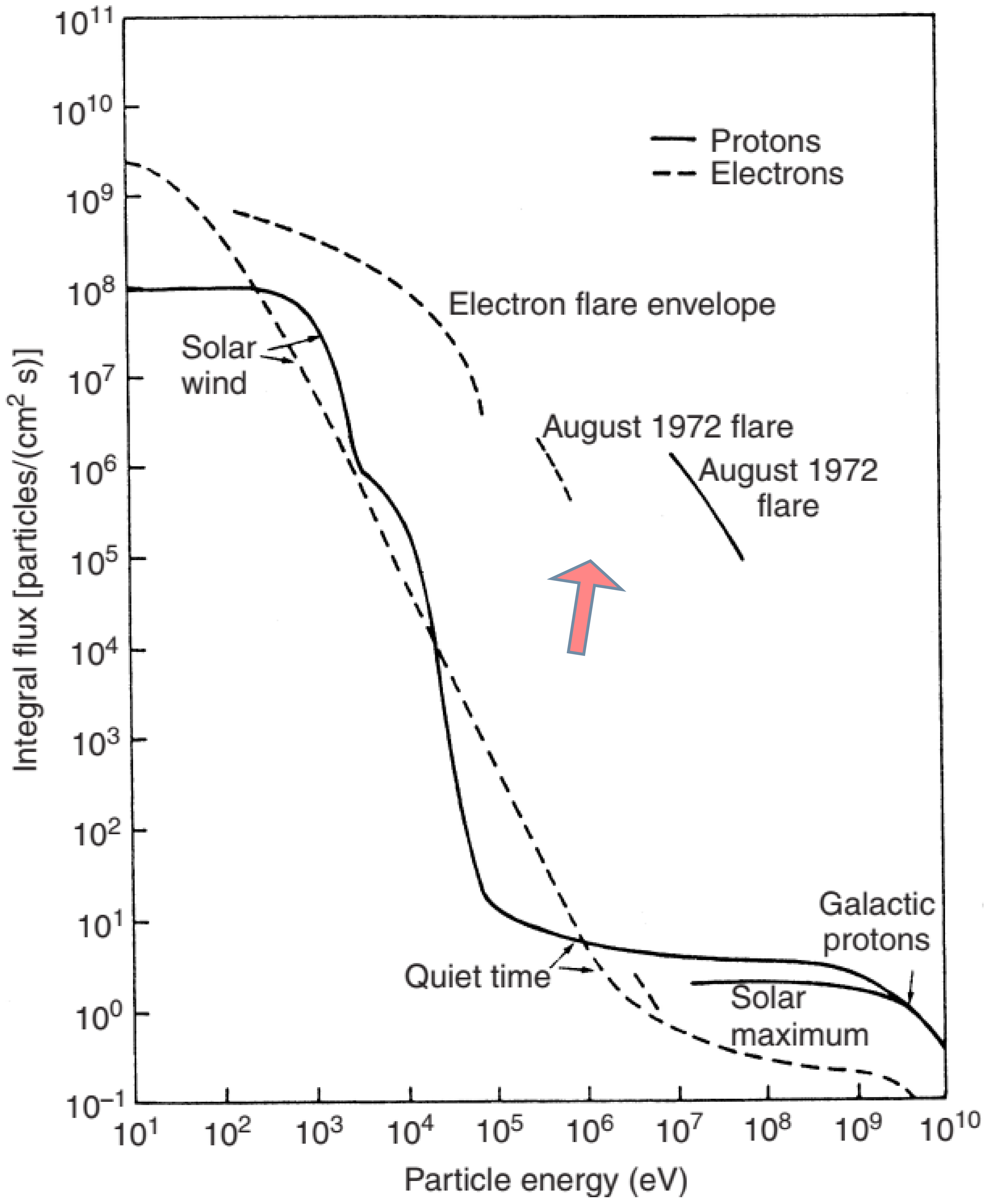
- the first occurs a **few minutes after the flare** (therefore they travel at a **speed close to the light** one), when electromagnetic emissions increase for the first time;
- while **a more prolonged component** arrives about a **day later**: these latter particles appear to be an enhanced component of the solar wind, traveling at speeds of ~10^3 km s^{-1}.

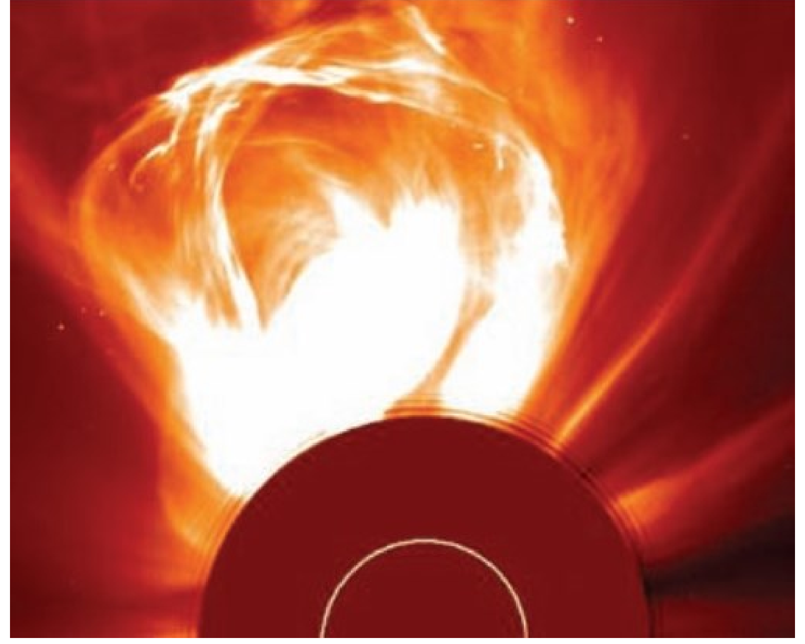
Solar flares

Figure shows the **variability of particle fluxes in the interplanetary medium caused by solar activity**.

The particles expelled by the flares give rise to the **aurora** and in extreme cases can cause **interruptions in radio transmission and energy transmission lines**:

- the **Carrington Event** was the most intense geomagnetic storm in recorded history, peaking on 1–2 September 1859: the geomagnetic storm was most likely the result of a coronal mass ejection (CME) from the Sun colliding with Earth's magnetosphere.





CMEs

Coronal mass ejections (CMEs) are made up by **largely massive plasma** (up to $2 \cdot 10^{13}$ kg) with a structured magnetic field that are ejected from the solar corona over several hours:

- compared to solar flares, CMEs travel at a **slower speed around 200 km s^{-1}**;
- during minimum solar activity, a CME occurs approximately every 5-7 days; while during maximum solar activity there may be 2-3 per day.

If they impact Earth, they can **cause geomagnetic storms** that can **damage** power grids and **spacecraft**:

- the enhanced radiation environment can **damage electronics** and **expose people** in space to excessive radiation;
- as an example, a failure of the attitude control system and its backup, on board the Galaxy 4 spacecraft, at 22:00 UT on 19 May 1998, is believed to have been caused by increased radiation following a CME.

Solar flare vs CME

Both

- they are explosions of energy;
- they occur simultaneously (especially at the peak of the solar cycle);
- they are caused by internal motions in the Sun which realign the magnetic field causing energy leaks.

However, they **differ** in

- the scale, mainly:
  - solar flares are relatively small and local, they occur in the lower solar atmosphere, near sunspots, where magnetic field lines are concentrated;
  - CMEs, on the other hand, are huge;
- the duration:
  - flares from minutes to hours;
  - CME several hours;

Solar flare vs CME

- how they travel:
  - flares are high-energy particles and radiation that travel at **very high speed** (a few minutes to reach the Earth);
  - CMEs travel at millions of km per hour;
- how they **afflict our planet**:
  - flares alter the **atmosphere**, thus affecting radio telecommunications: for instance, navigation blackouts;
  - CMEs cause auroras, **satellite** short circuits and ground-based power grids.

SOLAR WIND

The solar wind is a **high-velocity stream of hot plasma**, emitted from the corona.

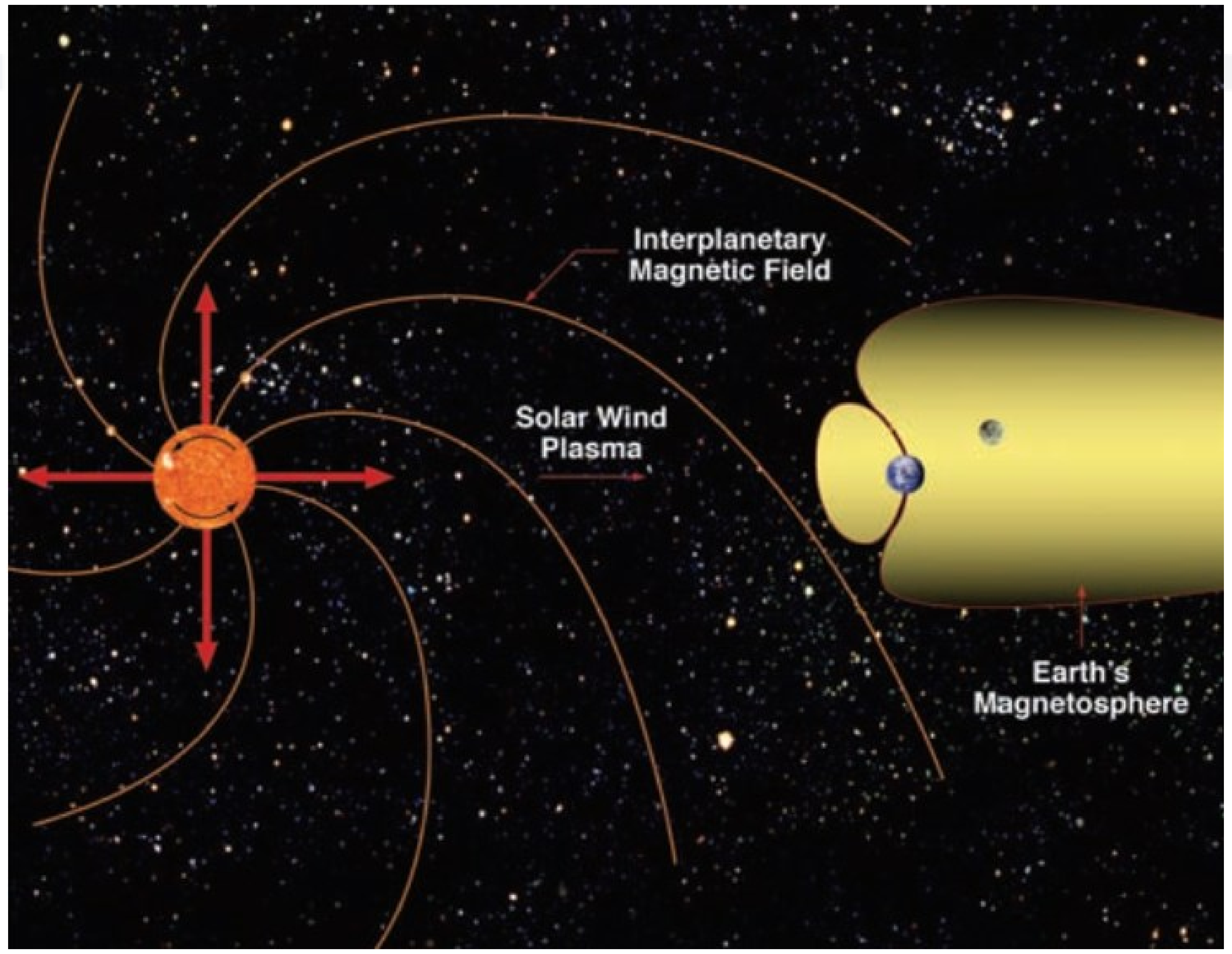
- It is essentially the **outermost layer of the solar atmosphere**, which is continually pushed outward by the pressure of the Sun radiation.
- Its composition is **~95% electrons and protons** in almost equal numbers, ~4% helium nuclei (alpha particles) and the rest heavy nuclei, so as to be electrically neutral.
- The solar wind varies in density, speed, temperature and magnetic field properties as a function of the solar cycle, heliographic latitude, heliocentric distance and rotational orientation of the Sun.

On Earth

- the wind speed is ~450 km s^{-1} (supersonic speed which can vary between 300-1000 km s^{-1} depending on solar activity),
- its density is ~5-10 particles cm^{-3} and
- its kinetic temperature is ~100 000-150 000 K.

