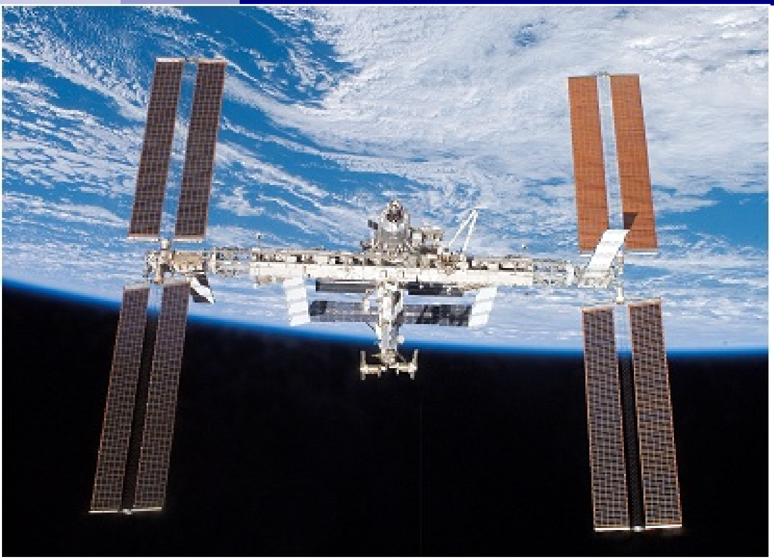
Space thermal environment



Isidoro Martínez
isidoro.martinez@upm.es

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Space thermal environment

(Thermal characteristics of the space environment)

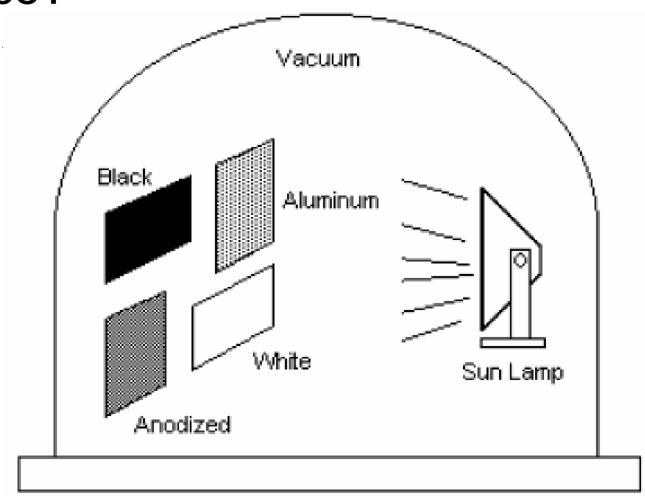
- Environment = external conditions or surroundings
- Space environment ≠ room conditions (vacuum, μg, radiations, wind…)
  - Mechanical effects: gravitational, vacuum, meteorites, debris, drag…
  - Thermal effects (what is the space temperature?)
  - Electric & magnetic effects: ionosphere, magnetosphere, telecom, remote sensing…

Space thermal environment

- Environment: vacuum and thermal radiations
- Thermal: temperature, heat, and thermal energy
- Space: at <100 km, at LEO, at GEO, interplanetary, planetary

- FUNDAMENTALS
  - Energy balance. What is thermal balance?
  - Heat transfer. What is thermal radiation

$$mc\frac{\mathrm{d}T}{\mathrm{d}t} = \sum \dot{W} + \sum \dot{Q}$$



Thermal radiation

$$M_{\lambda,\mathrm{bb}} = \frac{c_1}{\lambda^5\left[\exp\left(\dfrac{c_2}{\lambda T}\right)-1\right]}, \quad M_{\mathrm{bb}} = \int_0^\infty M_{\lambda,\mathrm{bb}}\,\mathrm{d}\lambda = \sigma T^4$$

Heat transfer theory

- What is heat? (≡heat flow)

$$Q \equiv \Delta E - W \quad \rightarrow \quad Q \equiv \Delta H|_p$$

- What is heat flux? (≡heat flow rate)

$$\dot{Q} \equiv \left.\frac{dE}{dt}\right|_{W=0} = \left.\frac{dH}{dt}\right|_p \equiv KA\Delta T$$

- Heat flux density (≈heat flux)

$$\vec{\dot{q}} = K\Delta T \begin{cases} \text{conduction} & \vec{\dot{q}} = -k\nabla T \\ \text{convection} & \dot{q} \equiv h\left(T - T_\infty\right) \\ \text{radiation} & \dot{q}_{bb} = \sigma\left(T^4 - T_0^4\right) \end{cases}$$

The environment. Ascent and low Earth orbit

Table 1. Some data for the rarefied Earth atmosphere at great altitudes.

