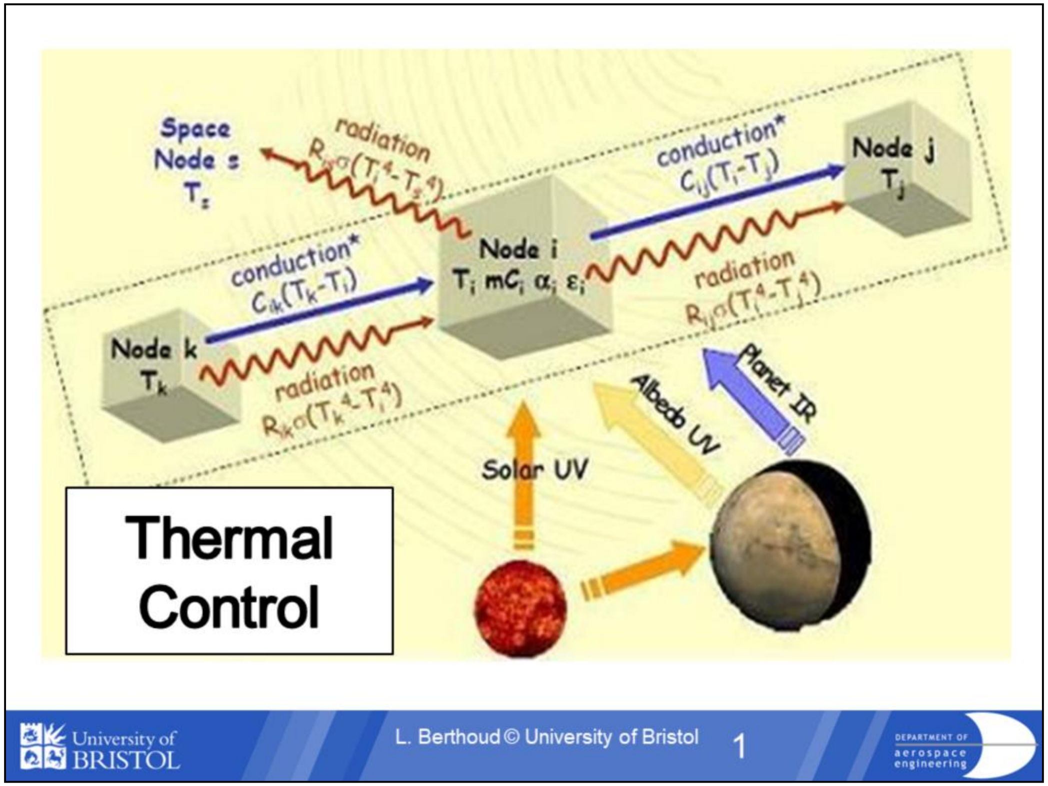


Why do we need thermal control on a spacecraft? There is no aerodynamic drag to cause heating and the spacecraft is going from hot sun (+100degC) to eclipse (-100degC)

Most systems become less reliable when operated outside their design operating environment

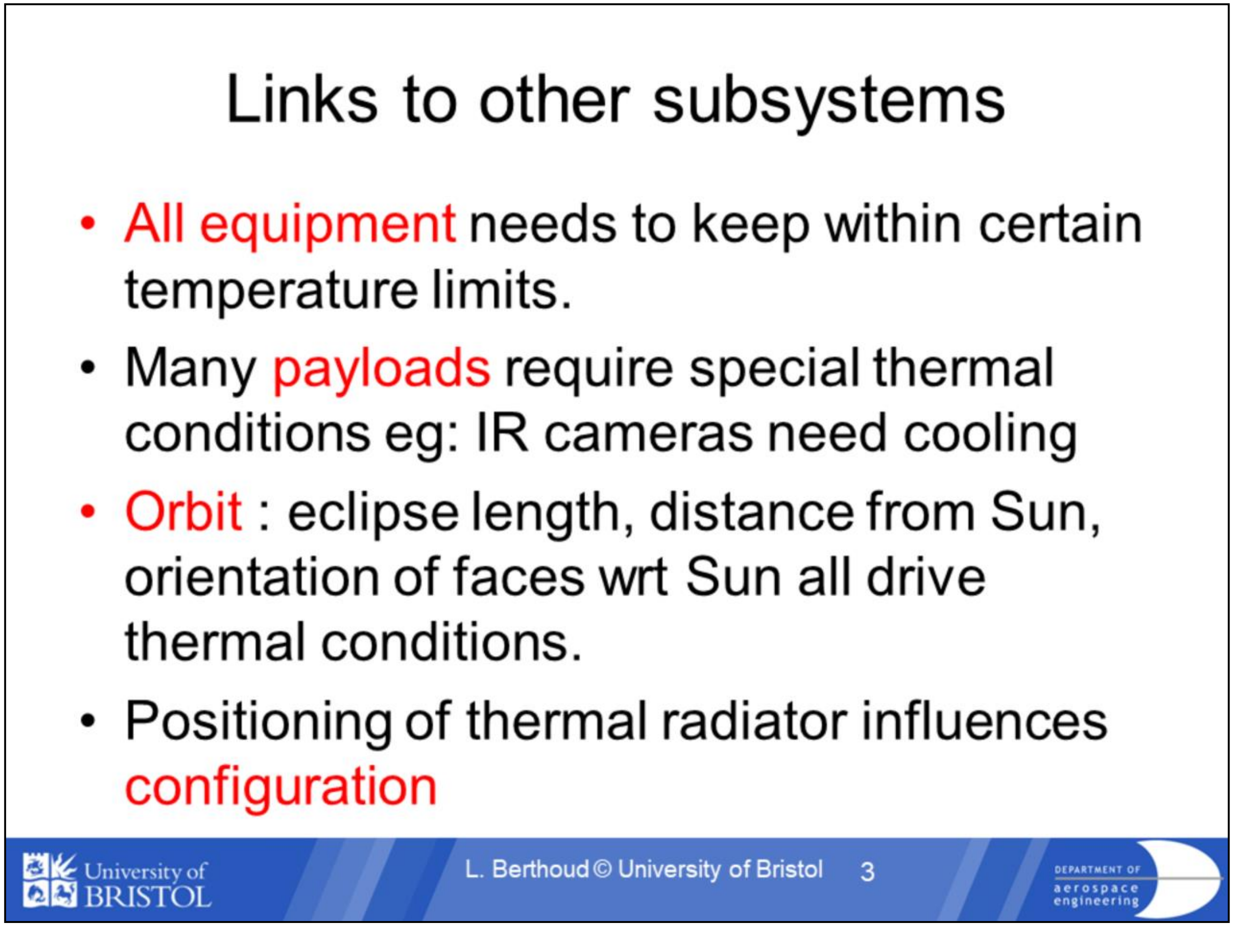
– Propellant freezes, electronics and batteries stop working.