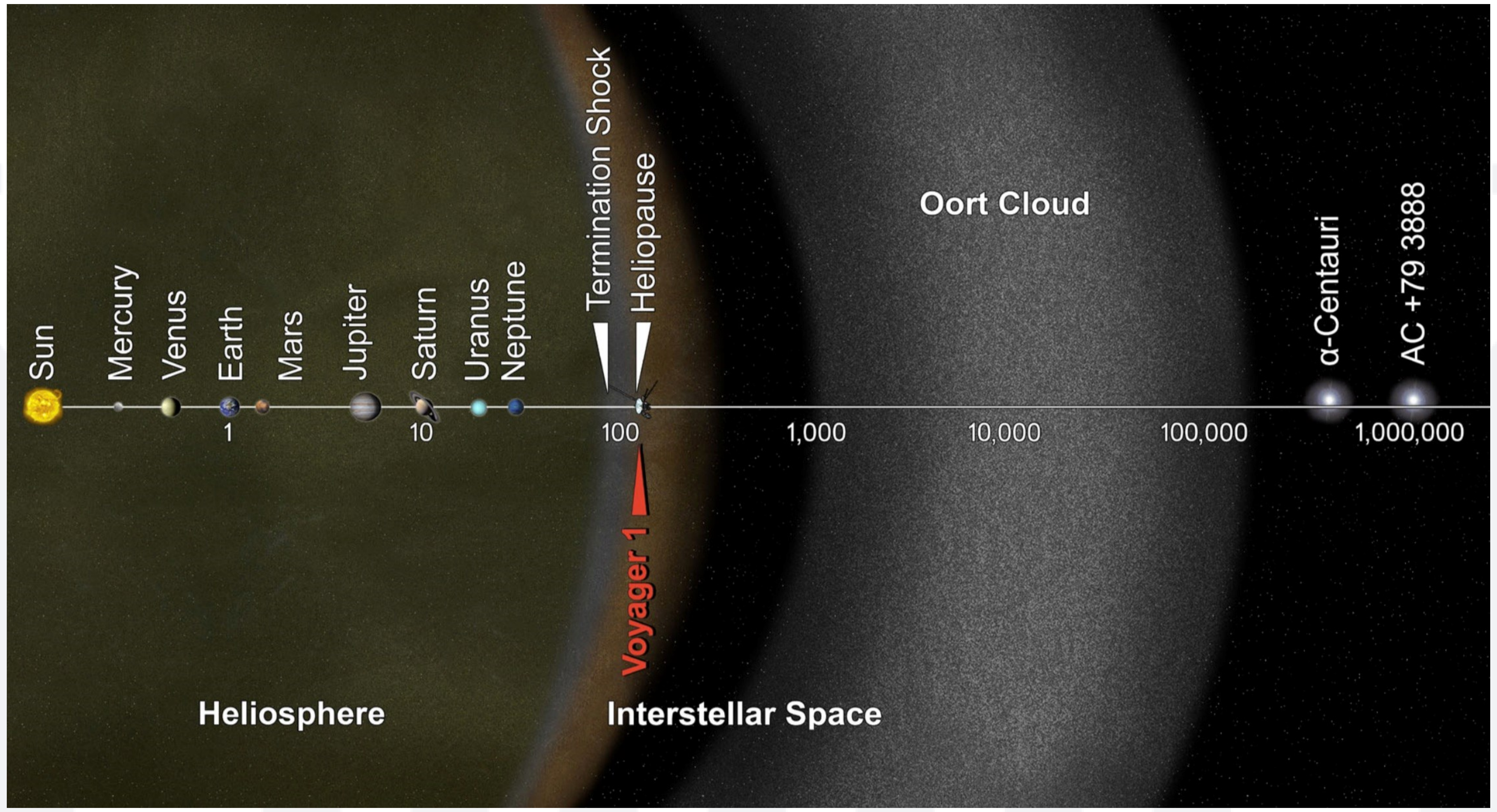
The **interplanetary magnetic field** is **embedded in the solar wind**:

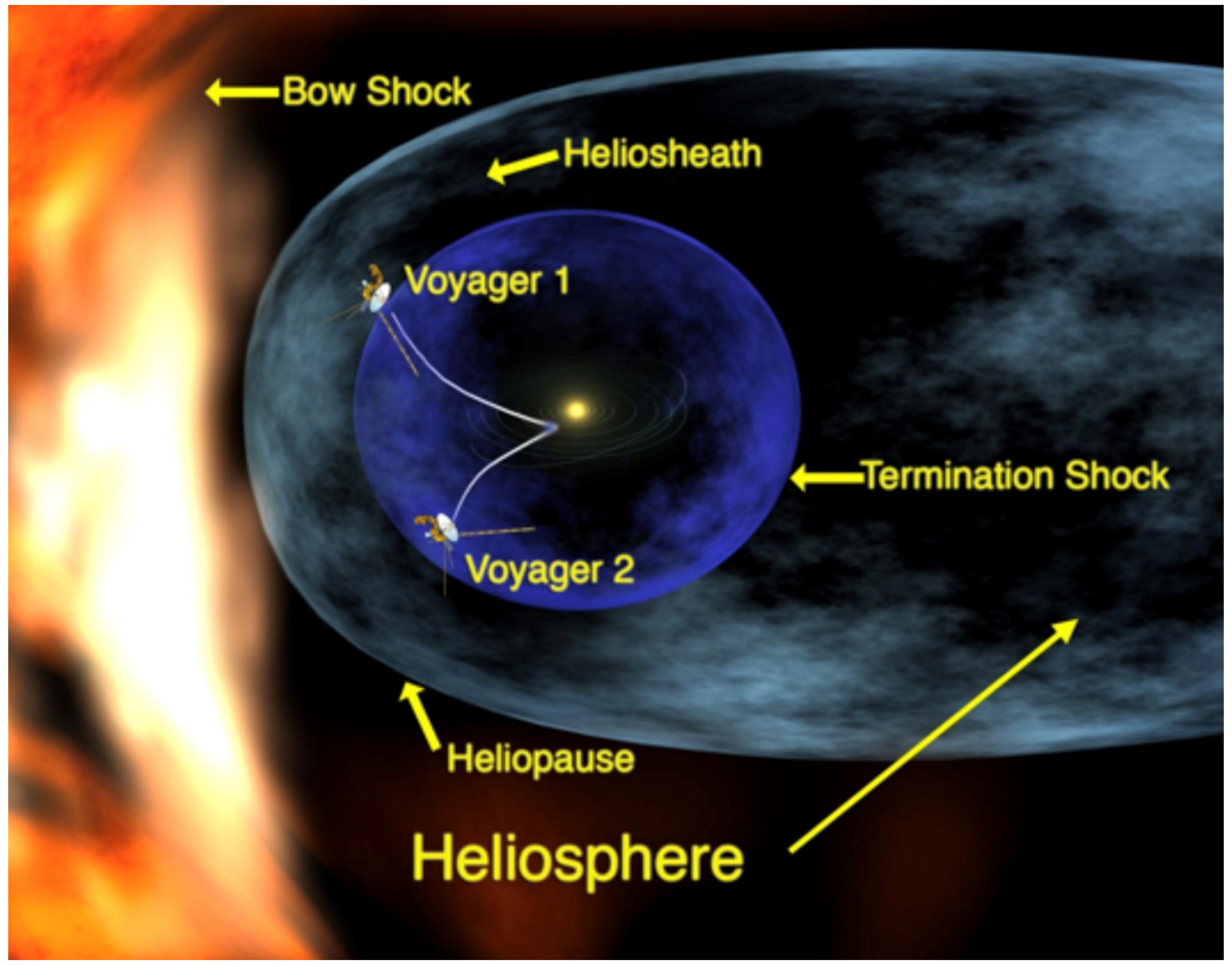
- it is relatively weak: its average value near Earth is about the order of 5-10 nT, with extremes in the range 1-37 nT;
- in the ecliptic plane, i.e. the plane of the Earth orbit, the interplanetary magnetic field has a spiral shape due to the rotation of the Sun around an axis inclined by 7.25 degrees with respect to the normal of the ecliptic plane.



The **heliosphere** is the region centered on the Sun that **contains the solar wind** and defines **interplanetary space**.

- As the **solar wind** expands outward from the Sun, its **density decreases with the inverse square of its distance** from the Sun, and slows down due to the Sun gravitational field.





Termination shock is the **surface** where the solar wind speed changes **from a supersonic flow to a subsonic flow**.

- Here large **changes** occur in the orientation of the **solar magnetic field** and in the direction of charged particles flow.
- This surface is thought to be at a distance about **100-120 AU**, with some evidence that the Voyager I probe may have crossed the boundary at around 95 AU.

Beyond the termination shock lies the actual interface between the solar wind and the constituents of the galaxy: interplanetary space extends up to this boundary called the **heliopause**, at a distance from the Sun of **150-160 AU**, where the galactic environment influence begins to dominate the magnetic field and the particles flow coming from the Sun.

The layer between the termination shock and the heliopause is called **heliosheath**.

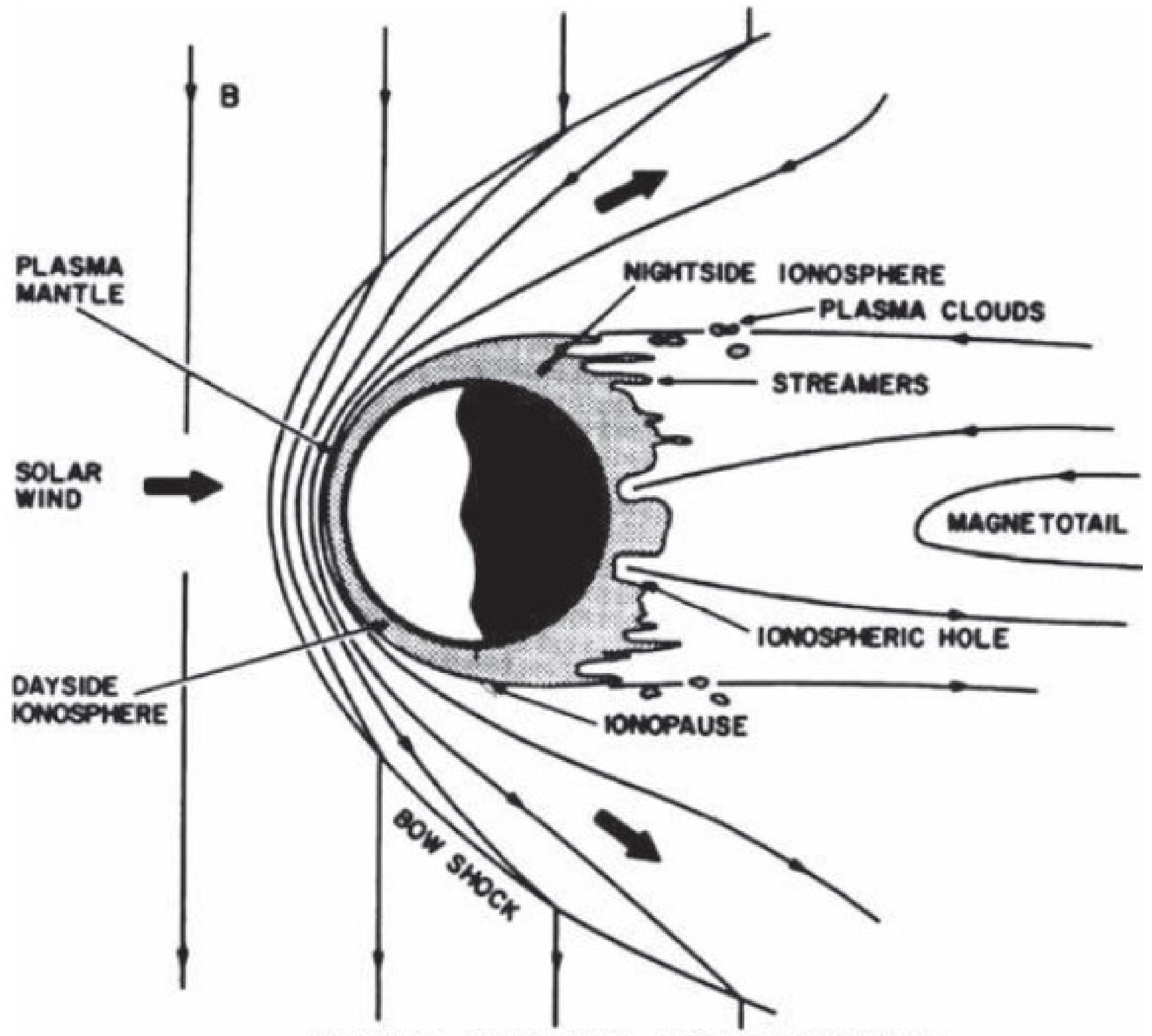
The **interstellar medium/plasma** is believed to have a velocity about ~26 km s^{-1} relative to the Sun and the heliosphere, that causes the heliopause to deform, forming a comet-like **tail** moving away from the Sun.

INTERACTION BETWEEN SOLAR WIND AND CELESTIAL BODIES

The way in which the magnetic field of the interplanetary medium interacts with the celestial bodies depends on whether or not magnetic fields – magnetospheres – are present.

- The **solar wind impacts directly on the surface** of those bodies with a weak or **absent magnetic field** and essentially **no atmosphere**.
  - In the case of the **Moon**, over billions of years, lunar regolith has acted as a collector for solar wind particles:
    - hence, studying lunar surface rocks can be valuable for solar wind studies;
    - high-energy particles from the solar wind impacting the lunar surface also cause a weak emission of X-rays.
- Instead, the **intersection of the solar wind plasma**, and its embedded magnetic field, with the **magnetic field** or highly conductive ionosphere of a celestial body results in the **flow of the solar wind plasma around the celestial body**, rather than mixing of the two plasmas.
  - This interaction establishes a **magnetohydrodynamic shock** or **bow shock** wave around the astronomical body that slows, compresses, heats and **deflects the solar wind**.
  - The mechanisms that cause the deviation are the **Lorentz force** on the charged particles of the plasma or **collisions** mediated by electromagnetic forces.

- When the solar wind encounters an astronomical **body without a global magnetic field, but with an atmosphere**, the body's **ionosphere** creates forces that slow and **deflect the solar wind**:
  - these forces also deflect the interplanetary magnetic field surrounding the body.



