Thermal Radiation

Objective: Measuring the emissivity and absorptivity of spacecraft thermal insulation garments

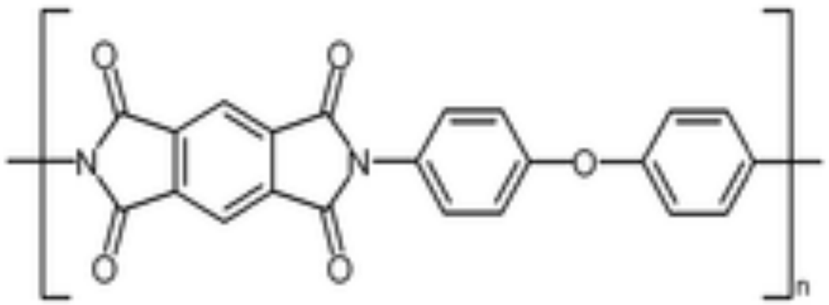
- For this purpose we will characterize Kapton materials

- We will be measuring the temperature over time
- Calibrating the power source
- Establishing vacuum
- Developing labview data acquisition VI

Experimental set-up

Kapton

Kapton is a polyimide film developed by DuPont that remains stable across a wide range of temperatures, from 4 to + 673 K



Kapton is used in flexible electronics, thermal micrometeorites garments and in multi-layer insulation **(MLI)** often used on spacecraft as well as in other equipments.

- Their gold color results from a reflective silvery aluminum coating behind sheets Kapton material.
- MLI reflects sunlight to shade the spacecraft against overheating, and retains internal spacecraft heat to prevent too much cooling

MLI

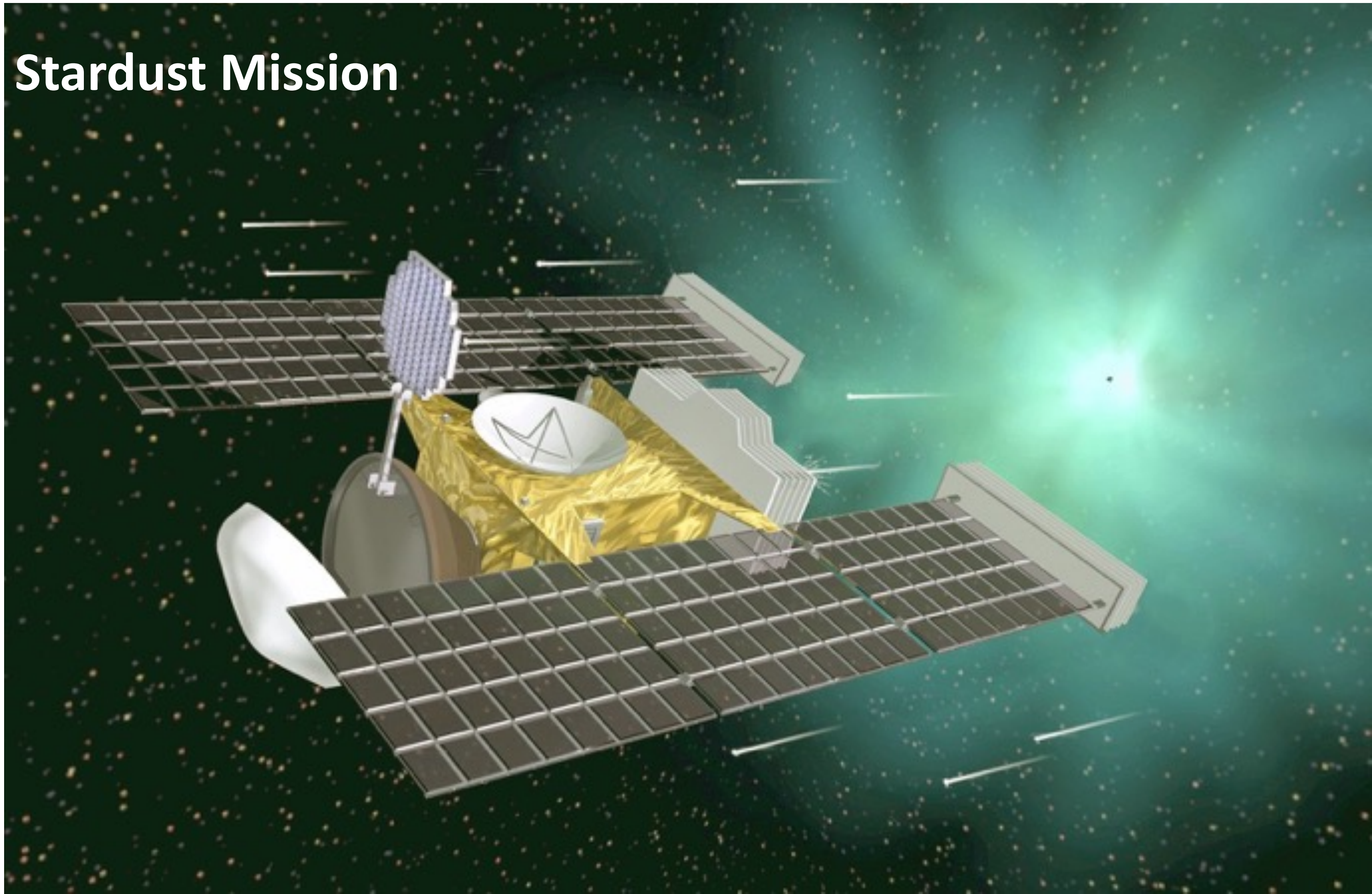
It does not appreciably insulate against thermal losses such as heat conduction or convection. It is employed to reduce heat transfer by thermal radiation.