– Instrument/antenna/camera alignment

– Instruments such as IR cameras may have requirements for very cold temperatures

Objectives

- Explain why thermal control is needed
- Know and use equations for conduction and radiation
- Be able to calculate thermal balances and equilibrium temperatures
- Be able to size and select thermal control systems
- *[From reading]: Be able to describe difference between active and passive thermal control*
- *[From reading]: Be able to describe means for active and passive thermal control.*



These are the links between the thermal subsystem and the other subsystems.

Typical temperature ranges

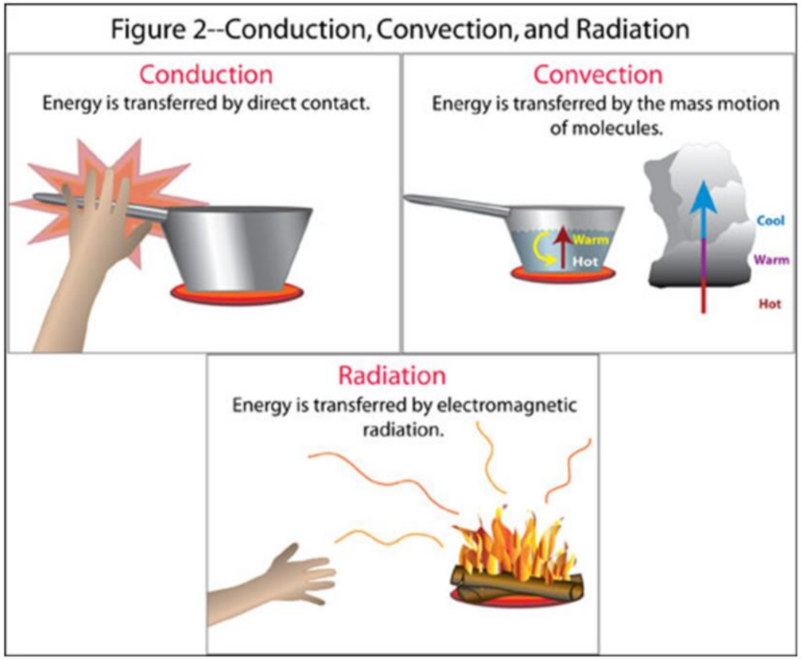
Component	Temp. range °C	Component	Temp. range °C
Batteries NiCd	5 to 20	Solar arrays	-100 to +100
Electronics	0 to 40	IR detectors	-200 to -80
Hydrazine	7 to 35	Structures	-46 to 65

These are the recommended limits for certain components.

There is a difference between operating and survival temperatures ie: the equipment will be more sensitive when it is operating compared to when it is off and just needs to survive.

Which components will most restrict the thermal design of the spacecraft do you think?

Heat transfer Revision

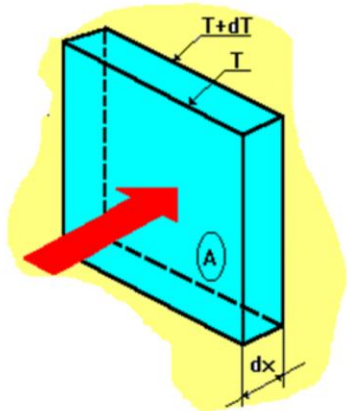


Which do we have in space?

Convection only applies when there are molecules and there are no molecules in space. On other planets there is sometimes an atmosphere and therefore molecules, so we need to include convection.