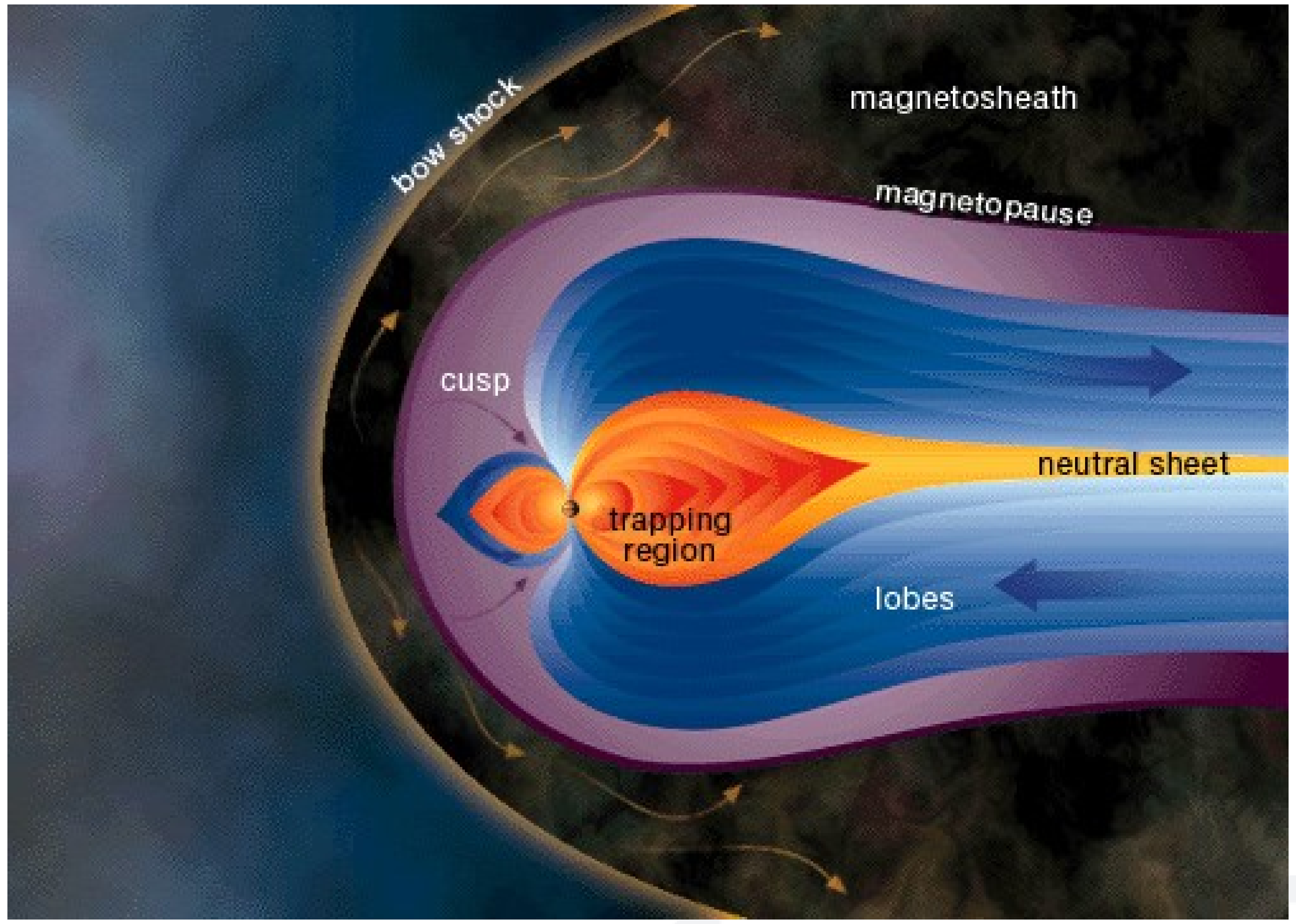
VENUS PLASMA ENVIRONMENT

Among the planets, only Venus and Mars have little or no intrinsic magnetic fields.

The region separating the planetary plasma from the solar wind is called the **ionopause**, where the **pressure of the solar wind is balanced by the thermal energy of the ionosphere**.

- A **bow shock wave** develops because the diffusion time of the magnetized plasma of the solar wind in the ionosphere, under typical conditions, is very long.
- Consequently, the **location of the shock wave** upstream of the ionopause is a **function of solar activity**.

MAGNETOSPHERE



The **solar wind**, when it encounters an astronomical body with a global magnetic field, **confines the magnetic field of planetary bodies**: the magnetic field is **compressed on the side facing the Sun** and **extended on the opposite side**.

The **magnetosphere** is defined as the **volume surrounding an astronomical body equipped with a global magnetic field**, in which the planetary magnetic field, rather than the Sun one, dominates the motion of the charged particles.

- This magnetic field alters the solar wind flow, which is channelled around the magnetosphere.

The **magnetopause** is the **region separating the planetary plasma from the solar wind**.

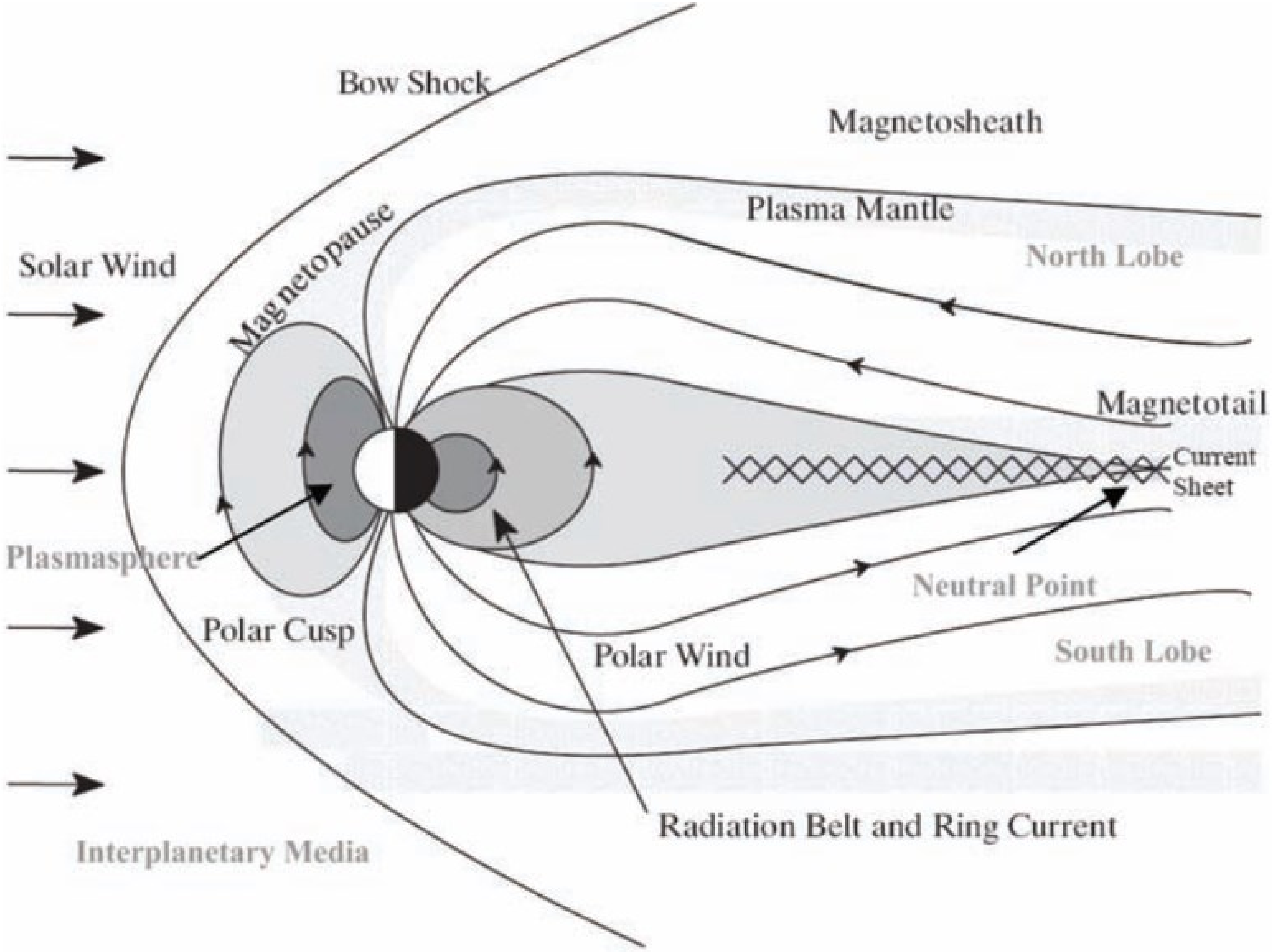
- **Solar activity** causes changes in the **position of the magnetopause** and **variations in the geomagnetic field**, such as **geomagnetic storms** and the particle precipitation in the atmosphere that cause **auroras**.

Earth, Jupiter, Saturn, Uranus, and Neptune have strong intrinsic magnetic fields that are capable of trapping plasmas and creating planetary magnetospheres.

EARTH MAGNETOSPHERE

The **Earth magnetosphere** is the region **between the Earth ionosphere and the interplanetary magnetic field**:

- It is compressed by the solar wind on the side facing the Sun, while the opposite side, the **magnetic tail**, extends **hundreds of Earth radii**.



- **Bow shock**. A celestial body that has either a magnetosphere or a highly conducting ionosphere exhibits a bow shock on the sunward side and deflection of the solar wind around the body. The bow shock is a supersonic shock wave formed by the collision of the solar wind with the outermost layer of the astronomical body's magnetosphere or ionosphere. It deflects the solar wind around the astronomical body, and the plasma that penetrates the bow shock is slowed to subsonic speeds. At the bow shock, the kinetic energy of the plasma particles in the solar wind is converted into thermal energy. Consequently, the solar wind downstream of the bow shock is slower, compressed, and hotter than the unperturbed supersonic solar wind. The bow shock of the Earth is about two Earth radii in front of the magnetopause toward the Sun.
- **Magnetopause**. The magnetopause is the boundary of the magnetosphere resulting from the interaction of the solar wind and the magnetosphere. It represents the transition region between the magnetosheath and magnetosphere where plasma of both regions mixes. Charged particles usually have gyroradii larger than the thickness of the magnetopause and can transition the region because their Lorentz forces are insufficient to reflect them. The location of the magnetopause, or magnetospheric standoff, is determined by the balance between the dynamic pressure of the solar wind and the pressure of the magnetic field.

- **Magnetosheath**. The *magnetosheath* is the region between the bow shock and the magnetopause. Within the magnetosheath, the magnetic field is turbulent, distorted, and weaker than the magnetospheric field. Near the subsolar point of the bow shock, the magnetosheath plasma is hotter, denser, and slower than the solar wind but remains a collisionless plasma. The ion density is between 2-50 cm^{-3}, and the temperature is $5 \cdot 10^5$ to $5 \cdot 10^6$ K. However, the plasma accelerates to the solar wind speed and becomes increasingly like the solar wind in the flanks of the bow shock, as the shock becomes increasingly weak.
- **Magnetotail.** The *magnetotail* is the portion of the magnetosphere in opposition to the sun behind the Earth. In contrast to the dayside magnetosphere that is compressed and confined by the solar wind, the nightside magnetosphere is stretched into the long magnetotail. This part of the magnetosphere is quite dynamic, with large changes in the energy of the ambient ions and electrons. In the magnetotail, the solar wind tends to extend the dipole field lines into an equatorial current sheet with field lines that are almost antiparallel or parallel to the Earth-Sun line.

- **Neutral point**. A *neutral point* is where several field lines converge, which can happen only where the magnetic flux density is near zero. At this point, plasmas on both sides of the field line could become separated and reconnect to different field lines. It is believed that when a neutral point forms, energy stored in the magnetotail is released through a process called reconnection. During reconnection, field lines upwind of the neutral point reconnect, accelerating plasma particles with sufficient force to inject them into the upper atmosphere. On the far side of the pinch, a bubble of plasma is generally forced out of the magnetotail.
- **Neutral sheet**. The *neutral sheet* is a thin surface where the geomagnetic fields from the northern and southern hemispheres essentially cancel so that the geomagnetic equatorial plane is essentially magnetically neutral, dividing the plasma into the northern and southern lobes. It is the boundary between the inward geomagnetic field lines of the northern lobe and the outward geomagnetic field lines of the southern lobe.
- **Plasma mantle**. The *plasma mantle* is the boundary layer just inside the magnetopause that extends from the polar cusps, with mixed characteristics of the interplanetary and terrestrial geomagnetic fields.

- **Current (plasma) sheet**. The *current or plasma sheet* is a layer of weaker geomagnetic field and dense hot plasma centered on the equator on both sides of the neutral sheet. In the northern portion of the plasma sheet, the geomagnetic field is directed toward Earth, and in the southern portion, the field is directed away from Earth. The plasma sheet exists in equilibrium as long as the solar wind remains steady with little solar activity. When the neutral sheet balance is disturbed, its dimensions are altered radically, with consequences throughout the magnetosphere. The plasma sheet is typically 4–8 Earth radii thick with an ion density typically 0.1–10 cm^{-3} and temperature $8 \cdot 10^6$ to $8 \cdot 10^7$ K. The plasma sheet is the scene of much magnetic activity, particularly during magnetic storms. In quiet times the plasma sheet primarily contains plasma of solar wind origin, but in active times plasma of ionospheric origin may dominate. The plasma sheet boundary layer is magnetically connected to the Earth's auroral field lines.
- **Plasmasphere**. The *plasmasphere* is a toroidal region of cold, dense plasma between the top of the ionosphere and the magnetopause. It is populated by the outflow of ionospheric plasma along the geomagnetic field lines.