MLI blankets also provide some protection against micro-meteoroid impacts.

Launch: February 7, 1999

Comet Wild 2: January 1, 2004

Earth return: January 15, 2006



Heat transfert

Heat transfer changes the **internal energy** of both systems involved according to the **First Law of Thermodynamics**.

$$\Delta U = Q - W$$

Change in internal energy

Heat added to the system

Work done by the system

- **Conduction or diffusion:** the transfer of energy between objects that are in physical contact.

- **Convection:** the transfer of energy between an object and its environment, due to fluid motion.

- **Radiation:** the transfer of energy to or from a body by means of the emission or absorption of electromagnetic radiation.

Black body radiation

- A black body is an idealized physical body/system that absorbs all incident electromagnetic radiation, regardless of frequency or angle of incidence.
- A black body in thermal equilibrium emits electromagnetic radiation called black-body radiation.
- The emitted radiation energy which is characteristic of this radiating system only, it doesn't depend upon the type of radiation which is incident upon it.
- The radiation is emitted according to Planck's law
- It emits as much or more energy at every frequency than any other body at the same temperature
- The energy radiated from a blackbody is isotropically diffused (independent of direction)

Planck radiation formula

Planck radiation formula can be described as follow:

$$S_\lambda(T) = \frac{8\pi hc}{\lambda^5}\frac{1}{\exp(\frac{hc}{\lambda k_B T}) - 1}$$

- *$S_\lambda(T)$:* energy per unit volume per unit wavelength
- *h:* Planck constant (6.62617x1024 J.s)
- *k_B :* Boltzman constant (1.38066x10-23 J/K)

A widely used model of a blackbody is a small hole in a cavity with walls that are opaque to radiation

It is a pioneer result of modern physics and quantum theory

Planck radiation formula

- From the assumption that the electromagnetic modes in a cavity were quantized in energy with the quantum energy equal to Planck's constant times the frequency (hv)

- The average energy per mode or quantum is the energy of the quantum times the probability that it will be occupied

$$\langle E \rangle = \frac{hc}{\lambda \exp(\frac{hc}{\lambda k_B T}) - 1}$$

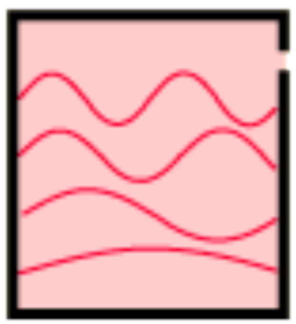
with $\frac{1}{\exp(\lambda \frac{hc}{k_B T}) - 1}$ being the Einstein-Bose distribution function and ν=c/λ

- This average energy times the density of such states $(\frac{8\pi}{\lambda^4})$ gives

$$S_\lambda(T) = \frac{8\pi hc}{\lambda^5} \frac{1}{\exp(\frac{hc}{\lambda k_B T}) - 1}$$