Conduction – Fourier's law

$$Q_x = -k.A.\frac{dT}{dx}$$

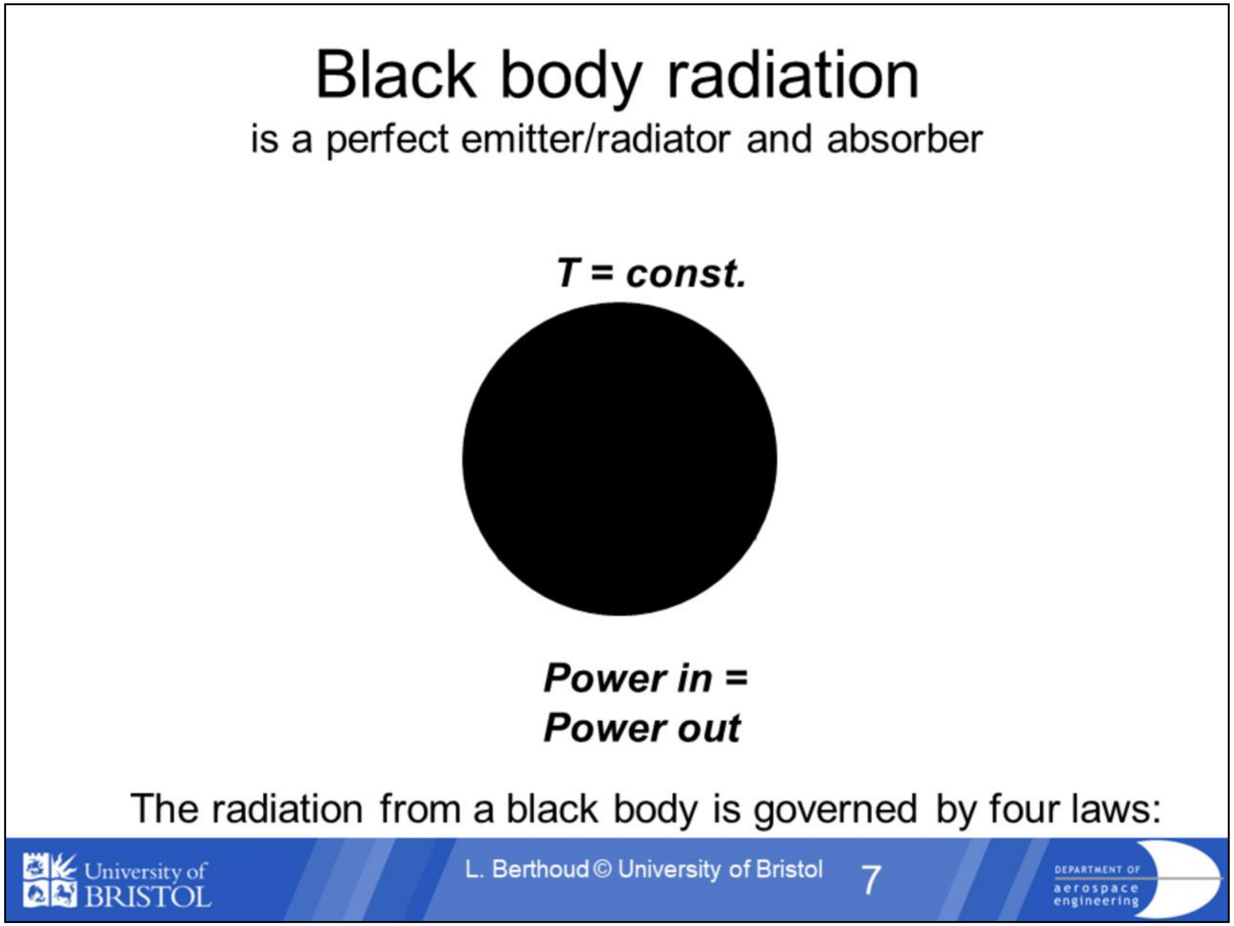


Q: Vector heat flow in x direction (W)
k : thermal conductivity (W/m.K)
A : cross sectional area (m^2)
T : temperature (K)
dx : length of heat transfer path (m)

Assumptions:

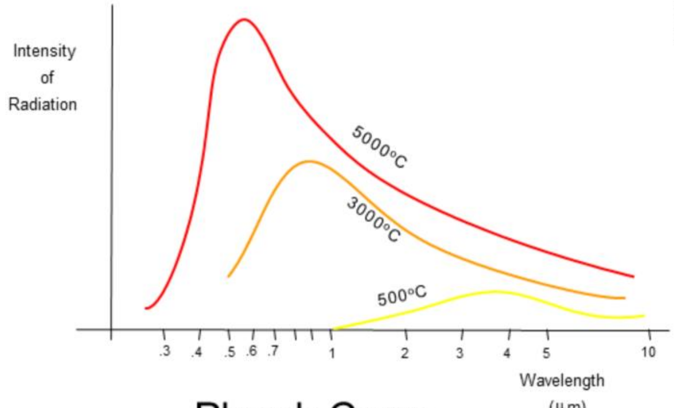
- steady state conduction heat transfer
- 1D heat flow
- no internal heat generation.
- constant and uniform temperatures
- isotropic and homogeneous material
- constant temperature gradient

Fourier's law is an empirical law based on observation. It states that the vector heat flow or energy transfer rate, Qx, through a homogeneous solid is directly proportional to the area, **A**, of the section at right angles to the direction of heat flow, and to the temperature difference along the path of heat flow, d**T**/d**x**. It is analogous to Ohm's law in electricity.



A black body absorbs all the energy incident on it and reradiates at a certain frequencies dependent on the temperature of the body. In the diagram one temperature and its equivalent frequency is shown. Power in =power out. It is a theoretical concept.

Radiation law 1 - Planck's law



Planck Curve

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5}\frac{1}{e^{hc/\lambda kT}-1}$$

Where;

B = specific intensity

h = Planck constant

λ = Wavelength

T = Temperature

k = Stefan Boltzmann const
= 5.67×10^{-8} (W/m^2K^4)

c = speed of light

This is called a Planck Curve. The distribution of power that a black body emits with varying frequency is described by Planck's law.

The temperature of a object alters the spectrum of the EM radiation as well as the intensity (think of a heated metal bar). Higher temperatures produce an increase in radiation at all frequencies. At any given temperature, there is a frequency fmax at which the power emitted is a maximum. You will not be expected to know this equation but you must be able to manipulate it.

Radiation Law 2 – Stefan's law

The total power radiated is determined by:

Black body radiation

$$\boxed{q = \sigma T^4 A}$$

Grey body radiation

$$\boxed{q = \varepsilon \sigma T^4 A}$$

Where:
q : total energy per unit time (W)
ε : emissivity
T : temperature (K)
A : Surface area of emitter (m^2)
σ : Stefan Boltzmann constant
5.67×10^{-8} Watts m^{-2} K^{-4}

Since power radiated 'q' is related to the fourth power of T, small increases in temperature lead to large increases in radiated power.

Emissivity varies between 0 and 1 (1 for black body). Grey body is where some of light is reflected (ie: not a perfect blackbody). We can take emissivity as constant over a limited wavelength range for 'greybody approximations'.