- **Polar cusps**. The *polar cusps* or *polar clefts* are two funnel shaped regions, one in the vicinity of the north geomagnetic pole and one in the vicinity of the south geomagnetic pole, where there is a bifurcation of the magnetic field lines into some terrestrial field lines that travel sunward and some that travel tailward. The pressure of the solar wind causes the polar cusps to be displaced from the poles of the dipole toward the geomagnetic equator. Because charged particles experience little resistance to traveling along field lines, the cusps act to channel the solar wind to low altitudes where it interacts with the ionosphere and atmosphere to cause the aurora oval during periods when the solar wind is enhanced by solar activity.
- **Tail lobes**. The north and south *tail lobes* comprise the major part of the magnetotail lying between the plasma sheet and the plasma mantle. In the north tail lobe the field lines travel toward the Earth to the northern polar cusp, and in the south tail lobe the field lines travel away from the southern polar cusp tailward. The geomagnetic field lines are nearly parallel to the neutral sheet with only a relatively small polar component, being greatly stretched tailwards from a pure dipole field. They can extend to great lengths, on the order of 200 Earth radii. The number density of the tail lobes is low, on the order of 0.001-0.01 cm^{-3}. Ions and electrons can easily flow away along lobe field lines, until they are swept up by the solar wind. However, few solar wind ions can oppose the wind’s general flow and travel upstream toward Earth. This reduces the number density of the plasma in the lobes.

GEOMAGNETIC FIELD

The **magnetosphere is generated by the Earth magnetic field**, the geomagnetic field.

- At first order, it is as if the **Earth had inside an iron bar uniformly magnetized along the Earth's rotation axis**.
- The geomagnetic field can be divided into **three components**.
  - The **dominant component** is the so-called main field or **dipole field**, with a magnetic flux density at the Earth surface, varying from about 30 000 nT at the geomagnetic equator to about 60 000 nT at the geomagnetic poles. The magnetic field is produced by electric currents **produced mostly in the Earth core**. The **solid inner core**, mostly made of **iron**, is **surrounded by a liquid outer core**, mostly made up by **molten iron**, in turn surrounded by the solid mantle: the **relative movement of the inner and outer core produces the geomagnetic field** through a process known as **hydromagnetic dynamo**.
  - The **second component** comes from the **magnetized rocks** of the Earth **lithosphere**, which has a thickness ranging from 1.6 km in the mid-ocean ridges to 130 km under the oldest oceanic crusts. The lithosphere contributes a few hundred nT to the magnetic flux density at the Earth's surface.
  - The **third component** arises from **current systems in the ionosphere and magnetosphere**. This component can vary rapidly **depending on solar activity**.

Mathematical model

To a first approximation, the Earth magnetic field is approximately dipolar and decreases with the cube of the distance, up to be **negligible at distances about a few thousand km**.

Therefore, **magnetosphere models vary with altitude**:

- at **low altitudes**, the so-called **internal models** are valid, based on the semi-normalized Schmidt functions associated with the Legendre functions;
- at **intermediate altitudes**, higher-order terms become negligible and the **dipole** is often a good **approximation**;
- at **higher altitudes**, **solar wind** and current systems cause high-frequency **diurnal variations** in the magnetic field: an international standard for representing the external geomagnetic field has not yet been recognized; however, some simple models are available to estimate the boundaries of the magnetosphere.

Mathematical model

The dipole geomagnetic field can be approximated by three configurations with increasing precision:

1. **concentric centered dipole**: the axis of the dipole is parallel to the axis of rotation of the celestial body through its center of mass;
2. **inclined centered dipole**: the axis of the dipole is inclined with respect to the axis of the celestial body passing through its center of mass;
3. **inclined eccentric dipole**: the axis of the dipole is inclined with respect to the axis of the figures or the axis of rotation of the celestial body and off-center with respect to its center of mass.

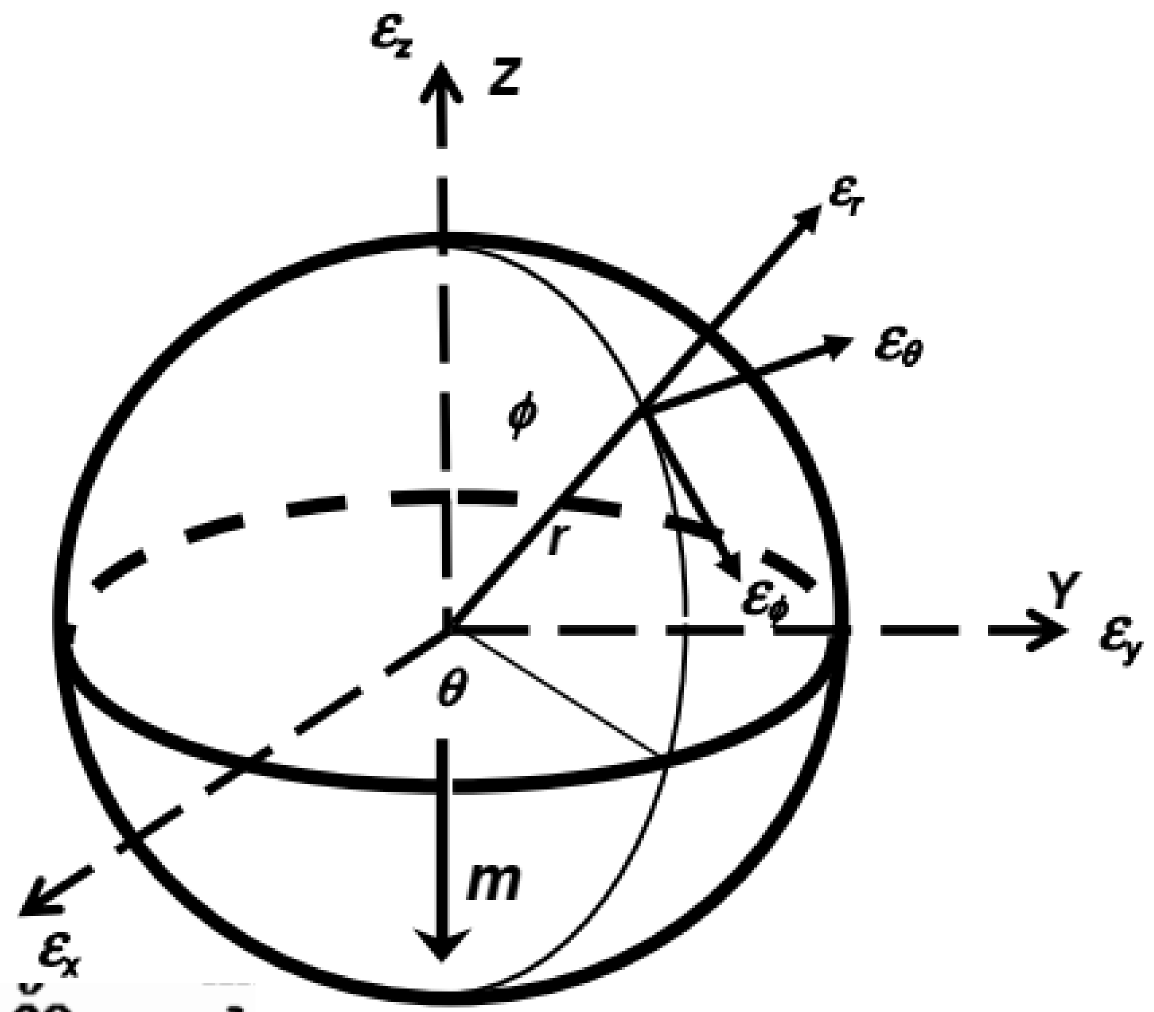
In all cases the magnetic dipole field can be represented in spherical and Cartesian coordinates.

$$\boldsymbol{B} = B_r\varepsilon_r + B_\phi\varepsilon_\phi + B_\theta\varepsilon_\theta = B_x\varepsilon_x + B_y\varepsilon_y + B_z\varepsilon_z$$

$$B_r = -\frac{2B_0}{(r/R)^3}\cos\phi,\ B_\phi = -\frac{B_0}{(r/R)^3}\sin\phi,\ B_\theta = 0$$

$$B_x = -\frac{3xzR^3B_0}{r^5},\ B_y = -\frac{3yzR^3B_0}{r^5},\ B_z = -\frac{(3z^2 - r^2)R^3B_0}{r^5}$$

m = magnetic dipole moment of celestial body [A m^2]
r = radius [m]
R = reference radius of celestial body [m]
x, y, z = Cartesian position [m]
θ = longitude east from Greenwich
φ = magnetic colatitude



$B_0 = \frac{\mu_0 m}{4\pi R^3}$, campo magnetico sulla superficie della Terra all'equatore geomagnetico. $[B_0 = B(R = R_E, \lambda = 0) = 0.30\ \text{gauss}]$.

Mathematical model

From these equations the magnitude of the magnetic flux density is derived $B = \frac{\mu_0 m}{4\pi r^3}(1+3\cos^2\phi)^{1/2} = \frac{B_0}{(r/R)^3}(1+3\cos^2\phi)^{1/2}$

or in terms of magnetic latitude $B(r,\lambda) = B_0 \frac{\sqrt{1+sin^2\lambda}}{r^3}$

- as you can see, the **approximate dipolar magnetic field decreases with distance from the Earth**.

At high altitudes, solar wind and current systems cause diurnal and high-frequency field variations:

- an international standard for representing the external geomagnetic field has not yet been recognized;
- however, some simple models are available to estimate the boundaries of the magnetosphere.

Indeed, the solar wind, i.e. the flow of charged particles formed by protons, ions, electrons and others emitted by the Sun, confines the lines of force of the field within the magnetosphere.

- **In the night part of the Earth**, the magnetic field stretches into a very elongated structure: magnetotail. Through the interaction between the solar wind and the Earth magnetic field, part of the **kinetic energy of the solar wind is converted into magnetic energy stored in the magnetotail**. **Since this energy cannot accumulate indefinitely, magnetic substorms dissipate it** from time to time. These **substorms** produce an excited plasma (5 to 50 keV) that is injected toward Earth. This **hot plasma can extend into geosynchronous orbits**, **charging the surface of any spacecraft** within it by high negative voltages.

Mathematical model

- **On the sunlit side of the magnetosphere**, the magnetic field pressure ($B^2 / 2\mu_0$) can balance the dynamic pressure of the solar wind ($nmv^2/2$):
  - from here, the radial distance from the magnetic field boundary, known as the magnetopause, towards the Sun can be approximated using

$$L_{mp} = \left(\frac{4 B_0^2}{\mu_0 n m v^2} \right)^{1/6} \approx 10943 (n v^2)^{-1/6}$$

$L_{mp} \approx 10\ R_e$ = distance to the shell at the equator, units of Earth radii $\frac{r}{Re}$

n = number density of the solar wind, m^{-3} (typical solar wind value is $8 \cdot 10^6$ particles m^{-3})

v = solar wind bulk velocity, $\mathrm{m\ s}^{-1}$ (typical solar wind speed is $4 \cdot 10^5\ \mathrm{m\ s}^{-1}$)

m = proton mass since electron mass is negligible, kg

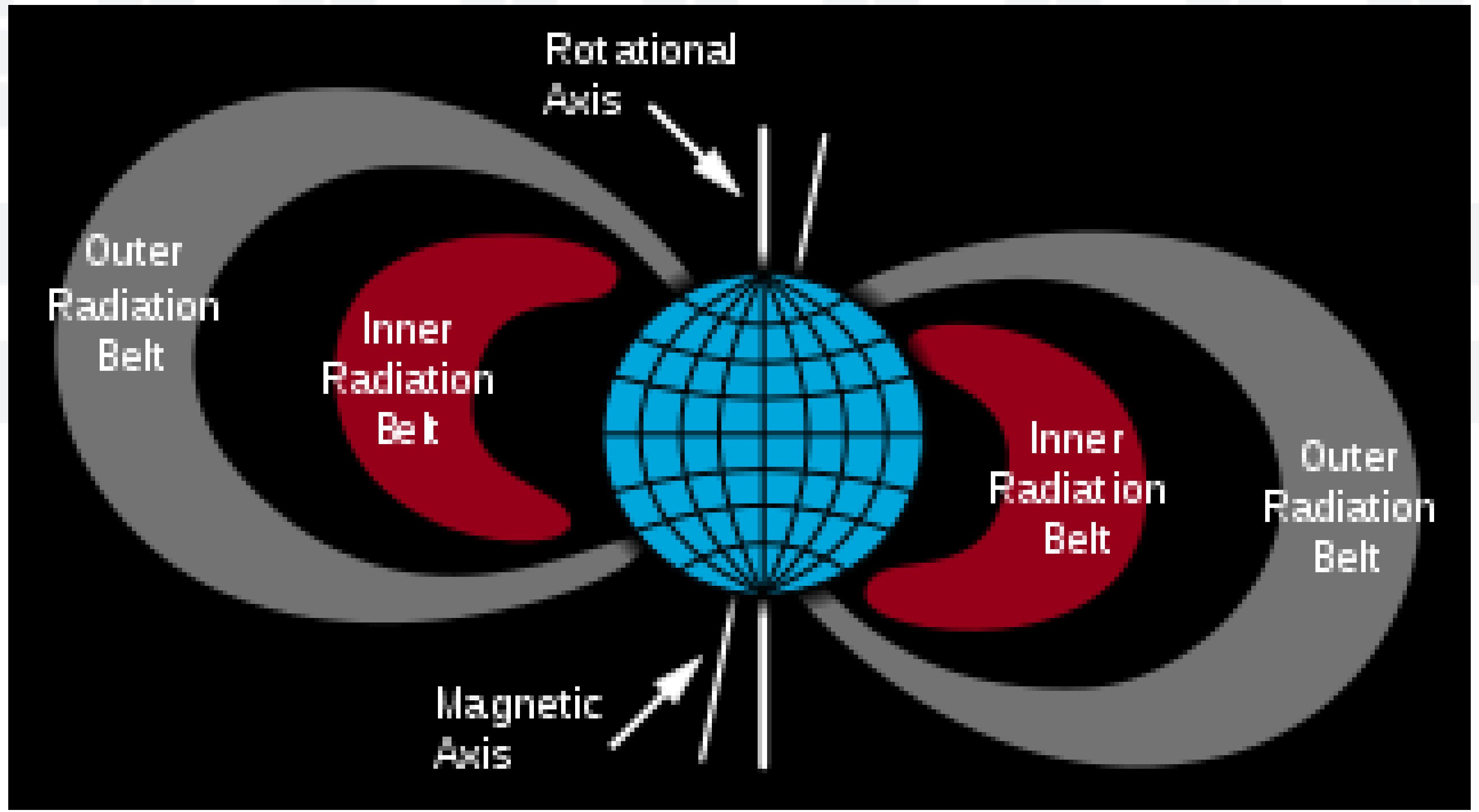
4 = coefficient that represents the magnetic filed compression in the Sun direction: $B_{compres.dip.} = \frac{4B_0}{(\frac{r}{Re})^3}$