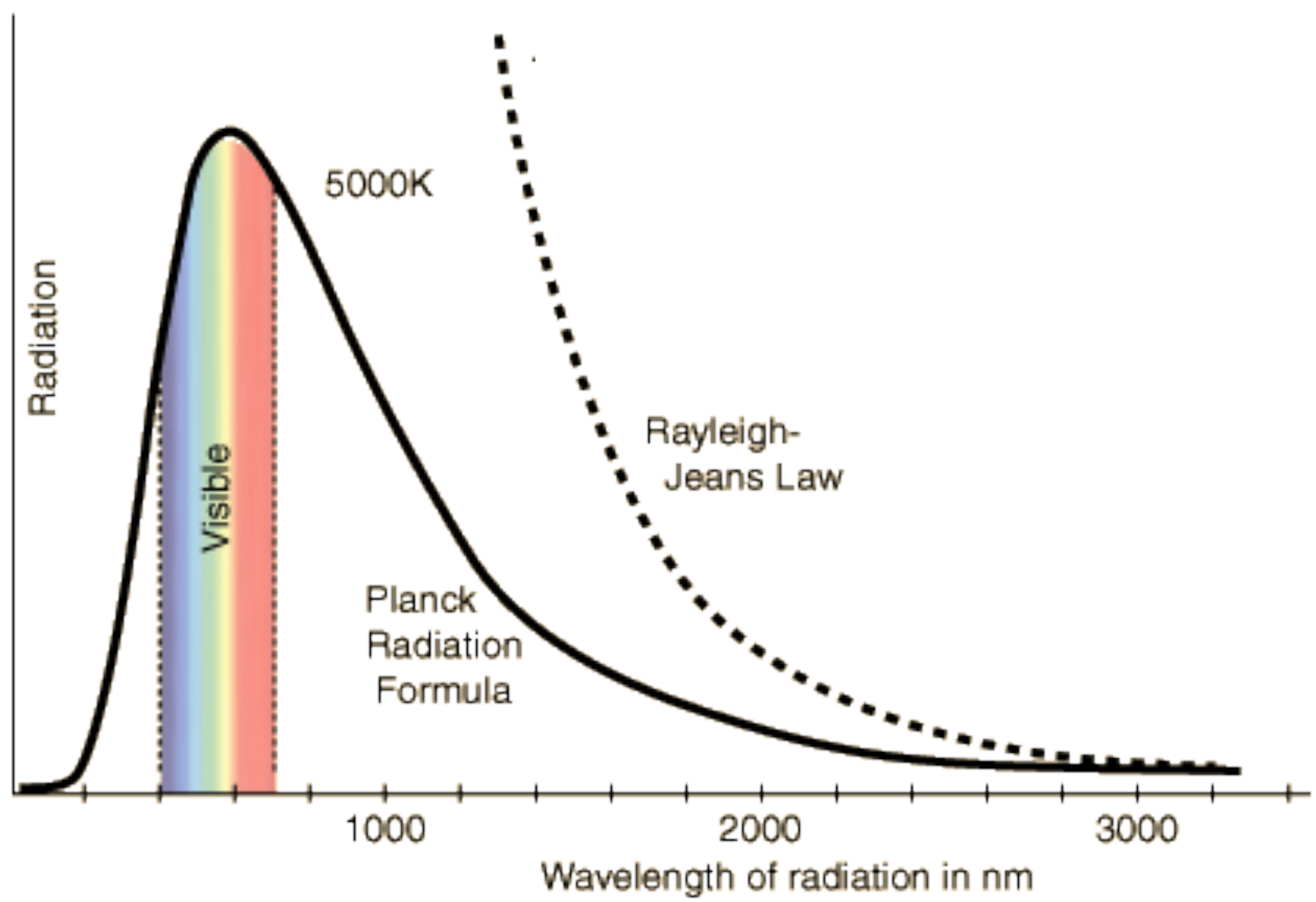
Classical vs quantum

Radiation modes in a hot cavity provide a test of quantum theory



	#Modes per unit frequency per unit volume	Probability of occupying modes	Average energy per mode
CLASSICAL	$\frac{8\pi\nu^2}{c^3}$	Equal for all modes	kT
QUANTUM	$\frac{8\pi\nu^2}{c^3}$	Quantized modes: require $h\nu$ energy to excite upper modes, less probable	$\frac{h\nu}{e^{\frac{h\nu}{kT}} - 1}$

The Rayleigh-Jeans curve agrees with the Planck radiation formula for long wavelengths, low frequencies



Classical vs quantum

Classical

Rayleigh-Jeans Law

$$\frac{8\pi\nu^2}{c^3}kT$$

Planck Law

$$\frac{8\pi\nu^2}{c^3}\frac{h\nu}{e^{\frac{h\nu}{kT}}-1}$$

Quantum

Making use of the series expansion of the exponential:

$$e^x = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \ldots$$

$$e^{\frac{h\nu}{kT}} = 1 + \frac{h\nu}{kT} + \frac{\left[\frac{h\nu}{kT}\right]^2}{2!} + \frac{\left[\frac{h\nu}{kT}\right]^3}{3!} + \ldots$$