Numerical Example

Q: If the surface temperature of the sun is 5800 K, and if we assume that the sun can be regarded as a black body, what is the radiation energy per unit time per unit surface area?

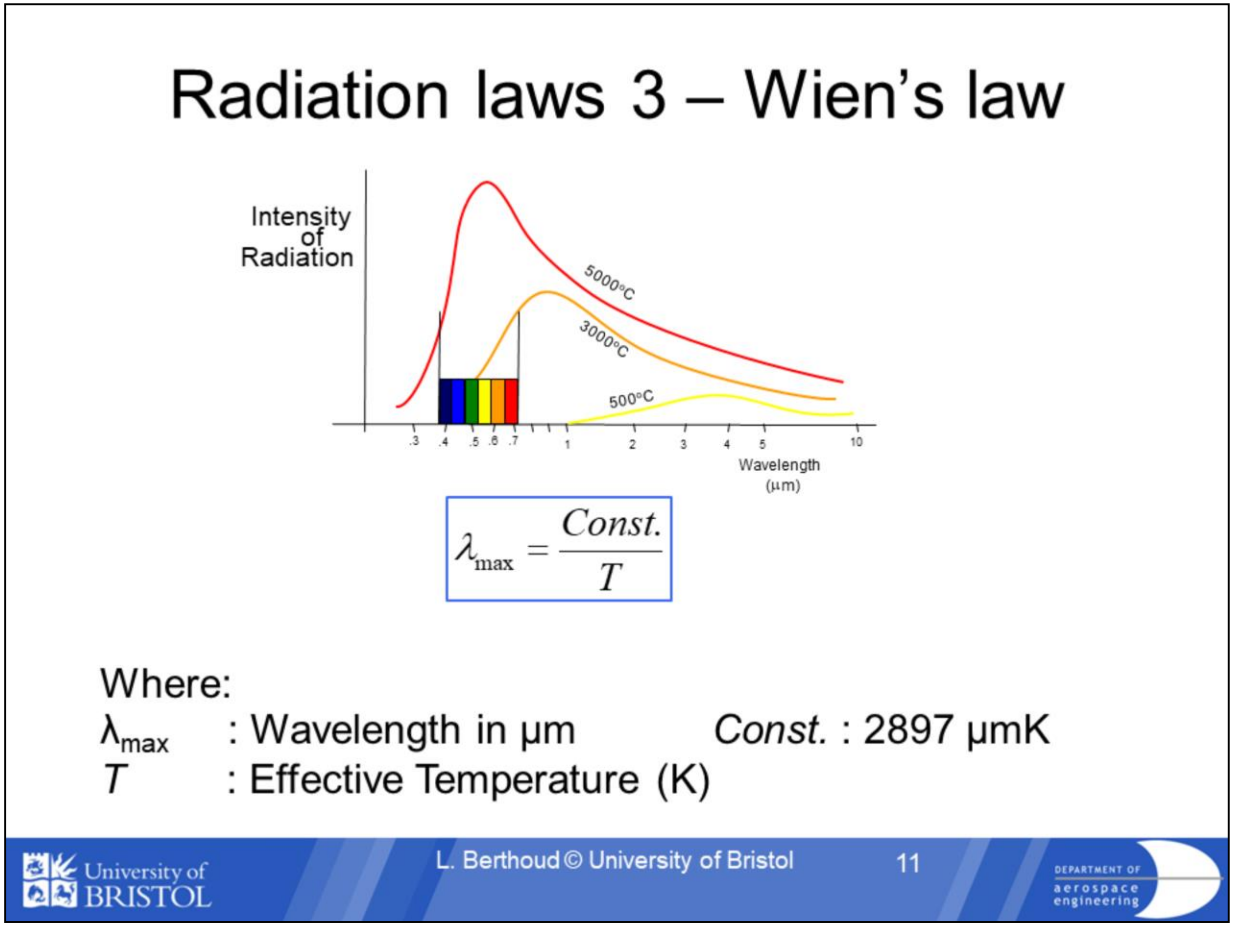
A: We can use Stefan's Law for black body radiation:

$q / A = \sigma T^4$

$= 5.67 \times 10^{-8} \times 5800^{4}$

$= 6.42 \times 10^{7}\ W/m^2$

Reminder that W=J/s



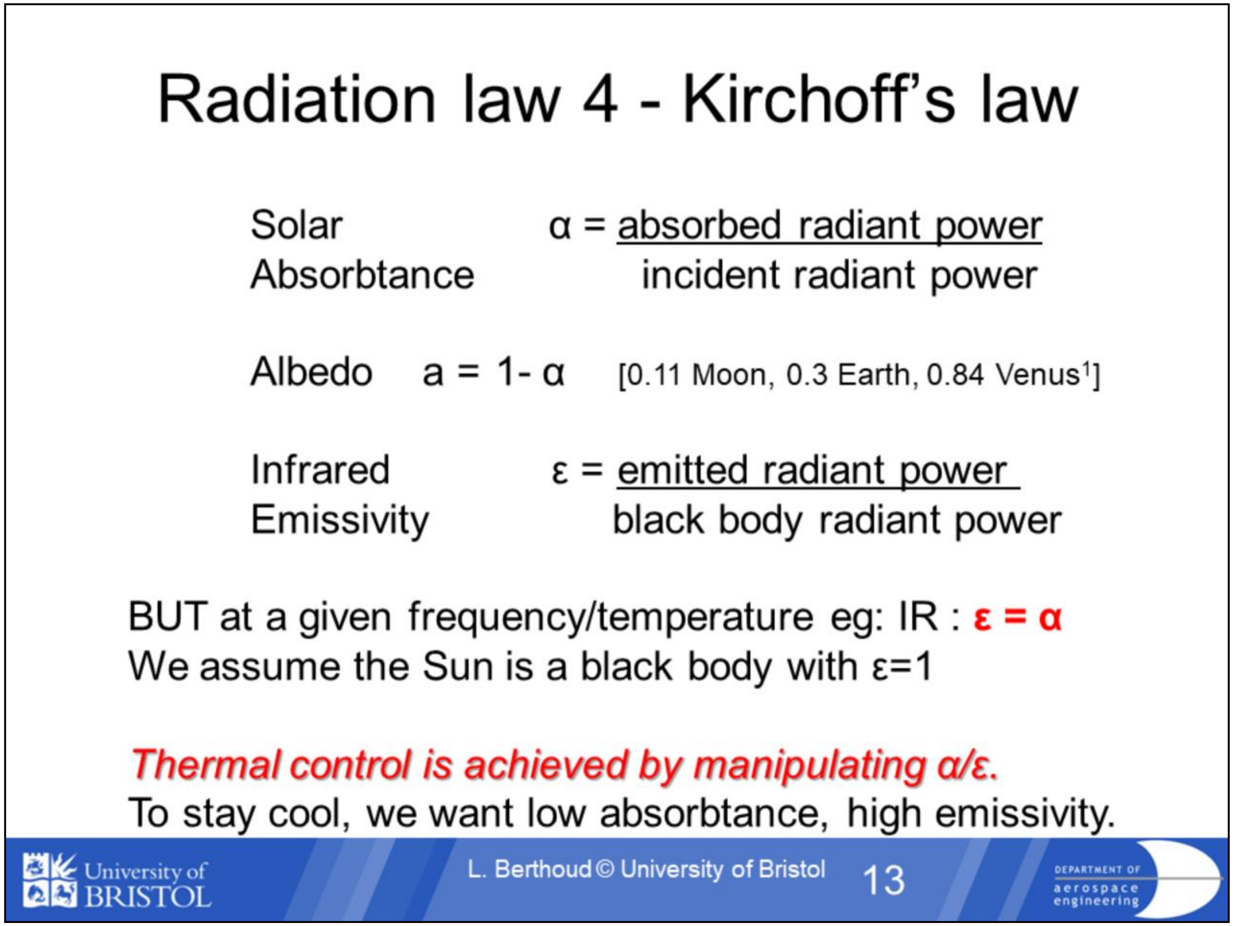
The third radiation law describes the wavelength of peak emission. This law describes the frequency at which most power is radiated. It can be seen that peak of the energy radiated by a body at the temperature of the sun falls within the visible light part of the spectrum.

Numerical Example

Q: What is peak emission wavelength for Saturn (effective Temp 95K)?

A: Using Wien's Law,

λ_{max} = 2897/95 = 30μm



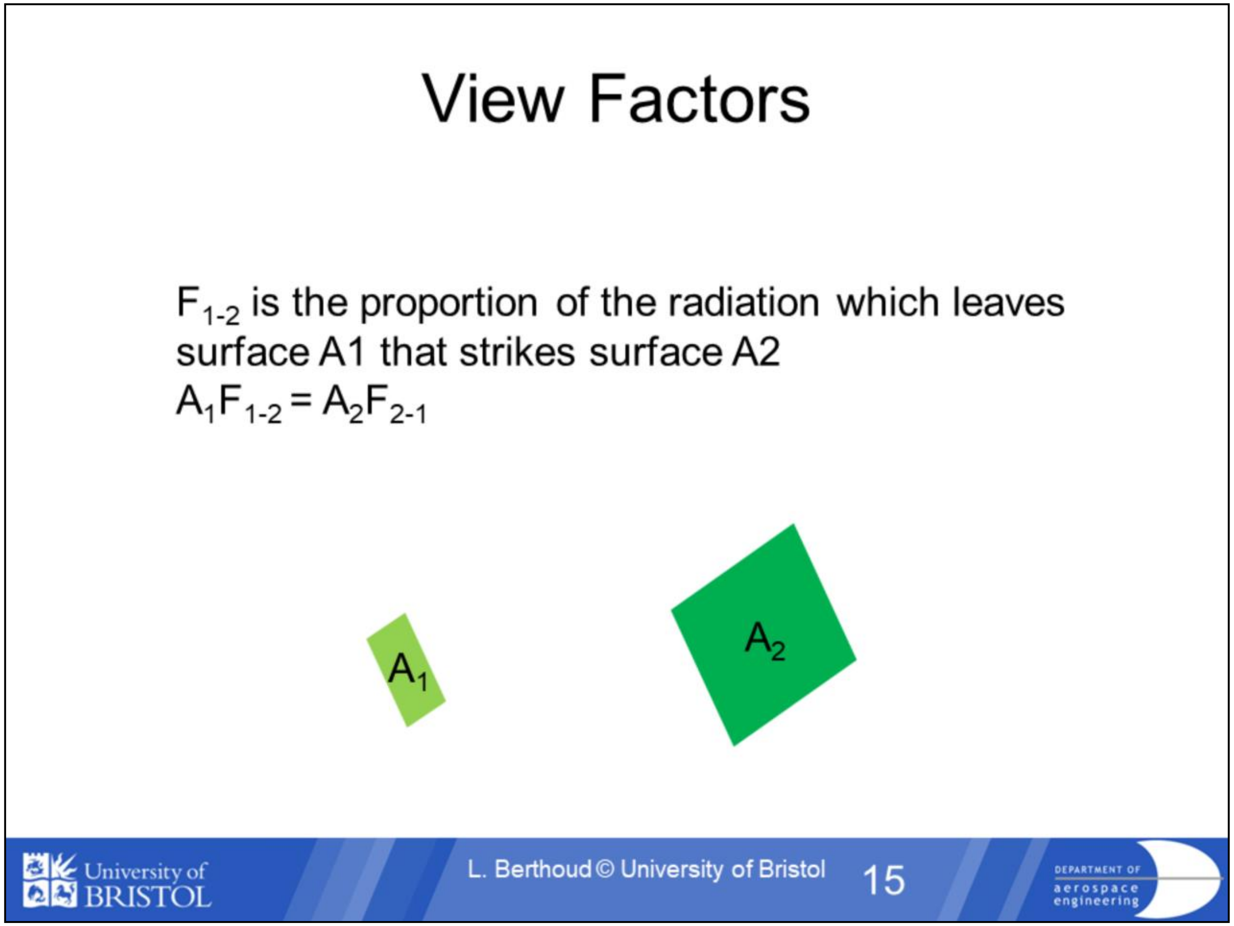
Kirchoff's law covers 3 key concepts: albedo, absorbtance and emittance. If spacecraft were black bodies then then would just radiate out all the energy they absorbed, however they *absorb in the visible* with α and *emit in the IR* with emissivity ε, so we can manipulate this ratio to do thermal control of the spacecraft. But Kirchoff's law says that for each particular frequency then ε = α. So for IR absorbtance we use ε instead of the usual solar radiation α (peak intensity at 500nm).