(there may be large variations in typical solar wind values during large solar particle events)

VAN ALLEN RADIATION BELTS

The **geomagnetic field** is a significant factor in **deflecting and trapping charged particle** radiation from the solar wind: this reduces the probability of particles impacting the Earth surface.

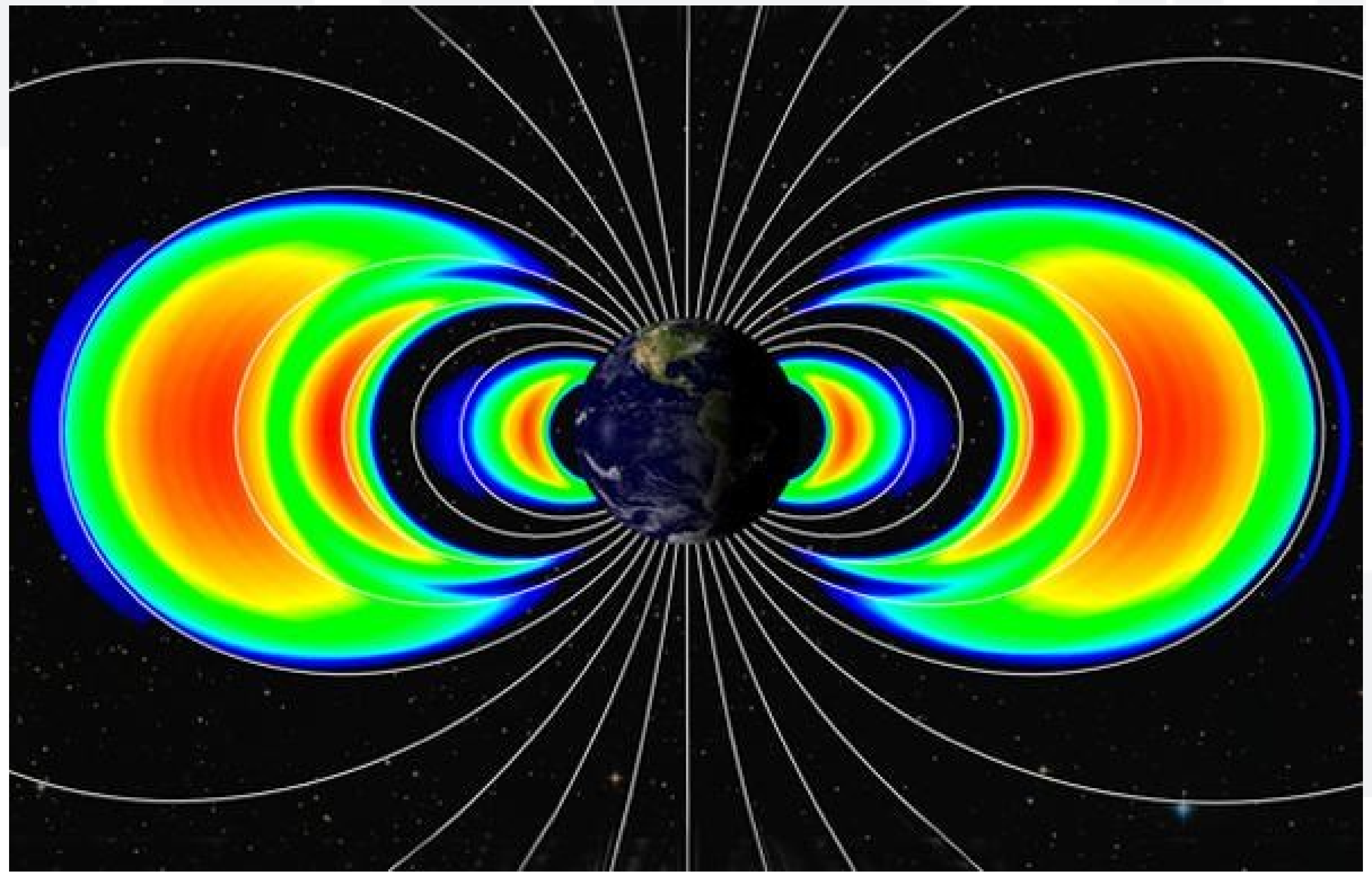
- When the solar wind meets the magnetosphere, it creates a bow shock due to the high speed of the solar wind (hundreds of km s^{-1}) relative to the magnetosphere. Propagation through the bow shock reduces the speed and **changes the flow direction**, diverting most of it **around the magnetosphere**.
- Some of the material in the solar wind **transits through the magnetosphere**. In particular, ionised particles are trapped under the Lorentz force **in the van Allen Belts**. They are two **toroidal zones within the magnetosphere populated** precisely by **ionised** material (mainly from the solar wind and cosmic rays) arranged along the geomagnetic field.



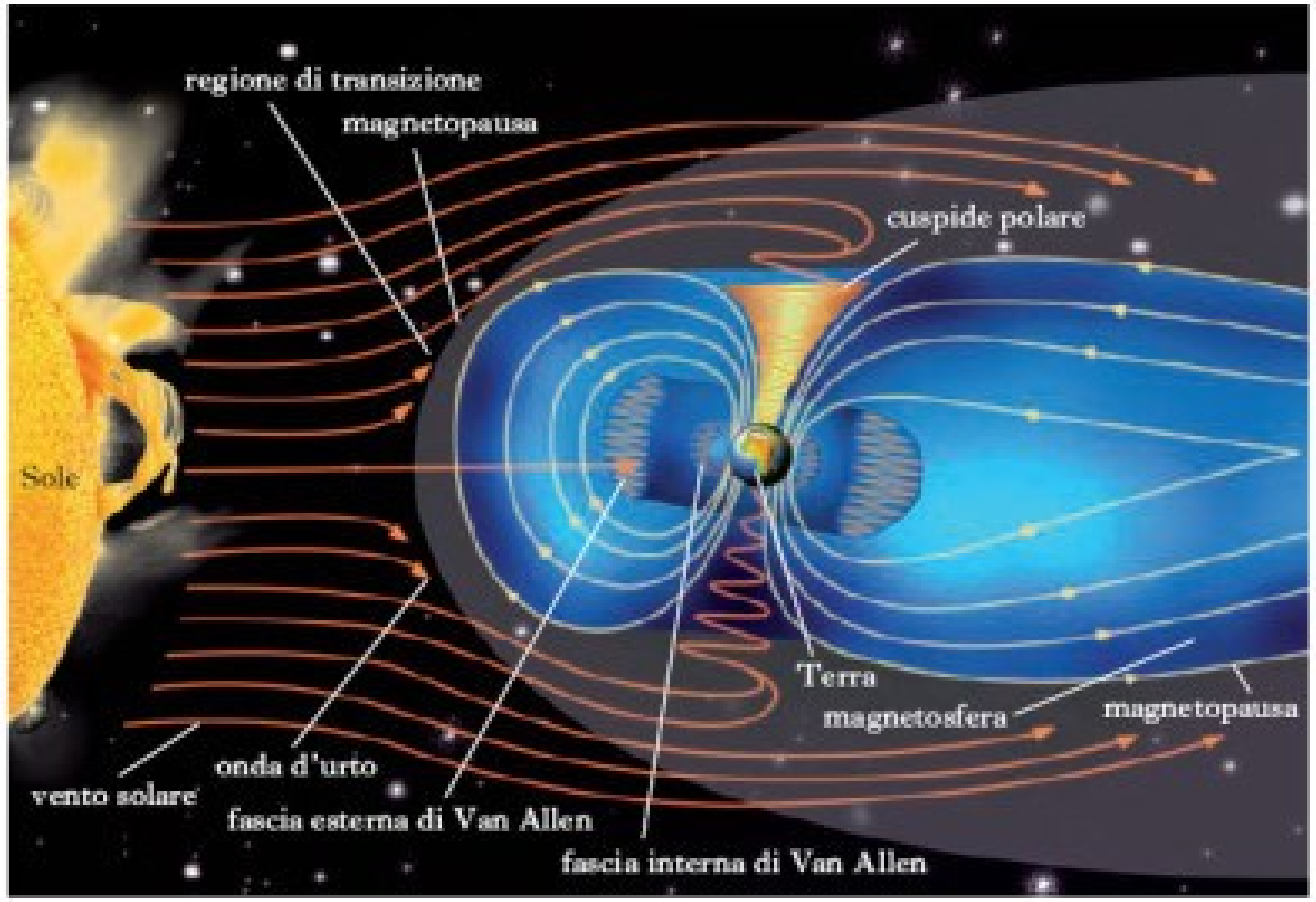
- **inner belt**:
  - it extends between about **1 000 km and 12 000 km** in altitude: in particular situations of intense solar activity or in particular areas, such as the South Atlantic Anomaly (South Atlantic Anomaly SAA), the inner boundary may also be only about 200 km from the sea level;
  - it contains concentrations of **electrons** with energies about **hundreds keV**, and **especially energetic protons**, **starting from 100 keV** up to **above 100 MeV**:
    - protons are trapped here by the local **magnetic field**, which is relatively **more intense than in the outer belt**;
    - in particular, protons with energies above 50 MeV, which are found **at lower altitudes**, are the **result of neutron decays produced by cosmic ray collisions** with atomic nuclei in the upper atmosphere;
- **outer belt**:
  - it extends at an altitude of approximately **13 000-60 000 km** and is particularly intense between 15 000-20 000 km;
  - it contains various **energetic ions** (alpha particles, oxygen O^+) and **especially electrons with 0.1-10 MeV energy**, **originating from various phenomena** (solar and outer atmospheric) and injected from the outer magnetosphere.

- The **gap** between the inner and outer Van Allen belts is sometimes called the "safe zone" or "safe slot", and is the location of medium Earth orbits.
  - This gap between the two Van Allen belts is caused by **low-frequency radio waves** (3-30 kHz) that eject energy particles which would otherwise accumulate there.
    - The origins of these waves are not clear: they might be generated by lightning within Earth atmosphere.