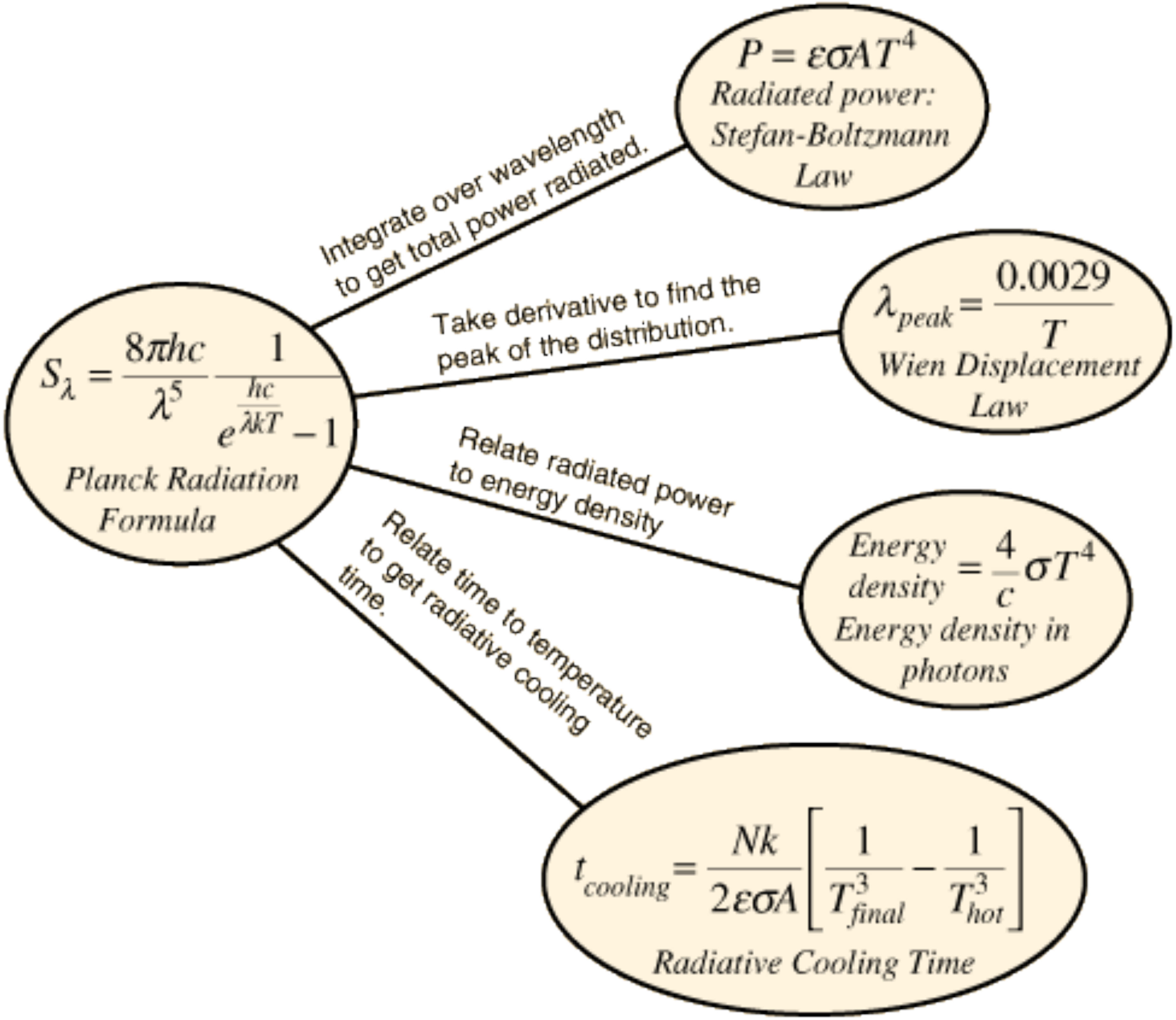
$$\approx 1 + \frac{h\nu}{kT} \quad \text{for} \quad h\nu << kT$$