Altitude	Satellite lifetime[a)]	Density[b)]	Composition and particle density	Temperature and pressure[c)]	Mean free-path[c)]
50 km	NA	$1\cdot10^{-3}$ kg/m^3	N_2 78%, O_2 21%, Ar 1%	271 K, 76 Pa	$\lambda=10^{-4}$ m
100 km	NA	$0.6\cdot10^{-6}$ kg/m^3	N_2 77%, O_2 18%, O 4%	195 K, 0.03 Pa	$\lambda=0.1$ m
120 km	<1 orbit	$2\cdot10^{-8}$ kg/m^3		360 K, 0.003 Pa	$\lambda=3$ m
200 km	1 day..1 wk	$10^{-10}..10^{-9}$ kg/m^3	O>50%, $N_O=10^{15}$ 1/m^3.	500..1100 K, 10^{-4} Pa	$\lambda=200$ m
300 km	1 wk..1 mt	$10^{-11}..10^{-10}$ kg/m^3	O 83%, N_2 15%, He 1%	600..1500 K, 10^{-5} Pa	$\lambda=2.5$ km
400 km	0.1 yr..5 yr	$10^{-12}..10^{-11}$ kg/m^3	O 91%, He 5%, N_2 4%	600..1800 K, 10^{-6} Pa	$\lambda=20$ km
500 km	1 yr..50 yr	$10^{-13}..10^{-11}$ kg/m^3		600..1800 K, 10^{-7} Pa	$\lambda=100$ km
600 km		$10^{-14}..10^{-12}$ kg/m^3	$N_O=10^{11}..10^{14}$ 1/m^3.	600..1800 K, 10^{-8} Pa	$\lambda=300$ km
1000 km		$10^{-15}..10^{-14}$ kg/m^3	He 84%, H 14%, O 2%	600..1800 K, 10^{-8} Pa	$\lambda=400$ km
GEO	Do not fall but drift		H, $N_H=3\cdot10^6$ at/m^3.		

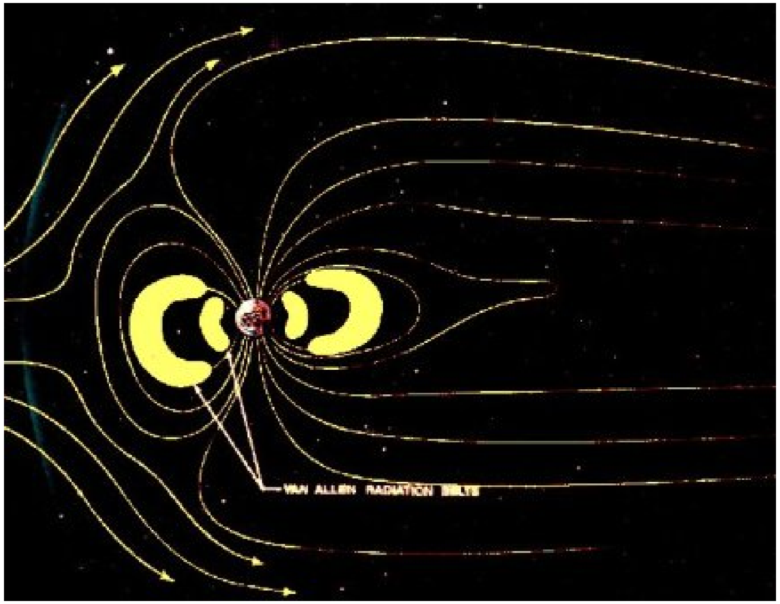
a) Satellite lifetime is based on a ballistic coefficient $c_B \equiv m/(c_D A) \sim 1$ kg/m^2 for typical satellites.

b) Maximum density corresponds to solar maximum.

c) Kinetic theory shows that pressure and temperature are related to kinetic energy in the form $p=(N/V)mv^2_{rms}/3$, and $(3/2)kT=(1/2)mv^2_{rms}$, and mean free path to particle density N and effective particle diameter d by $\lambda = 1/\left(\sqrt{2}\pi N d^2\right)$.