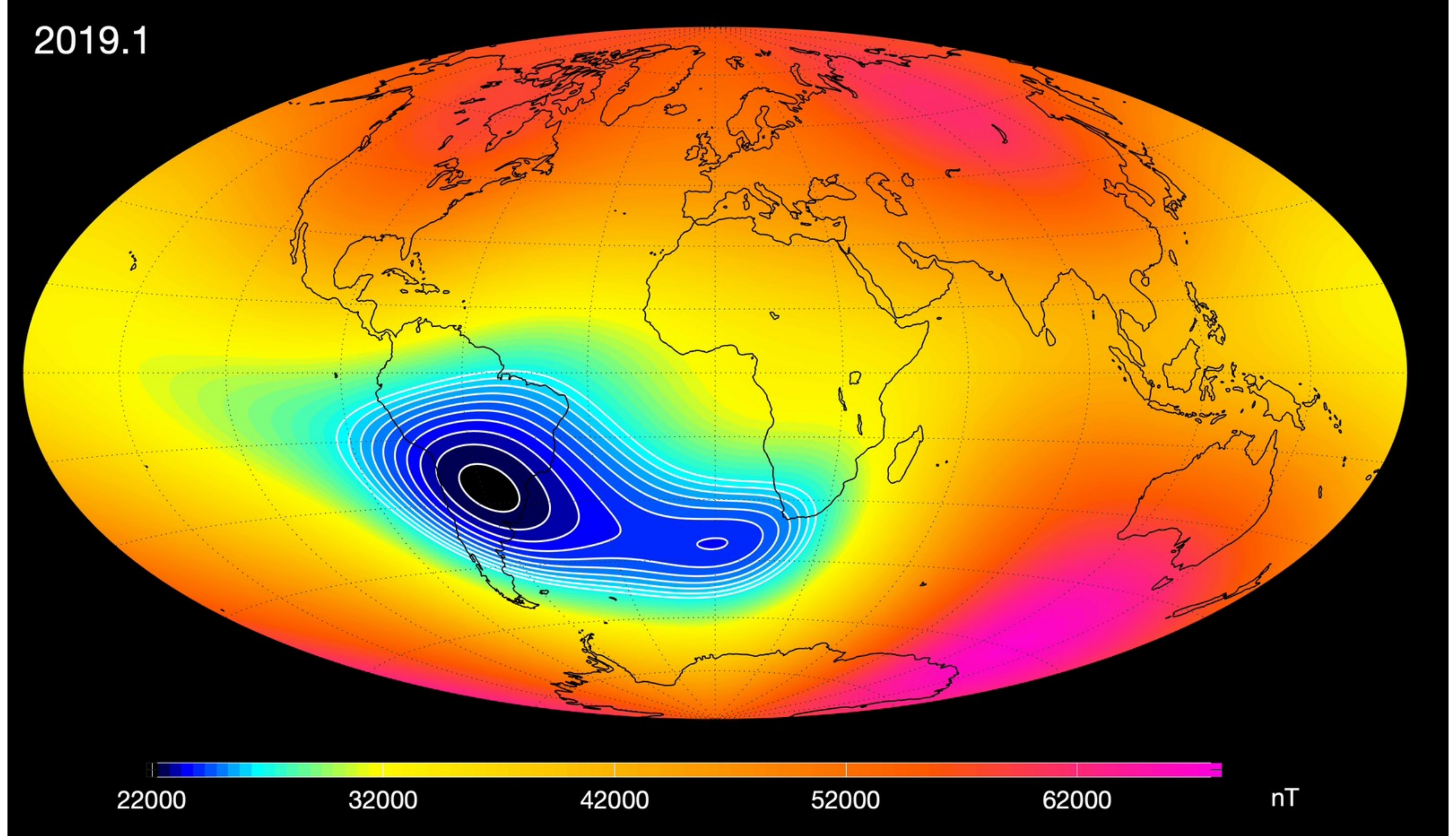
- Some times a **third transient belt** emerges in between the other two, close to the inner part of the outer belt.



Parts of the solar wind plasma trapped in the Van Allen belts follow the geomagnetic field lines to the polar regions, helping to form the polar cusps. When these particles have sufficient energy to reach Earth neutral atmosphere, they cause the polar **aurora**.



South Atlantic Anomaly (SAA)



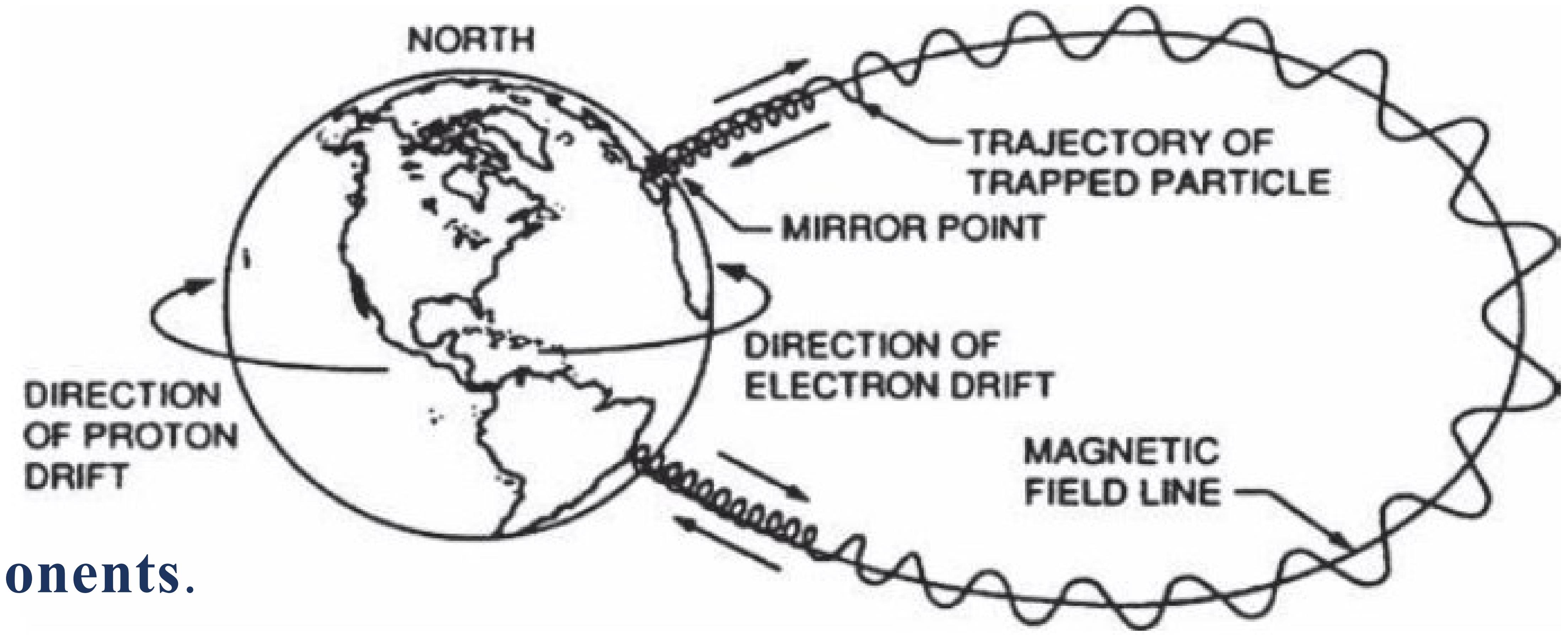
At **LEO** altitudes, the **highest concentration of particles** is observed in the **polar regions** and coinciding with **South Atlantic Anomaly** (SAA).

- **Due to a misalignment of the inner Van Allen belt with respect to the geometric** centre of the Earth, the inner Van Allen belt comes **closest to the Earth surface at SAA**.
- As we have seen, the best approximation of the dipole model for the geomagnetic field is represented by a **tilted eccentric dipole**: specifically, a dipole whose distance from the centre of the Earth is about 550 km: this **offset gives rise to the South Atlantic Anomaly**, in which a shell of the inner van Allen belt, in one hemisphere, is closer to the Earth's surface, and, in the other hemisphere, is further away.

This is important because the **magnetosphere provides little protection** in the region of the South Atlantic Anomaly, so spacecraft and humans are **exposed to more trapped radiation**.

- In **scientific high-energy space missions** with **low inclination** the detection is altered: during SAA flyovers, a periodic modulation of the detector current, and thus a periodic **degradation** of the energy **resolution** may occur.

Particle motion in Van Allen Belts

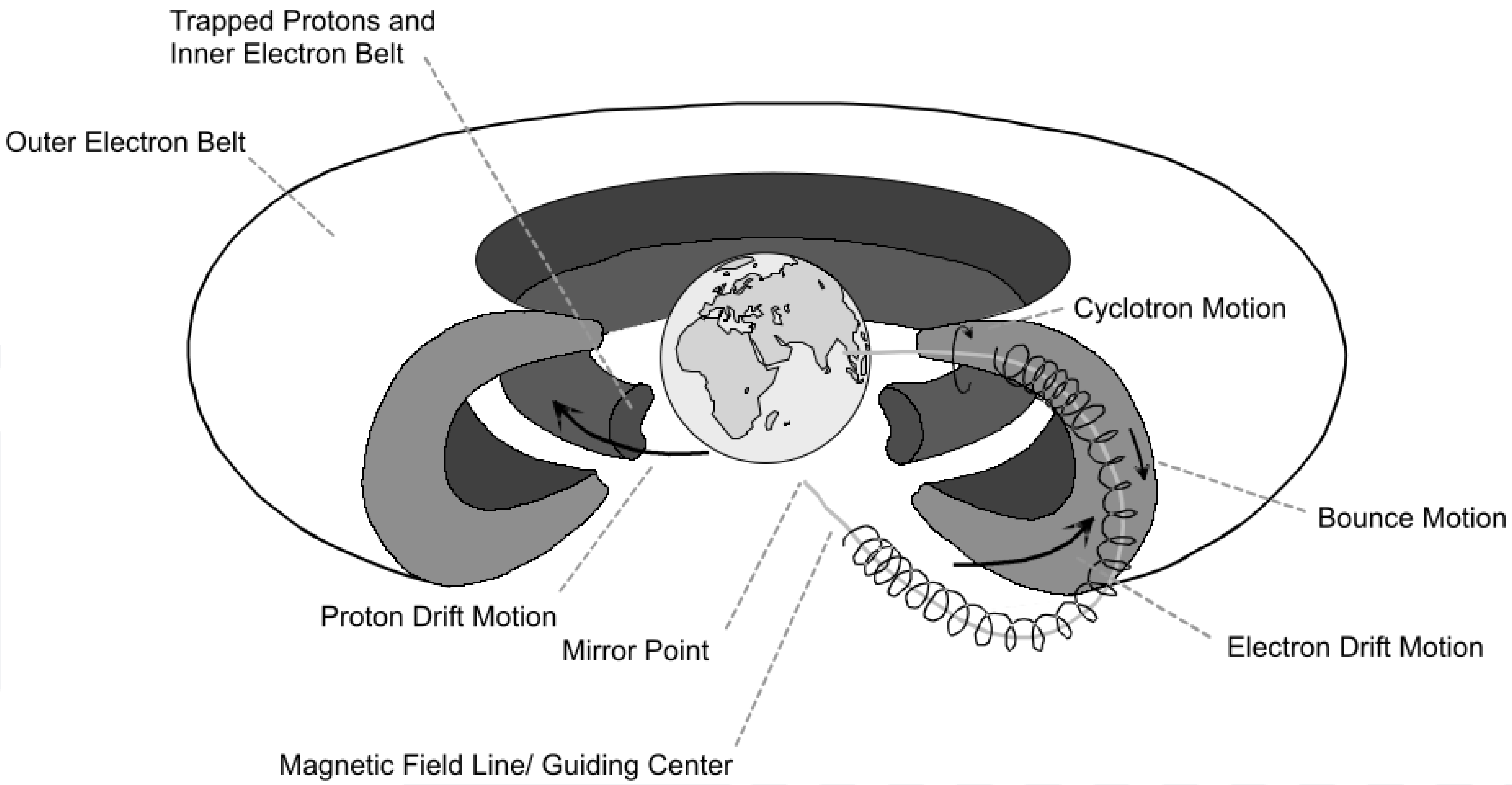


The motion of trapped radiation consists of **three primary components**.

- A charged particle undergoes a rotation, or **gyration**, **around** a geomagnetic **field line**, with respect to which the radius of the circular motion is known as gyration radius or Larmor radius. The period of rotation, or **gyration period**, is the time it takes the particle to complete one **revolution around the field line**, typically **much less than one second**.
- A charged particle undergoes a **mirroring along the field lines** by **bouncing** between the northern and southern geomagnetic hemispheres. The mirror point is the point along the field line where the particle reverses direction. The **bounce period** is the time it takes for a particle to move **from a mirror point in one hemisphere to the mirror point in the other hemisphere and back** to its starting point, with typical bounce periods of about **one second**.
- A charged particle undergoes a **longitudinal drift around the geomagnetic axis** forming a shell around the Earth with typical **drift periods of several minutes**. The positively charged particles, the **protons, drift westwards** and the negatively charged particles, the **electrons, drift eastwards**.

Particles confined in these shells can **remain** there **for long periods**, up to years for protons at altitudes about a few thousand kilometres, hence the term "trapped particles".

Particle motion in Van Allen Belts



PLASMA ORBIT THEORY

Particle motion in a uniform static magnetic field

The variation rate of **energy** U of a particle (charge q, mass m) in a **static electromagnetic field** is given by

$$\frac{\mathrm{d}U}{\mathrm{d}t}=\mathbf{v}\cdot\left(q\mathbf{E}+\frac{q}{c}\mathbf{v}\times\mathbf{B}\right)=q\mathbf{v}\cdot\mathbf{E}.$$

- so, the **energy of a particle** can be **changed only by** an **electric field**;
- that is, the **energy** of a particle moving in a pure **magnetic field** is a **conserved quantity**, or a **constant of motion**.

The relativistic equation for the particle motion is $\frac{\mathrm{d}}{\mathrm{d}t}(\gamma m\mathbf{v})=q\mathbf{E}+\frac{q}{c}\mathbf{v}\times\mathbf{B},\qquad \gamma=(1-\beta^2)^{-1/2}\qquad \beta=\frac{v}{c}.$

- in a static magnetic field, γ is constant.