Low frequencies

For low frequencies the Planck Law agrees with the classical Rayleigh-Jeans Law

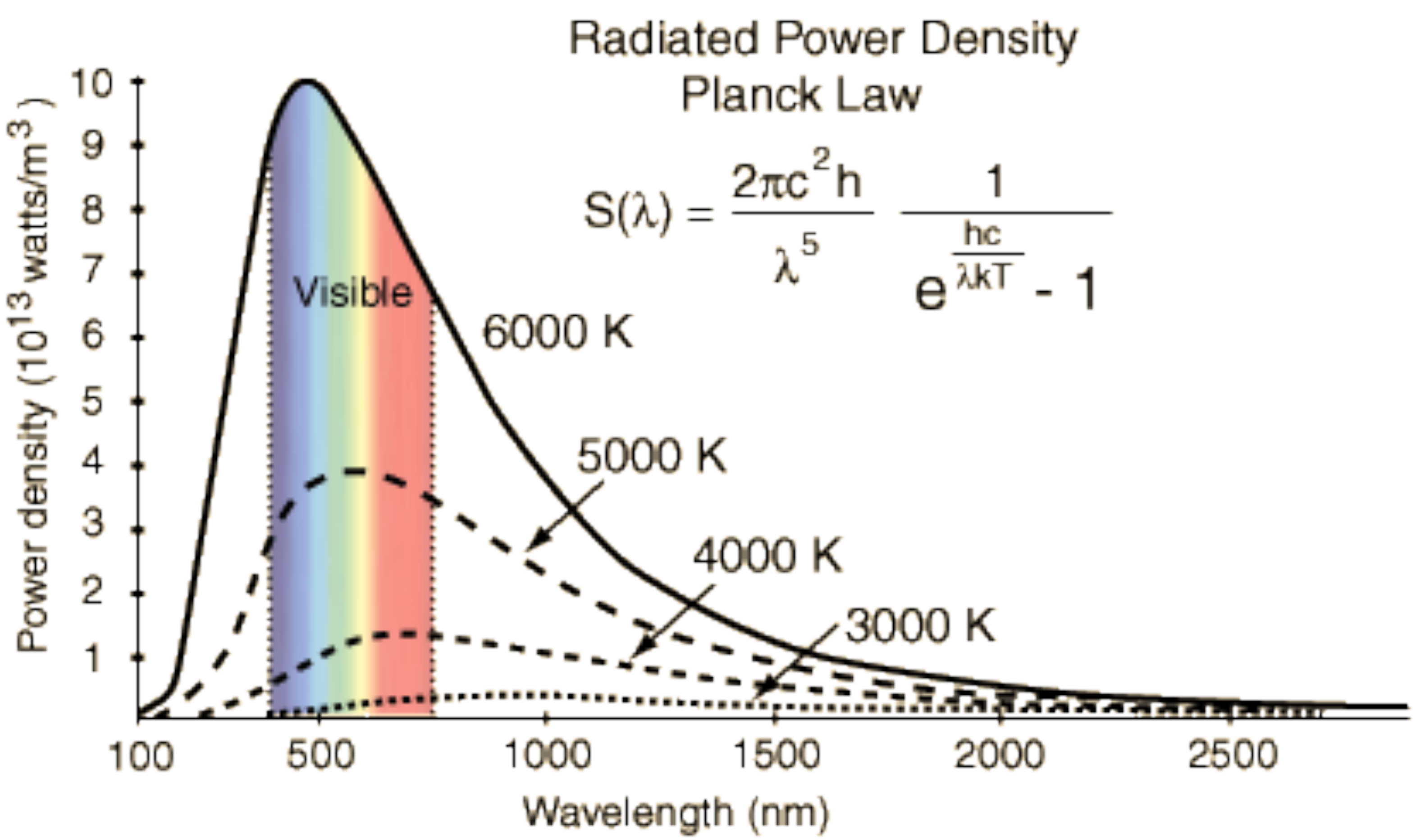
$$\frac{8\pi\nu^2}{c^3}\frac{h\nu}{1+\frac{h\nu}{kT}-1} = \frac{8\pi\nu^2}{c^3}kT$$