Example values for α, ε

	α	ε	α/ε
White paint	0.20	0.90	0.22
Black paint	0.95	0.90	1.05
Aluminium (unpolished)	0.25	0.25	1.00
Aluminium (polished)	0.20	0.05	4.00
Gold	0.25	0.05	5.00
Graphite epoxy	0.95	0.75	1.25
Glass fibre	0.90	0.90	1.00
Aluminized kapton	0.50	0.60	0.83
Optical solar reflector	0.08	0.80	0.10
Second surface mirror	0.15	0.80	0.19
Solar cells, Si, filtered	0.80	0.90	0.90

Which material would you use to gain heat? To cool?

To cool: OSR. To gain heat: gold. Average and overall absorptivity and emissivity data are often given for materials with values which *differ* from each other. For example, white paint is quoted as having an absorptivity of 0.2, while having an emissivity of 0.90. This is because the absorptivity is averaged with weighting for the solar spectrum, while the emissivity is weighted for the emission of the paint itself at normal ambient temperatures.



The view factor is what one surface sees of the other. Ie: if you look from A2, how much of the radiation from A1 is visible?

View factors are a function of the size, geometry, relative position, and orientation of two surfaces and are often calculated by computer models as they involve complex geometry.

h= altitude,
R= radius of Earth

View factor values will be quoted in an exam

View Factors

From spherical geometry, View factor $F_{\text{Earth to spherical spacecraft}}$:

$$F_{planet-sc} = 0.5\left[1 - \frac{(h^2 + 2hR)^{0.5}}{h + R}\right]$$

$$= 0.5\left[1 - \frac{(1000^2+2.1000.6378)^{0.5}}{7378}\right] = 0.25$$

View factor $F_{\text{Earth to flat panel}}$:

$$F_{planet-sc} = \frac{4\pi R^2}{4\pi(h + R)^2}$$

$$= \frac{6378^2}{(1000+6378)^2} = 0.75$$

h is spacecraft altitude, R is radius of Earth. You do not need to understand these formulae which result from spherical geometry. You will not be expected to produce them in an exam.