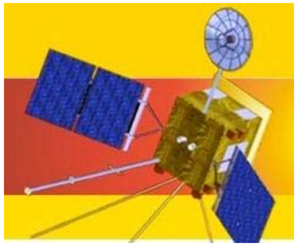
Background radiations

- Cosmic isotropic microwave radiation (2.7 K)
- Solar wind
  - van Allen radiation belts
- Cosmic radiation

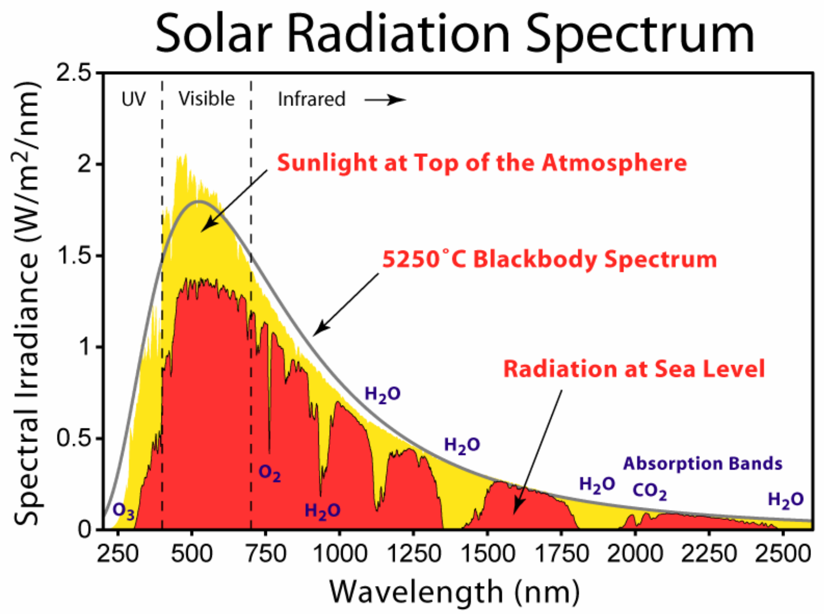


Solar radiation

- Amount: the solar constant