Planck radiation formula



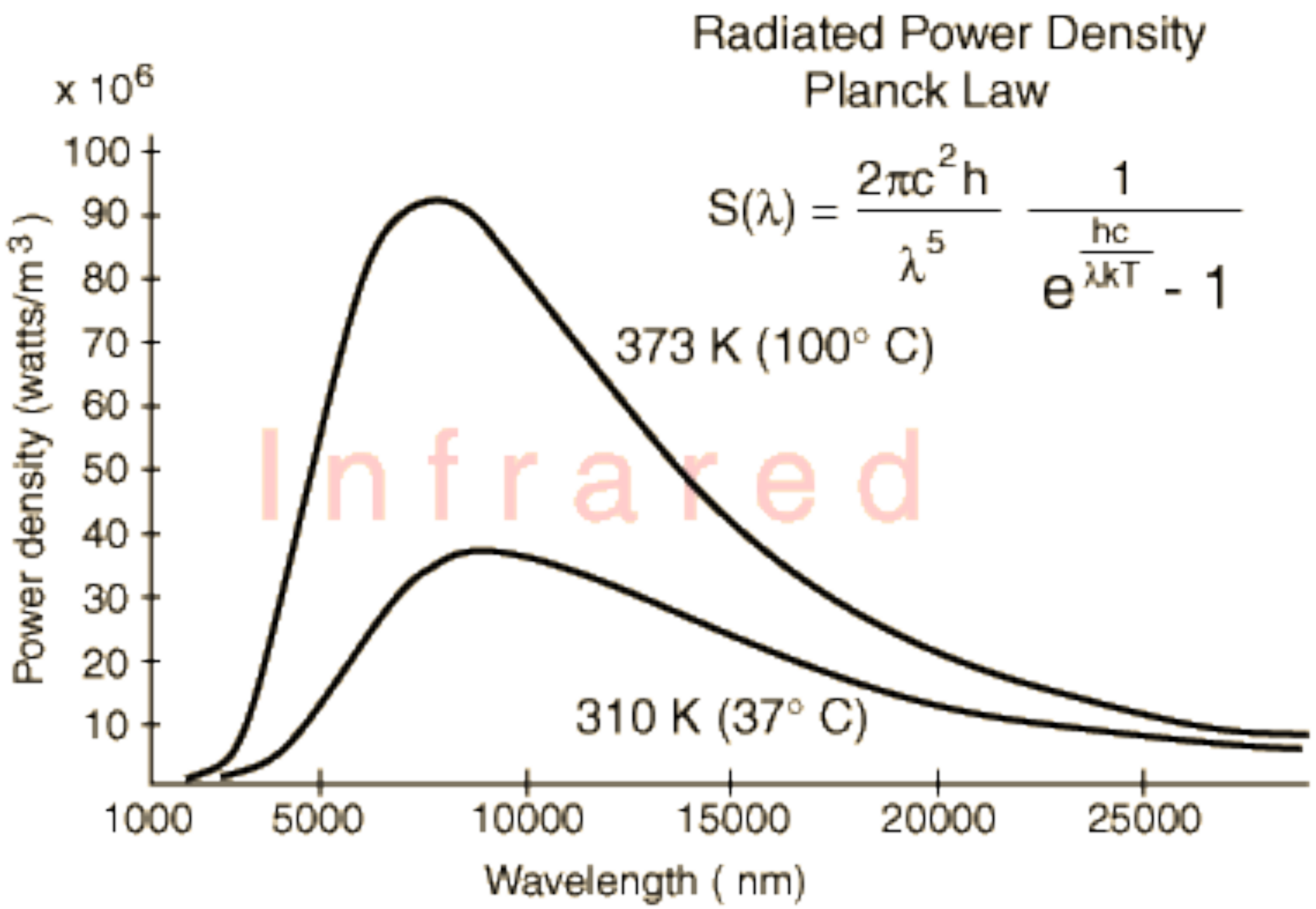
Applications of Planck formula

Irradiance curve of the sun



What Planck and the others found was that as the temperature of a blackbody increases, the total amount of light emitted per second increases, and the wavelength of the spectrum's peak shifts to bluer colors

Other example



- Essentially all of the radiation from the human body and its ordinary surroundings is in the infrared portion of the electromagnetic spectrum

From Planck radiation formula to Stefan-Boltzman Law

The total power per unit area from a blackbody radiator can be obtained by integrating the Planck radiation formula over all wavelengths:

$$\frac{P}{A} = 2hc^2 \int_0^\infty \frac{d\lambda}{\lambda^5 \exp\left(\frac{hc}{\lambda k_B T}\right) - 1}$$

$$\frac{P}{A} = \boxed{\sigma} T^4 = \boxed{\frac{2\pi^5 k^4}{15 h^3 c^2}} T^4$$

Stefan-Boltzman Law

The energy radiated by a blackbody radiator per second per unit area is proportional to the fourth power of the absolute temperature and is given by:

$$\frac{P}{A} = \sigma T^4$$

For hot objects other than ideal radiators, the law is expressed in the form:

$$\frac{P}{A} = \varepsilon \sigma T^4$$

- *P:* net radiated power (watt)
- *A:* radiating area (m^2)
- *σ:* Stefan's constant = 5.6703×10^{-8} watt/m^2K^4
- *ε:* emissivity which ranges from 0 to 1, ε=1 for black body
- *T:* temperature of radiator (K)

Thermal radiation

Thermal radiation is heat transfer by the emission of electromagnetic waves which carry energy away from the emitting object.