So, $\frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t}=\frac{q}{\gamma mc}\mathbf{v}\times\mathbf{B}$ can be written as

$$\frac{\mathrm{d}v_1}{\mathrm{d}t}=\frac{qB}{\gamma mc}v_2,\qquad \frac{\mathrm{d}v_2}{\mathrm{d}t}=-\frac{qB}{\gamma mc}v_1,\qquad \frac{\mathrm{d}v_3}{\mathrm{d}t}=0.$$

with solutions

$$v_1=v_\perp\cos(\omega_g t),\qquad v_2=-\varepsilon v_\perp\sin(\omega_g t),$$

ε for the sign of the charge, $\varepsilon=\frac{q}{|q|}$

$v_\perp$ is the magnitude of the velocity component perpendicular to B:

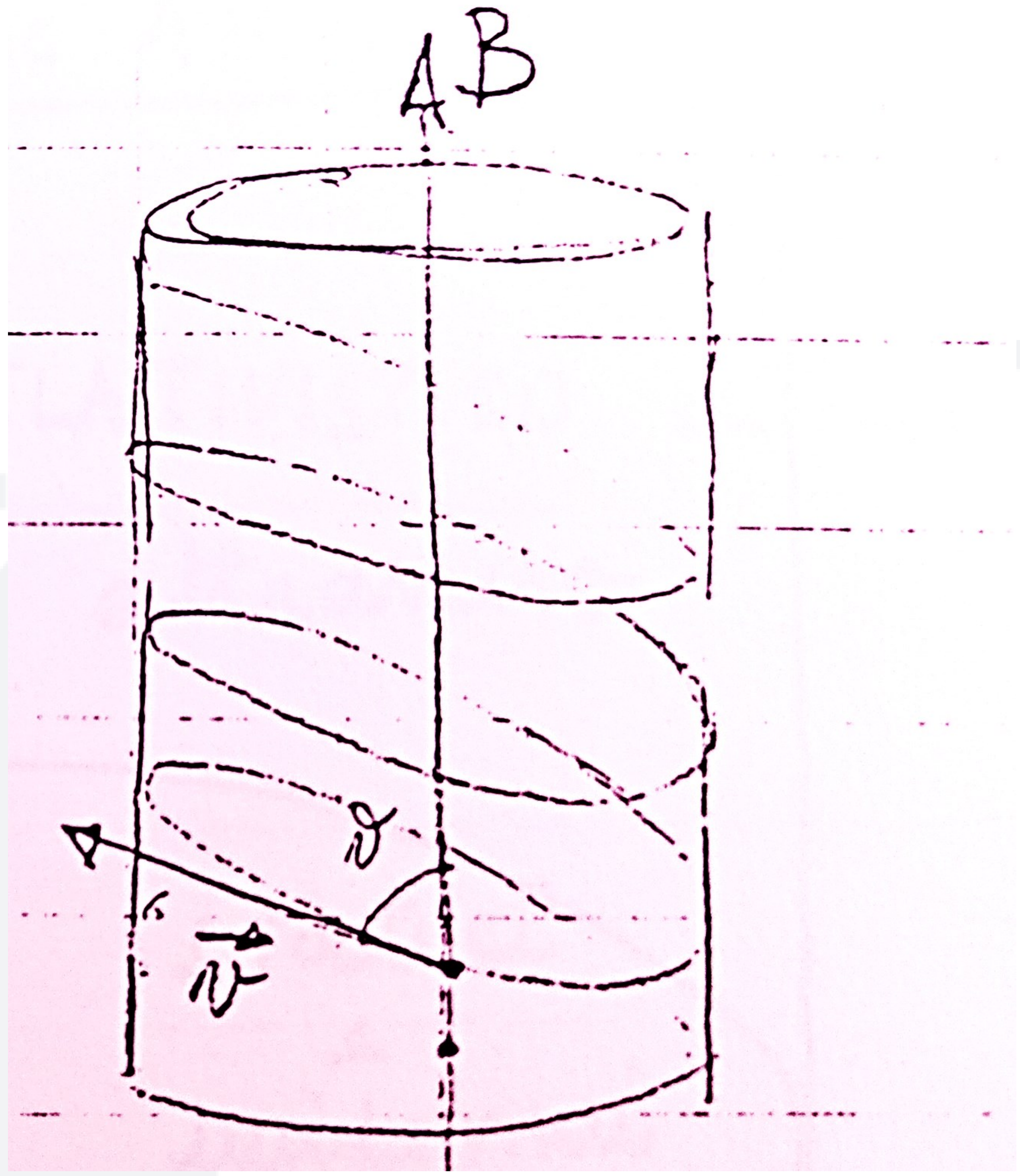
$$v_\perp=(v_1^2+v_2^2)^{1/2}.$$

$v_\parallel$, the component of $\mathbf{v}$ parallel to $\mathbf{B}$, is a constant.

Particle motion in a uniform static magnetic field

In such conditions, the particle displacement can be expressed by

$$x_1 = r_\perp \sin(\omega_g t),$$
$$x_2 = \varepsilon r_\perp \cos(\omega_g t),$$
$$x_3 = v_\parallel t,$$



where we define

- **gyrofrequency**: the angular frequency of the circular motion of a charged particle in the plane perpendicular to the magnetic field ***B***

$$\omega_g = \frac{|q|B}{\gamma m c}$$

- **gyroradius**: the radius of the circular motion of a charged particle in the plane perpendicular to the magnetic field

$$r_\perp = \frac{v_\perp}{\omega_g}$$

Particles, whose projection moves in the X_1-X_2 plane, looking along the direction of the magnetic field, move in **circular motion leftwards** if they are **positive ions**, or **rightwards** if they are **negative electrons**.

Particle motion in uniform static magnetic and normal gravitational fields

The equation of motion in the presence of a **perpendicular force** is

$$\frac{d\mathbf{v}}{dt}=\mathbf{g}+\frac{q}{mc}\,\mathbf{v}\times\mathbf{B},$$

- *m**g*** is the **gravitational attraction** on a particle of mass *m*.

This equation is equivalent to that one regarding the motion in an effective electric field ***E*** = *m**g*** / *q* .

In this case (***E***), particles accelerates freely in response to the electric field component along the magnetic field:

$$\frac{dv_\parallel}{dt}=\frac{q}{m}E_\parallel$$

So, let us separate the transverse velocity into

a time-constant (drift) component and

a time-varying (gyro) component

$$\mathbf{v}_\perp(t)=\mathbf{v}_d+\mathbf{v}_g(t).$$

$$\frac{d\mathbf{v}_\perp}{dt}=\frac{q}{m}\left\{\mathbf{E}_\perp+\frac{1}{c}\mathbf{v}_\perp\times\mathbf{B}\right\},$$

As a consequence,

$$\frac{d\mathbf{v}_g}{dt}=\frac{q}{m}\left\{\mathbf{E}_\perp+\frac{1}{c}\mathbf{v}_d\times\mathbf{B}+\frac{1}{c}\mathbf{v}_g\times\mathbf{B}\right\}$$

time-independent part

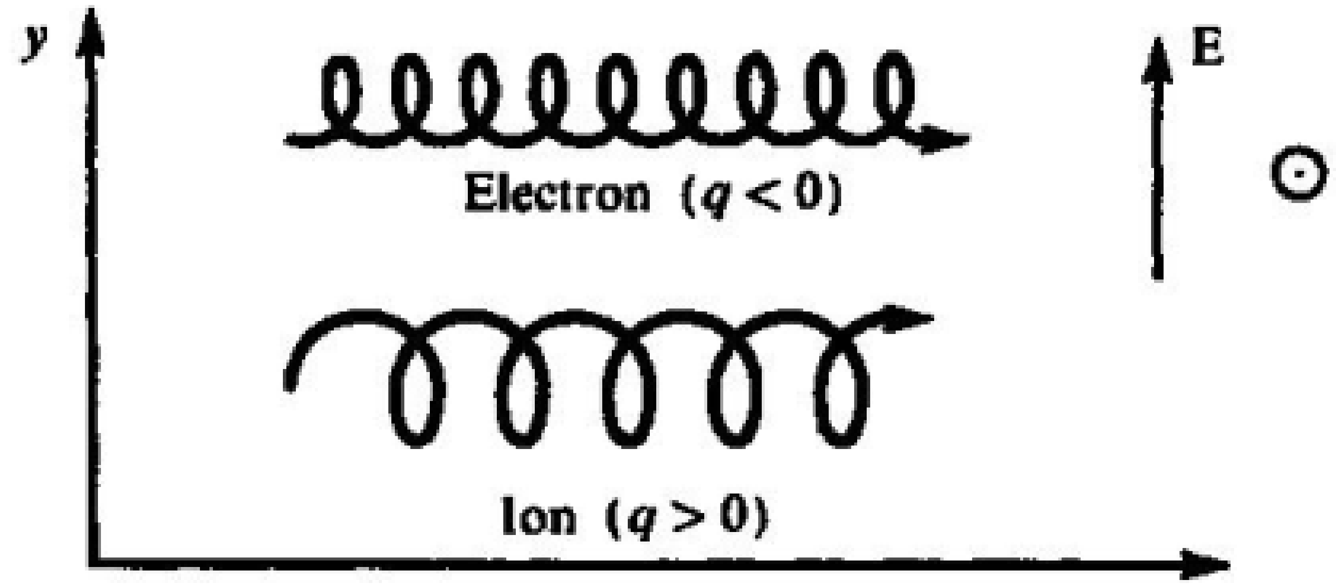
$$\mathbf{E}_\perp+\frac{1}{c}\mathbf{v}_d\times\mathbf{B}=0 \Rightarrow \mathbf{v}_d=c\frac{\mathbf{E}\times\mathbf{B}}{B^2}.$$

dirft velocity in electric field

time-dependent part

$$\frac{d\mathbf{v}_g}{dt}=\frac{q}{mc}(\mathbf{v}_g\times\mathbf{B}).$$

Particle motion in uniform static magnetic and normal fields



The calculated drift velocity does **not depend on particle charge nor mass**:

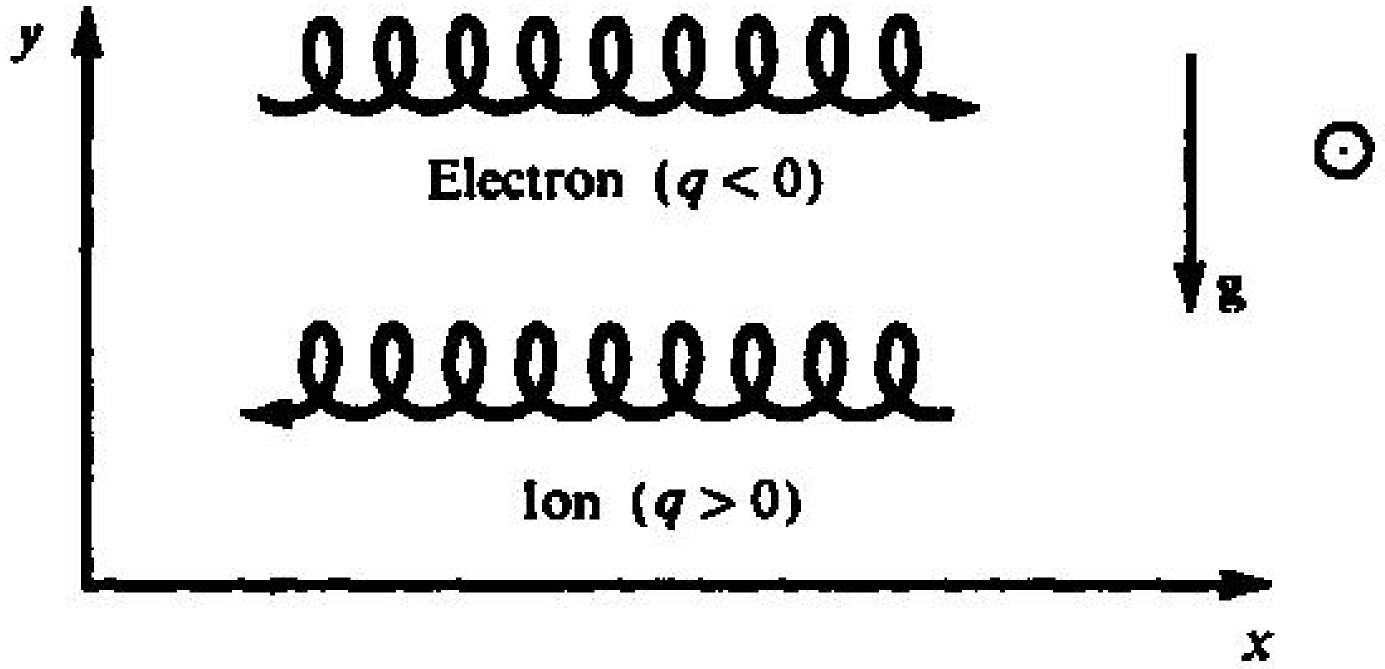
- electrons and positive ions drift in the **same direction**;
- if a plasma comprises an equal number of electrons and ions, the drift motion will **not** lead to a **current**.

Let us come back to a gravitational field through $\boldsymbol{E} = m\mathbf{g} / q$:

- in this case the **drift velocity** is given by $\mathbf{v}_d = \frac{mc}{q}\frac{\mathbf{g}\times\mathbf{B}}{B^2}$

The calculated drift velocity now **depend on particle charge nor mass**:

- electrons and positive ions drift in **opposite directions**:
- therefore the combined effect of gravitational and magnetic field results in a **current**.