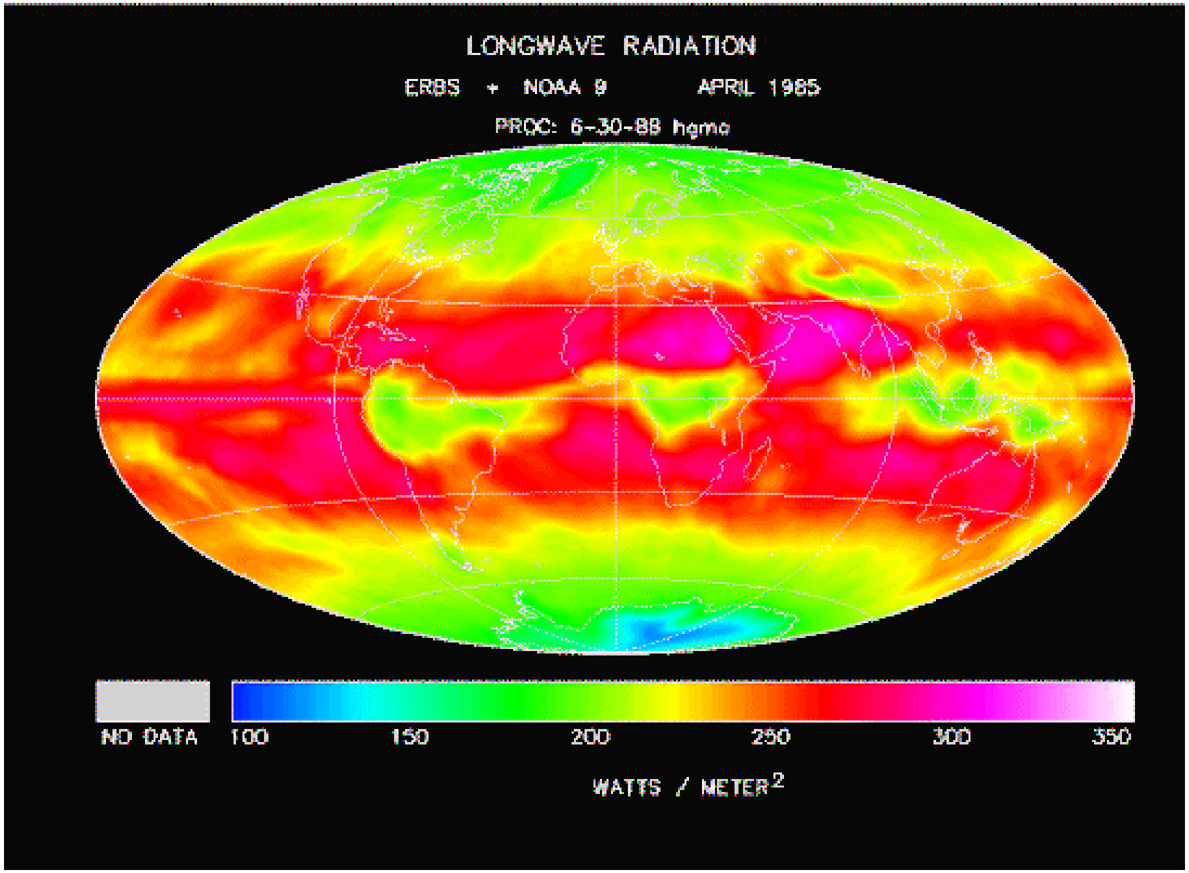


- Spectrum

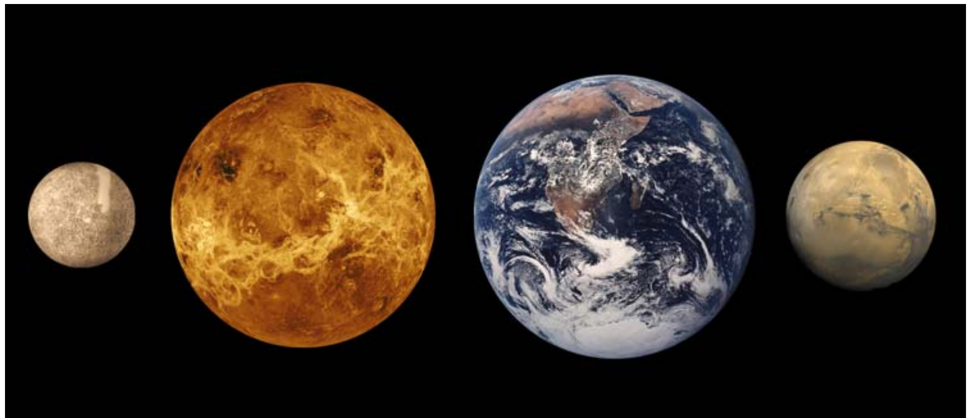


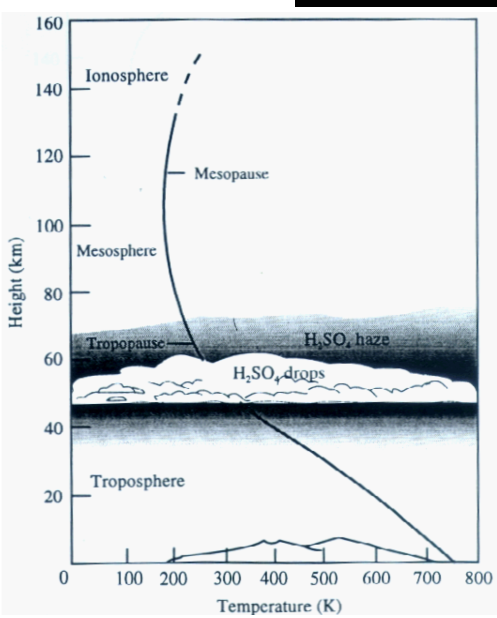
- Absorptance
- Transmittance
- Reflectance

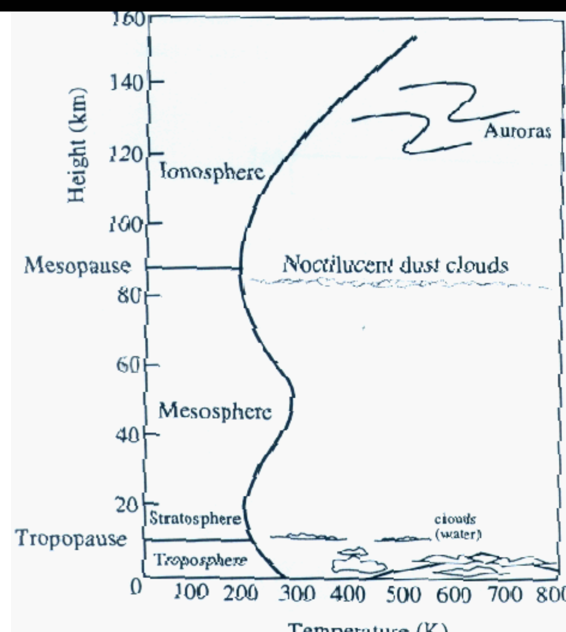
Thermal characteristics of planetary missions
Planet IR emission