- The relationship governing radiation from hot objects

$$P = \varepsilon \sigma A (T^4 - T_c^4)$$

- *P:* net radiated power (watt)
- *A:* radiating area (m^2)
- *σ:* Stefan's constant = 5.6703×10^{-8} watt/m^2K^4
- *ε:* emissivity which ranges from 0 to 1, e=1 for black *body*
- *T:* temperature of radiator (K)
- T_c: temperature of surroundings (K)

Experimental set-up

- The system is pumped with a rotary vane pump
- The pressure at which we will be operating is around 10^{-3} mbar (primary vacuum)

Reproducing the pressure conditions of outer space

Vacuum is space that is empty of matter!

The quality of a partial vacuum refers to how closely it approaches a perfect vacuum. Lower gas pressure means higher-quality vacuum.

	Pressure (Torr)	Pressure (Pa)	Mean free path	molecules /cm^3
Primary vacuum	*1 to 10^{-3}*	*10^{2} to 10^{-1}*	*100 µm to 10 cm*	*10^{16} to 10^{13}*
Secondary vacuum/high vacuum	*10^{-3} to 10^{-9}*	*10^{-1} to 10^{-7}*	*10cm to 100 km*	*10^{13} to 10^{7}*
Ultra high vacuum	*10^{-9} to 10^{-12}*	*10^{-7} to 10^{-10}*	*100 to 10^{5} km*	*10^{7} to 10^{5}*

1 Torr = 0.75 mbar = 133.33 Pa = 1 mm Hg

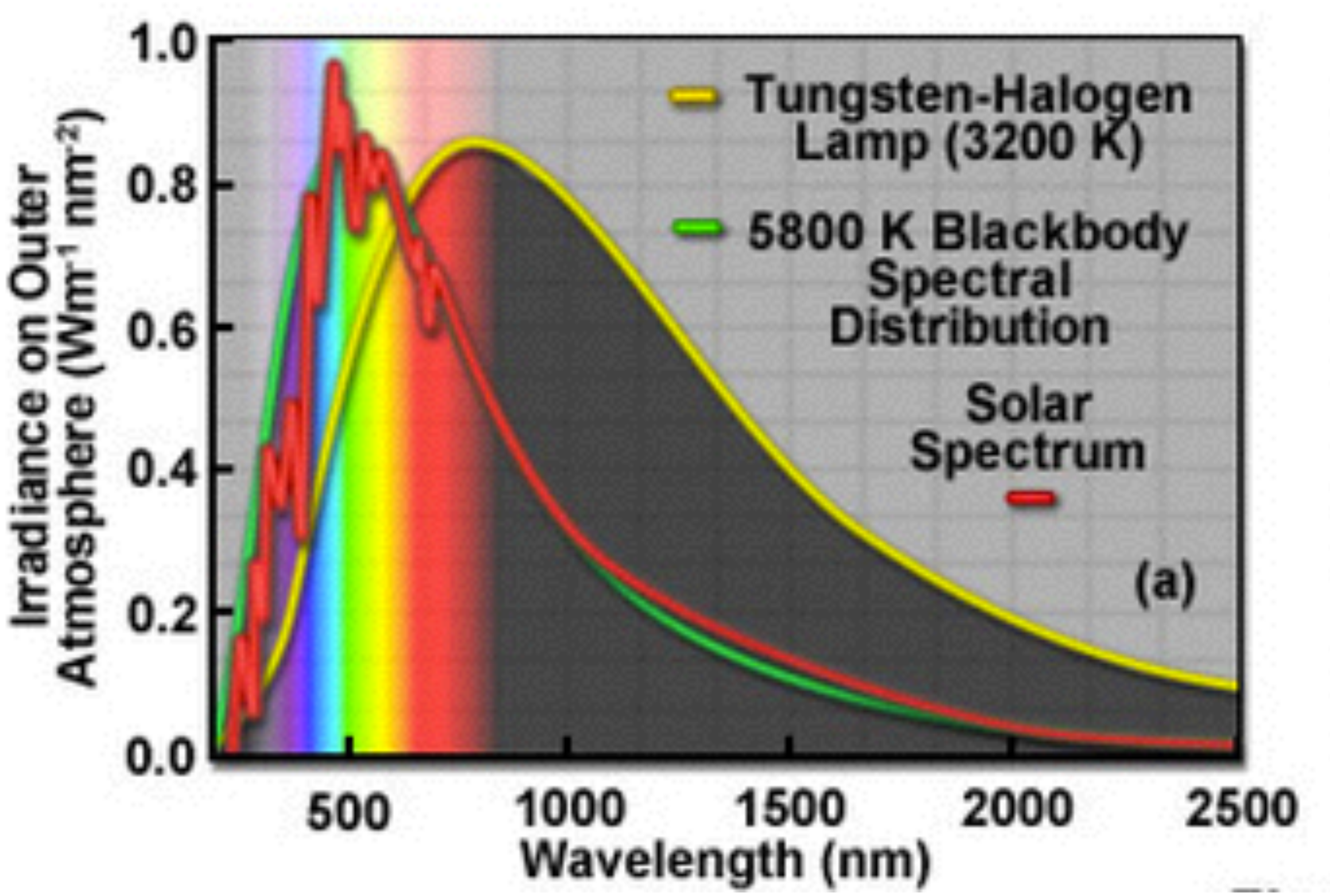
At atmospheric pressure 2.7×10^{19} molecules/cm^3