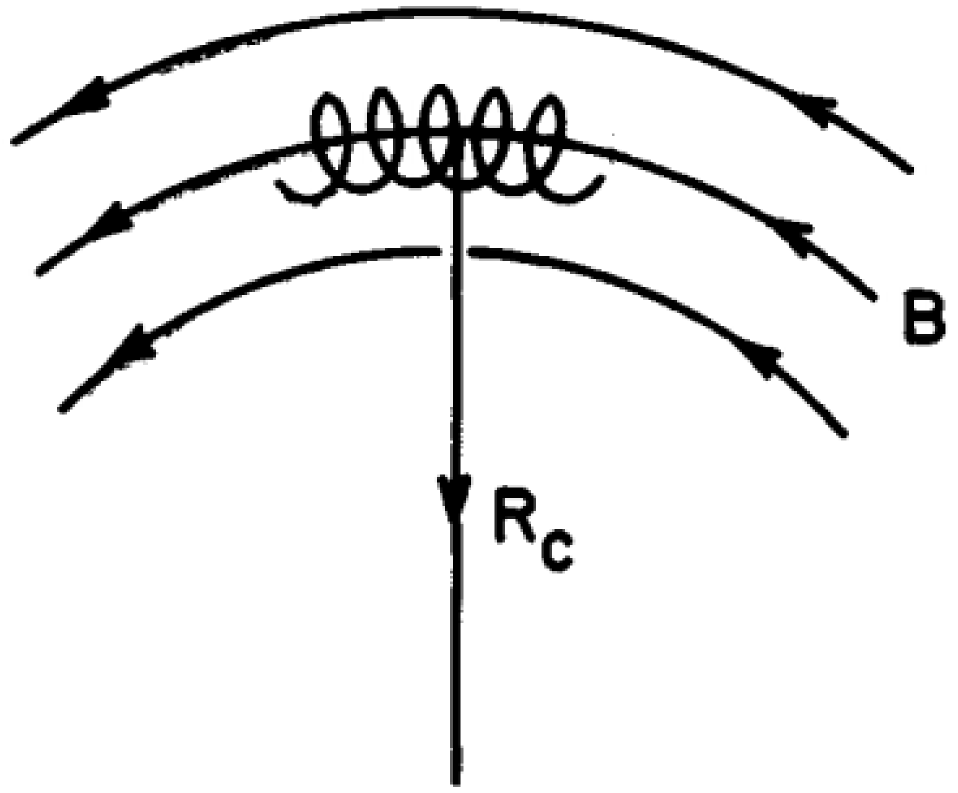


Particle motion in a constant magnetic field with a radius of curvature: curvature drift

Let us consider the magnetic field ***B*** to be constant in magnitude in a certain region, but to have a constant radius of curvature $\boldsymbol{R_C}$, directed towards curvature centre. Since a charged particle gyrates around a field line, under the effect of a centrifugal force

$$\mathbf{F}_\mathrm{C} = -mu_\parallel^2 \frac{\mathbf{R}_\mathrm{C}}{R_\mathrm{C}^2}$$

$u_{||}$ is the component of the velocity parallel to ***B***.



Since the force $\boldsymbol{F_C}$ is perpendicular to ***B***, then we obtain a curvature drift whose velocity is

$$\mathbf{u}_\mathrm{C} = -\frac{cmu_\parallel^2}{qB^2}\frac{\mathbf{R}_\mathrm{C}\times\mathbf{B}}{R_\mathrm{C}^2}.$$

The **curvature drift depends on the sign of the charge** for which it **gives rise to a current**, triggering **opposite drift** motions between positive ions and negative electrons.

The curvature drift together with another similar phenomenon, the gradient drift (due to the spatial variation of **B** with radius), are responsible to particle (longitudinal) drift around the Earth.

Particle trapping: magnetic mirror

Let us consider a magnetic configuration symmetric around a field line in such a way that the strength of the magnetic field varies as we move along the central field line.

Although the predominant component of the magnetic field is B_z, there is a small radial B_r component which gives, in cylindrical coordinates,

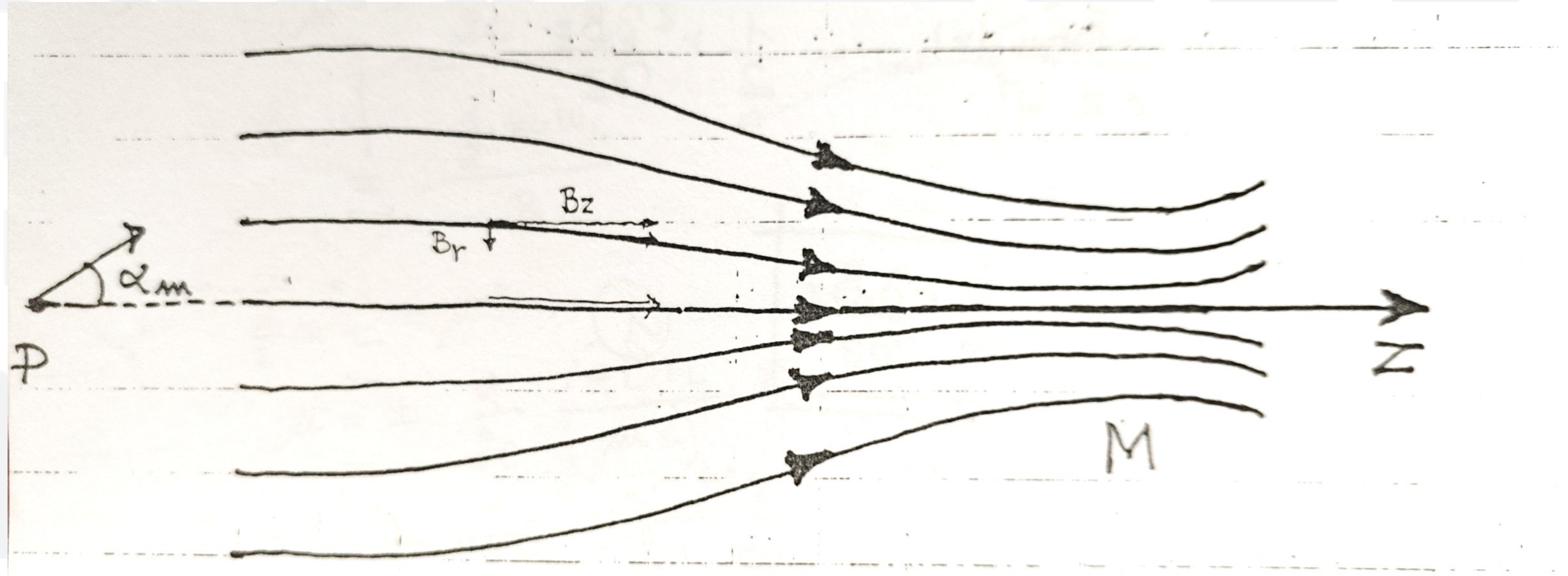
$$\frac{1}{r}\frac{\partial}{\partial r}(rB_r)+\frac{\partial B_z}{\partial z}=0.$$

Let us neglect the small radial variation of $\partial B_z/\partial z$ in the neighbourhood of the central axis and take it to be constant there ($\partial B_z/\partial z$ = constant). Then B_r in the central region can be readily obtained by integrating the previous equation

$$rB_r = -\int_0^r r'\frac{\partial B_z}{\partial z}\,dr' = -\frac{1}{2}r^2\frac{\partial B_z}{\partial z}$$

so that

$$B_r = -\frac{1}{2}r\frac{\partial B_z}{\partial z}.$$



Particle trapping: magnetic mirror

In this page we consider the two components of the kinetic energy / velocity: transverse and longitudinal.

For a particle gyrating around the central field line, the Z component of the Lorentz force is $F_z = -\frac{q}{c} u_\theta B_r.$

- we can write $\mp u_\perp$ in palce of u_θ , as θ-velocity $u_\perp$ for positively (negatively) charged particles is on the negative (positive) θ direction;
- and substituting for B_r : $F_z = \mp \frac{q}{2c} u_\perp r_L \frac{\partial B_z}{\partial z} = -\mu \frac{\partial B_z}{\partial z},$

$\mu = \pm \frac{q}{2c} u_\perp r_L = \frac{\frac{1}{2} m u_\perp^2}{B}$ is the **magnetic moment** of the gyrating particle.

The rate of change of the longitudinal kinetic energy is given by $\frac{d}{dt}\left(\frac{1}{2} m u_\parallel^2\right) = u_\parallel m \frac{du_\parallel}{dt} = -\mu \frac{dB}{dt},$ having considered:

- dB/dt for $u_\parallel (\partial B/\partial z)$
- the Z component of motion of the charged particle is $m \frac{du_\parallel}{dt} = F_z = -\mu \frac{\partial B_z}{\partial z}$

Particle trapping: magnetic mirror

Since the kinetic energy of a charged particle moving in a static magnetic field cannot change, the sum of the longitudinal and transverse kinetic energies must remain a constant so that (using also the previous results)

$$\frac{d}{dt}\left(\tfrac{1}{2}mu_{\parallel}^2\right)+\frac{d}{dt}\left(\tfrac{1}{2}mu_{\perp}^2\right)=0 \Longrightarrow -\mu\frac{dB}{dt}+\frac{d}{dt}(\mu B)=0 \Longrightarrow \frac{d\mu}{dt}=0$$

the magnetic moment is conserved during the motion.

The **transverse kinetic energy** then has to **increase** when the particle moves **into** regions of **stronger *B***.

- The transverse kinetic energy, however, **can never exceed the total kinetic energy**: therefore, when the particle reaches a region of sufficiently strong *B* where the transverse kinetic energy becomes equal to the total kinetic energy, it is not possible for the particle to penetrate further into regions of stronger magnetic field.
  - The only possibility is that the particle gets **reflected back**.

In the Van Allen Belts, as particles move toward the poles, the magnetic field line density increases, and their "latitudinal" velocity is slowed and can be reversed, deflecting the particles back towards the equatorial region, causing them to bounce back and forth between the Earth's poles

Particle trapping: magnetic mirror

A charged **particle** moving **along the symmetry axis** is **unaffected** by magnetic forces and hence is **not reflected** by the magnetic mirror.

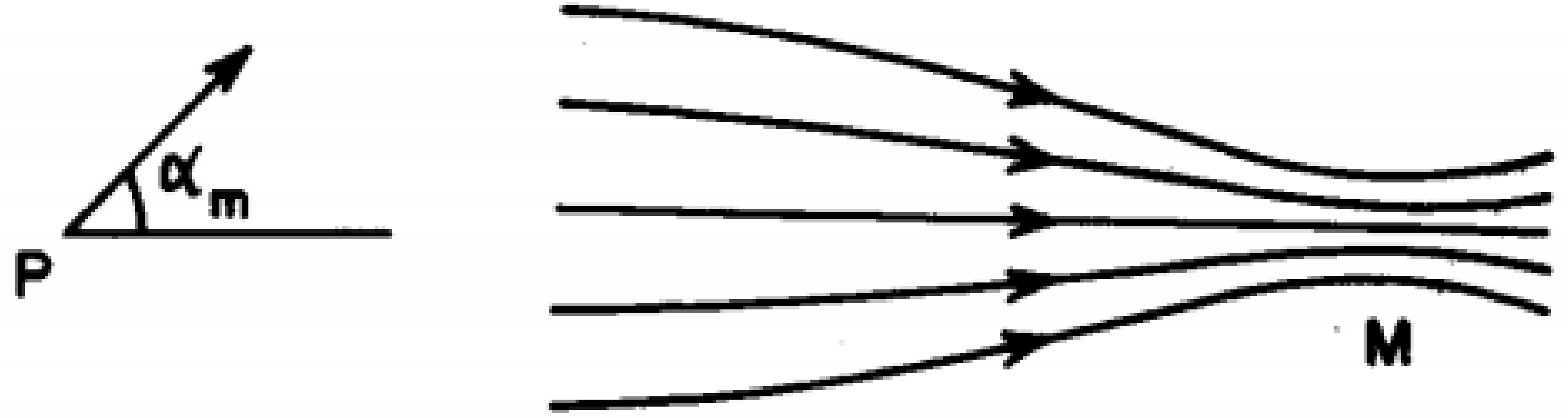
- If a magnetic mirror has a maximum magnetic field B_m at the point M, then charged particles from the point P are expected to **penetrate through the mirror** if they have velocity vectors sufficiently close to the symmetry axis, say within/**below a critical angle** α_m .

We can estimate this critical angle by using the fact that a charged particle at P with the velocity vector inclined to the central axis at the critical pitch-angle α_m is expected to be reflected from the region of maximum magnetic field B_m.

- Let u_0 be the velocity amplitude of the particle so that its starting transverse velocity at P is $u_{\perp 0} = u_0 \sin \alpha_\mathrm{m}$.
- If ***B* is the magnetic field at P**, then the **constancy of the magnetic moment** implies $\frac{u_{\perp 0}^2}{B} = \frac{u_0^2}{B_\mathrm{m}}$, since the transverse velocity at the time of reflection has to equal u_0.

From these two considerations $\sin^2 \alpha_\mathrm{m} = \frac{B}{B_\mathrm{m}}$.

A particle lying in a cone (**loss cone**) of such aperture α_m with respect to the central axis, passes through the mirror and is lost from the system.



Particle trapping: magnetic mirror

- The width of the loss cone is independent of the charge, the mass, or the energy of the particles drifting along a given field-line, and is a function only of the field-line radius on the equatorial plane.
- The loss cone aperture can be calculated substituting the value of the geomagnetic field $B = \frac{B_0}{(r/R)^3}(1+3\cos^2\phi)^{1/2}$
- The loss cone is surprisingly small: for instance, at the radius of a geostationary satellite orbit (6.6 R_E), the loss cone is less than 3° wide.
  - The smallness of the loss cone is a consequence of the very strong variation of the magnetic field-strength along field-lines in a dipole field.

- Charged particles with large equatorial critical pitch-angles have small parallel velocities, and mirror points located at relatively low latitudes.
- Conversely, charged particles with small equatorial critical pitch-angles have large parallel velocities, and mirror points located at high latitudes.
  - Of course, if the critical-angle becomes too small then the mirror points enter the Earth's atmosphere, and the particles are lost via collisions with neutral particles.

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