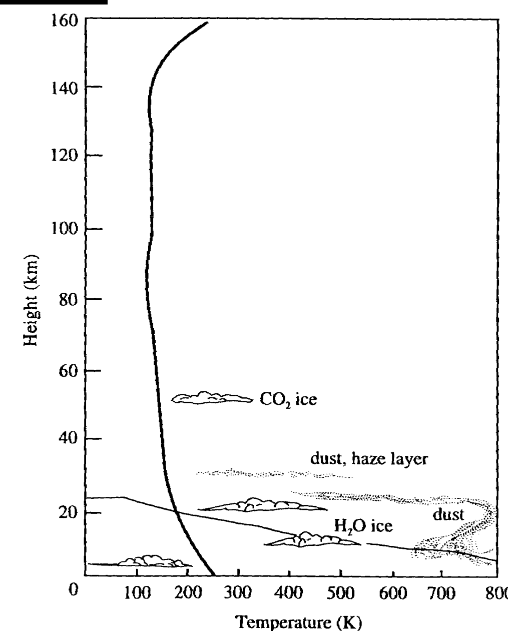


Planet characterization for thermal radiation



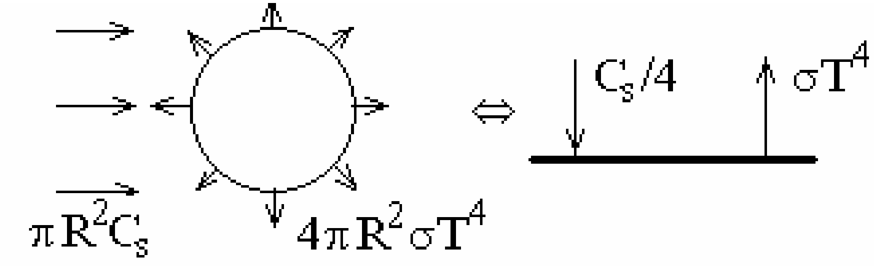






SIMPLIFIED THERMAL DESIGN COMPUTATIONS

- Thermal modelling approach: continuous, discrete, stochastic
- Global thermal balance. Isothermal bodies



$$C_s = \sigma T_s^4 \frac{4\pi R_s^2}{4\pi R_{s-p}^2}, \quad T_p = T_s \sqrt{\frac{R_s}{2R_{s-p}}}$$

Some space data to keep at hand

- Sun-Earth distance: $R_{S\text{-}E}=150 \cdot 10^9$ m (1 AU)
- Earth radius: $R_E=6.37 \cdot 10^6$ m
- Sun radius: $R_S=695 \cdot 10^6$ m ($R_S=109 \cdot R_E$)
- GEO radius: $R_{GEO}=42.16 \cdot 10^6$ m ($R_{GEO}=6.6 \cdot R_E$)
- Solar constant: $C_S=1370$ W/m^2 ($T_S=5800$ K)
- Stefan-Boltzmann law: $M_{bb}=\sigma T^4$, with $\sigma=5.67 \cdot 10^{-8}$ (W/m^2)/K^4
- Earth mean emissivity: $\varepsilon=0.59$ ($T_E=288$ K)
- Earth mean albedo: $\rho=0.30$ ($\alpha=0.70$)
- Background microwave radiation: $T_B=2.7$ K
- Aluminium: $\rho=2700$ kg/m^3, $\alpha_{lin}=24 \cdot 10^{-6}$ K^{-1}, $c=890$ J/(kg·K), $k=200$ W/(m·K), $\alpha=0.10$, $\varepsilon=0.05$.

Proposed exercises

1. Find the solar irradiance, E, near Mercury and Saturn
2. Find the heat flux between isothermal plates with n blackbody plates in between (radiation shields)
3. Find the steady temperature of an isothermal sphere at 1 AU
4. Find the steady temperature of a white ball and a black ball, at sea level and above the atmosphere
5. Find the steady temperature change from LEO to GEO of a spherical blackbody at noon
6. Find the steady temperature at 1 AU, for an isothermal blackbody with different geometries
7. Find the temperature evolution of a microsatellite 0.4 m in diameter when entering the equinox eclipse in GEO.
8. Find the two side temperatures of a white painted panel of k=0.1 W/(m·K) and 1•0.5•0.01 m^3 in size, tilted 30º to sun rays, and deployed from a spacecraft orbiting Mars.

SUMMARY

Space thermal environment

- Environment?: vacuum, radiations, meteorites?
- Thermal?: temperature, heat, or thermal energy?
- Space?: at <100 km, at LEO, at GEO, interplanetary, planetary?

- FUNDAMENTALS
  - Energy balance → thermal balance
  - Heat transfer → thermal radiation