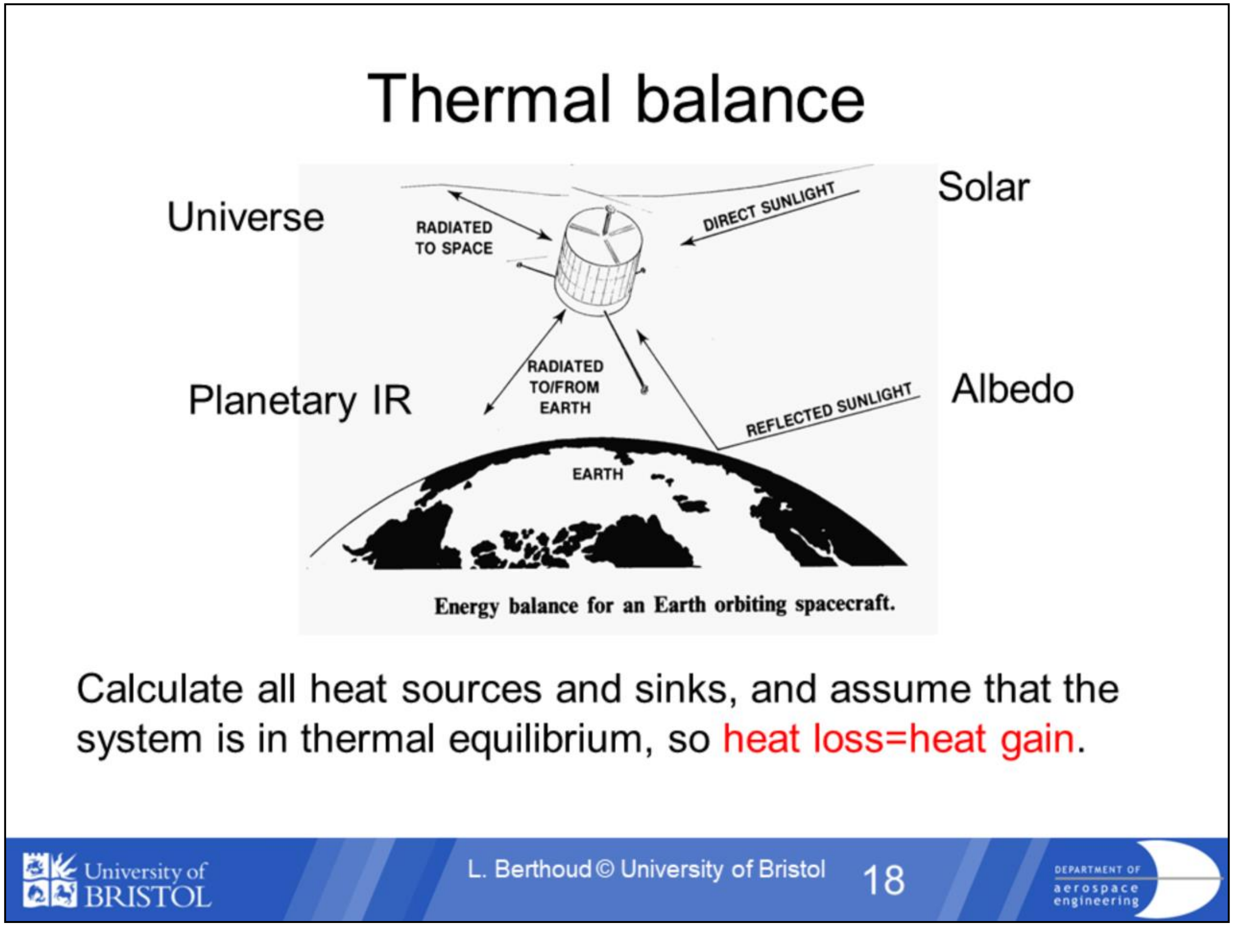
Radiation equation

$$q = \varepsilon_1 \, \varepsilon_2 \, \sigma \, F_{1\text{-}2} \, (T_1^4 - T_2^4) \, A \qquad (3)$$

Where:
q = heat transferred between two surfaces (W)
$F_{1\text{-}2}$=View Factor from surface 1 to surface 2
T_1 = hot body absolute temperature (K)
T_2 = cold surroundings absolute temperature (K)
A = emissive area of the object (m^2)

If one surface is Earth, assume ε=1 and T=250 to 260 K
If one surface is deep space, assume ε=1 and T=0 K

If a hot object is radiating energy to its cooler surroundings, the net radiation heat loss rate can be expressed as q. We assume that the Earth is a blackbody and so its emissivity is 1. Equally if we are doing a calculation to space then we can also assume emissivity is 1 but that the Temperature=0K.



In static conditions, a spacecraft will adjust its temperature so that its rate of heat loss by self-radiation is exactly balanced by its rate of gaining heat from all sources.

Thermal balance for spacecraft

Heat Loss

$$q = \varepsilon \sigma T^4 \mathrm{A}$$

=

Heat Gain:

a) Internal power dissipation from electronics, P
b) Direct solar input
c) Albedo input
d) Planetary thermal radiation input
e) Radiation from the rest of the Universe - *negligible*

Conservation of energy says that: in static conditions, a spacecraft will adjust its temperature so that its rate of heat loss by self-radiation is balanced by its rate of gaining heat from all sources. We will now go through these various terms, with the exception of the radiation from the rest of the Universe, which is so small it is considered negligible.

a) Internal power dissipation P

This is the power dissipated by the payload, electronics and other equipment (in W).

An instrument or equipment might be producing P power (in W) this is also absorbed by the spacecraft and included in the thermal balance

b) Direct Solar input

- At 1 AU from the Sun, the power incident on 1 m^2 normal to the radius vector to the Sun is the SOLAR CONSTANT 'S', 1370 Wm^{-2}.

- At 'd' AU, the incident power, 'G_s', is S/d^2 .

- When dealing with the absorbtion of heat fluxes, we use a projected Area, A_{proj}, which is the effective area when viewed from Sun.
- eg: for a spherical spacecraft: $A_s = 4\pi r^2$ (sphere)

$$A_{proj} = \pi r^2 \text{(disc)}$$

a) Power + b) Direct Solar input

The spacecraft with projected area A_{proj} and absorbtivity α, will absorb a total power q_a:

$$q_a = q_e = P + \alpha A_{proj}\frac{S}{d^2}$$

so… $$\varepsilon\sigma T^4 A_s = \mathrm{P} + \alpha A_{proj} G_s$$

Solving for T: $$T = \left[\frac{P+\alpha A_{proj} G_s}{\varepsilon\sigma A_s}\right]^{1/4}$$

Direct solar input ie: the amount of the Sun’s radiation absorbed directly by the spacecraft if it is in sunlight, is solar flux x projected area (as flux is W/m2) x absorbtance of the spacecraft.

Example:

A plane surface with ε=0.8 and α=0.15 is insulated on the back side and placed in space perpendicular to the solar vector. What would the temperature be?

For a plane surface: $A_{proj} = A_s$

$$T = \left(\frac{\alpha A_{proj} G_S}{\varepsilon \sigma A_s}\right)^{1/4}$$

Substituting in…

$$T = \left(\frac{0.15x1370}{0.8x5.67x10^{-8}}\right)^{1/4}$$

$$T = 259K$$

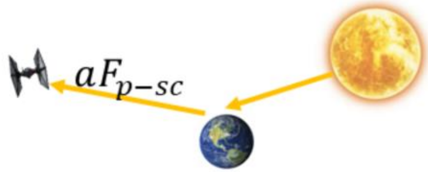
You can see that changing the ration alpha/eta will control the temperature of the plane surface. We do this by changing the material of the surface (see slide 14).

c) Earth Albedo

Albedo ‘a’ = 1-α [0.11 Moon, 0.3 Earth, 0.84 Venus[1]]

The spacecraft with area A, power P will absorb a total power:

$$q_a = P + \alpha A_{proj} \mathrm{G_s} + \alpha A_s \mathrm{G_s} a F_{p-sc}$$



F_{p-sc} : View factor from spacecraft to planet

a : albedo

1: de Pater, I. and Lissauer, J., Planetary Sciences, Cambridge University Press, 2001.