Pressure in outer space

	Pressure (Torr)	Pressure (Pa)	Mean free path	molecules /cm^3
Interplanetary space				***11***
Interstellar space				***1***
Intergalactic space				***10^{-6}***

The quality of a partial vacuum refers to how closely it approaches a perfect vacuum. Lower gas pressure means higher-quality vacuum.

Halogen lamp



As incandescent radiators, tungsten-halogen lamps generate a continuous spectrum of light that ranges from the central ultraviolet through the visible and into the infrared wavelength regions. Compared with the emission spectrum of sunlight and a theoretical 5800 K blackbody radiator, the longer wavelength regions always predominate in tungsten-halogen lamps. However, as filament temperature increases in a tungsten-halogen lamp, the light emission profile shifts to shorter wavelengths, the proportion of visible wavelengths emitted by the lamp increase substantially.

Formulas employed

Heat balance:

$$\boxed{m\, C_p(T)\, \frac{dT}{dt} = -\sigma\, \varepsilon(T)\; S\, T_S^4 + \sigma\, \alpha(T)\; S\, T_0^4 + P_c - P_p}$$

- *Cp:* specific heat capacity (J/K.Kg)
- *m: masse of the sample (Kg)*
- *σ:* Stefan's constant = 5.6703x10^{-8} watt/m^{2}K^4
- *ε:* emissivity of the sample used
- *α: absorptivity of the sample*
- *Ts:* temperature of the sample
- T_c: temperature of surroundings (K)
- *Pc*: heat power of the source (lamp)
- *Pp*: heat lost by convection and conduction

Formulas employed

Heat balance:

$$\boxed{m\, C_p(T)\, \frac{dT}{dt} = -\sigma\, \varepsilon(T)\, S\, T_S^4 + \sigma\, \alpha(T)\, S\, T_0^4 + P_c - P_p}$$

$m\, C_p(T)\, \frac{dT}{dt}$: Change in internal energy of the sample

$\sigma\, \varepsilon(T)\, S\, T_S^4$: heat radiated by the sample

$\sigma\, \alpha(T)\, S\, T_0^4$: heat absorbed by the sample

Static mode

Heat balance:

$$\boxed{m\ C_p\,(T)\ \frac{dT}{dt}\ =\ -\sigma\ \varepsilon\,(T)\ \ S\ T_S^4\ +\ \sigma\ \alpha\,(T)\ \ S\ T_0^4\ \ +\ P_c\ -\ P_p}$$

Thermal equilibrium:

$$m\ C_p\,(T)\ \frac{dT}{dt} = 0$$

$$\varepsilon\,(T) = \frac{P_c\ -\ P_p}{\sigma\ \ S\ \ (T_S^4\ -\ T_0^4)}$$

Operating mode – measurements in static mode

- Turn on the water cooling system
- Switch off the valve that let the air enter the vacuum chamber
- Turn on the pumping system (rotary pump) by plugging the electrical cable
- Turn on the halogen lamp and regulate the alternostat to 200. It need couple of minutes to be stable in terms of power.
- Estimate the power radiated from the lamp by adjusting the distance and using an external thermophile
- Start the data acquisition at regular time interval
- Turn the lamp in the direction of the samples
- Estimate the temperature of equilibrium that the sample will reach. Equilibrium is reached when the temperature variation is in the order of 1°C/hr

Operating mode – measurements in dynamic mode

- Remove the lamp but keep it on
- Continue data acquisition
- Calculate the emissivity using the dynamic mode

$$m\, C_p\, (T)\, \frac{dT}{dt} = -\sigma\, \varepsilon\, (T)\, S\, T_S^4 + \sigma\, \alpha\, (T)\, S\, T_0^4 - P_p$$

When is the experiment is done turn off the pumping system and the lamp. Break the vacuum by opening the valve that allow the air to enter the vacuum chamber

Thermocouple and data acquisition