When near a planet or other large body the spacecraft will intercept a fraction of the reflected or albedo sunlight. Calculating the amount of reflected sunlight from the Earth becomes a little complicated visibility-wise so we switch to a view factor and As instead of using projected area.

d) Planetary IR radiation

First: q_{ir}= emitted energy flux at surface of Earth/m^2

[Assuming that for Earth $\varepsilon = 1$ and T=254K:

$$q_{ir} = \varepsilon\sigma T^4 = 1x5.67x10^{-8}x254^4 = 237 \text{ Wm}^{-2}]$$

So, IR flux at spacecraft altitude $G_{ir} = q_{ir}F_{p-sc}$

So the spacecraft will absorb: $q_{ir}F_{p-sc}\,\alpha_{IR}A_s$ planetary IR

The spacecraft will absorb a total power:

$$q_a = P + \alpha A_{proj}G_s + \alpha A_s G_s a F_{p-sc} + q_{ir}\,\varepsilon A_s F_{p-sc}$$

From Kirchoff’s law for a given frequency, ie: in the IR section of the spectrum, absorbtance =emissivity . So we use ‘ε’ instead of the usual solar radiation ‘α’ (peak intensity at 500nm) as ε is actually nearer to the IR absorbtance (see notes in slide 14).

Thermal balance

Solar Albedo Planet IR

$$\varepsilon\sigma T^4 A_e = P + \alpha A_{proj} G_s + \alpha A_s G_s a F_{p-sc} + q_{ir}\, \varepsilon A_s F_{p-sc}$$

To calculate Temperatures:

Hot case:	calculate temps in hottest conditions: all elements power P, solar, albedo, planet IR
Cold case:	calculate temps in coldest conditions eg: eclipse yes P (if on), no solar, no albedo, yes planet IR.

In thermal design, they always ask you to calculate the hot case and the cold case. This will be different for different phases of the mission. The worst hot and cold cases will determine the thermal design.

Example:

A <u>spherical</u> satellite with <u>ε=α</u> in geosynchronous orbit has a surface area of 10 m². Albedo and IR inputs can be neglected. Inside is a high power radar which produces 800W when off and 4000W when on. When its off, the spacecraft operates at a mean temperature of 300K. What is the equilibrium temperature when the radar is switched on?

$$\varepsilon\sigma T^4 A_s = P + \alpha A_{proj}\mathrm{G_s} + \alpha A_s \cancel{\mathrm{G_s} a F_{p-sc}} + q_{ir}\varepsilon \cancel{A_s F_{p-sc}}$$

$$\varepsilon\sigma T^4 A_s = P + \alpha A_{proj}\ \mathrm{G_s}$$

$$A_s = 4\pi r^2 = 10, \qquad and\ A_{proj} = \pi r^2 = \frac{10}{4} = 2.5$$

$$\varepsilon. 5.67. 10^{-8}. 300^4. 10 = 800 + \varepsilon. 2.5. \frac{1370}{1}$$

$$\varepsilon = 0.69$$

Switch on radar:

$$0.69.\ 5.67. 10^{-8}. T^4. 10 = 4000 + 0.69\ 2.5. 1370$$

$$\boldsymbol{T = 357K}$$

The area for the emission ‘As’ will be the surface of a sphere ($4\pi r^2$), as the whole sphere is emitting heat. To overcome the difficulty posed by the fact that the planets are spherical and their surface tilts with respect to the incoming radiation, note that the amount distributed over the sphere is equal to the amount that would be collected on the planets surface if it was a disk placed perpendicular to the sunlight (πr^2).

Space radiator

To estimate the size of a radiator:

- If solar vector is not normal to the surface we need to put in cosine factor: cosθ
- Assume Earth orbit (so d^2=1).
- With radiator, A_{proj}=A_s, so we can divide through by A_s

$$\varepsilon\sigma A_s T^4 = Q_w + P + \alpha . A_{proj} \mathrm{G_s} . \cos\theta + \alpha A_s \mathrm{G_s} a F_{sc-p} + q_{ir} \varepsilon A_s F_{sc-p}$$

Q_w	*Waste heat rejected by radiator (W)*
T	*Operation temperature of radiator (K)*
θ	*Angle between surface normal and solar vector*
A_s	*Area of radiator (m²)*

A space radiator is a way of dumping/rejecting unwanted heat on a spacecraft. Note that we can divide through by area, as in the case of a radiator, the surface area As=projected area Aproj.

Reading

Read to find answers to the following:

1. What is the difference between active and passive thermal control?
2. What means do we have for active and passive thermal control?

Ecopy on SS2 BB site:

pp. 375-386 of '*Spacecraft Systems Engineering*' by Fortescue P., Swinerd G. and Stark J. 4th edition, Pub. Wiley and Sons, Chichester. 2011.

Summary

1. Thermal control is needed to keep temps within limits
2. Fourier's law: $Q_x = -k.A.\frac{dT}{dx}$
3. Wien's law: $\lambda_{\max} = \frac{Const.}{T}$
4. Heat loss=heat gain

$$\varepsilon\sigma T^4 A_e = P + \alpha A_{proj}\mathrm{G_s} + \alpha A_s \mathrm{G_s} a F_{sc-p} + \mathrm{q_{ir}}\, \varepsilon A_s F_{sc-p}$$

5. *Describe difference between active and passive thermal control*
6. *Be able to describe means for active and passive thermal control.*

Test Yourself! (Feedback)

1. What is the function of the thermal subsystem on a spacecraft?
2. Calculate the heat transfer through an aluminium (k=201W/mK) spacecraft wall which is 1mx1m wide and 1cm thick, if the surface temps are 20°C and -100°C.
3. If you double the temperature of an object, how much more radiation will it emit?
4. The star Betelgeuse has a surface temperature of 3250 K, what is the peak wavelength and what colour would it be?
5. Neglecting albedo and IR inputs, for a temperature of 300K, what would the size of a LEO spacecraft radiator (e=0.8 and a=0.15) be to reject 100W? Assume the Sun points directly at it. What difference will it makes if it faces deep space?