SO, SYSTEMS ARE RARELY INSULATED...

HEAT MIGRATES...

conduction	}	TRANSFER MECHANISMS
convection		
radiation		

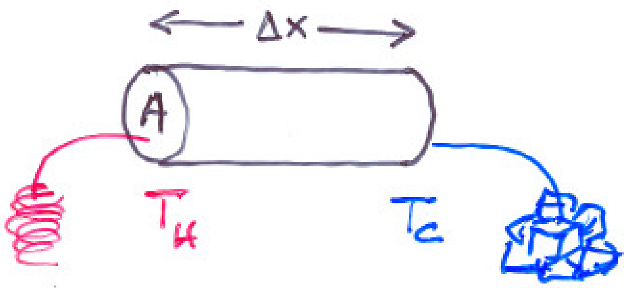
EVERYWHERE YOU ARE...

CONDUCTION

A HAND-OFF MECHANISM

- atoms of adjacent — touching — media move, rotate, and/or vibrate
- they collide and transmit these motions

  the energy moves... not typically the atoms
- atoms within one medium, or between dissimilar, adjacent media



AFTER SOME TRANSIENT EFFECTS.. STEADY STATE SETTLES IN

$$H = \frac{\Delta Q}{\Delta t} = kA\frac{\Delta T}{\Delta x} = \frac{kA(T_H - T_c)}{\Delta x}$$

heat conduction rate... J/s, cal/s
"
Watts

"THERMAL CONDUCTIVITY"
W/m·K

material	κ (W/m·K)
stainless steel	14
lead	35
copper	401
fiberglass	0.048
white pine	0.11
window glass	1.0
air (dry)	0.026
He	0.15
H_2	0.18

Sometimes see "thermal current", $I_T = \frac{\Delta Q}{\Delta t}$

$$\Delta T = I_T \frac{\Delta x}{KA}$$

$$\Delta T = I_T R$$

R: THERMAL RESISTANCE

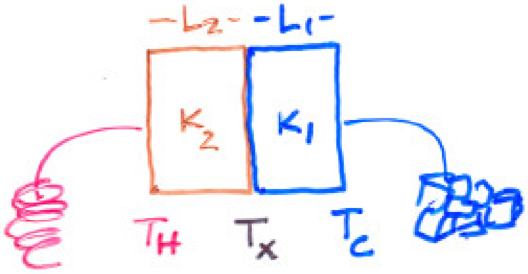
$$R = \frac{\Delta x}{K}$$

like Ohm's Law

$$\Delta T = \frac{R}{A} I_T$$

(sometimes $R = \frac{\Delta x}{AK}$)

Composite SLABS.



like series resistors...

ΔQ same through both

$$H = \frac{\Delta Q}{\Delta t} = \frac{K_2 A (T_H - T_x)}{L_2} = \frac{K_1 A (T_x - T_c)}{L_1}$$

$$T_x = \frac{K_1 L_2 T_c + K_2 L_1 T_H}{K_1 L_2 + K_2 L_1}$$

substituting...

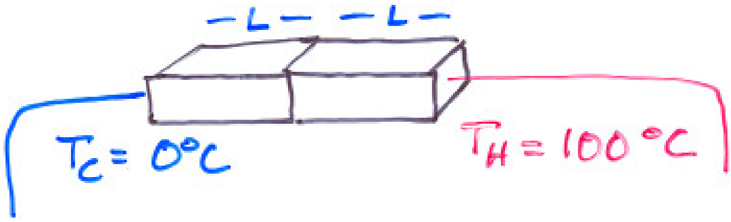
$$H = \frac{\Delta Q}{\Delta t} = \frac{A(T_H - T_C)}{L_1/K_1 + L_2/K_2}$$

so, since $R_1 = L_1/K_1$ & $R_2 = L_2/K_2$

$$\frac{\Delta Q}{\Delta t} = \frac{A(T_H - T_C)}{R_1 + R_2}$$

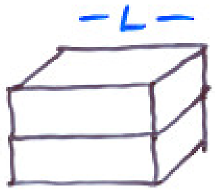
$$\Delta T = \frac{(R_1 + R_2)}{A} I_T$$

Problem 88P. Two identical slabs welded together like



A.

or like



B.

$T_C = 0°C$ $T_H = 100°C$

10 J of heat is conducted in ~~20~~ TWO min in situation A.
How long to conduct same heat in situation B?

$$H_A = \frac{\Delta Q}{\Delta t} = \frac{10\,J}{120\,s} = 0.08\,W = 80\,mW$$

$$H_A = \frac{A\,\Delta T}{R_1 + R_2} = \frac{A\,\Delta T}{2R} = \frac{\Delta Q}{\Delta t_A}$$

$$H_B = \frac{2A\,\Delta T}{R} = \frac{\Delta Q}{\Delta t_B}$$

$$\Delta t_B = \frac{\Delta Q\, R}{2A\,\Delta T}$$

$$\Delta t_B = \underbrace{\left(\frac{A\,\Delta T\,\Delta t_A}{2R}\right)}_{Q} \frac{R}{2A\,\Delta T} = \frac{\Delta t_A}{4} = \frac{2}{4} = 0.5\ \text{min}$$

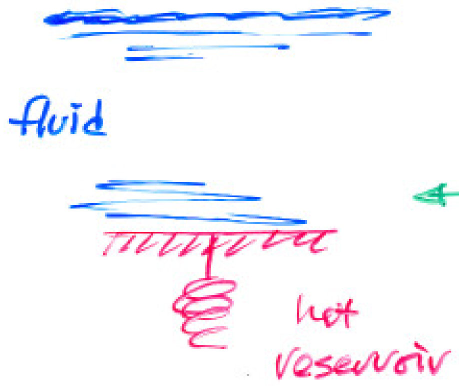
CONVECTION

STUFF MOVES... the material of the medium itself transports within

⇒ A FLUID... gas or liquid

mathematics beyond this course...

IN A NUTSHELL :

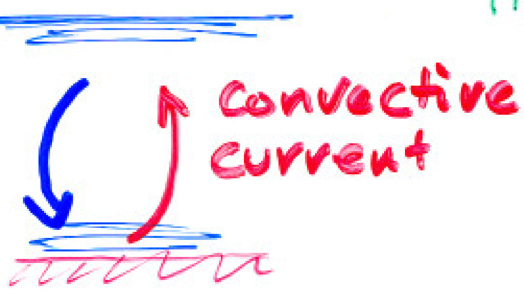


← temperature increases; becomes less dense;

so, it rises;

&

surrounding fluid (cooler) takes its place...



- fireplace
- climate – why Britain's not frozen
- atmosphere H & L
- solar convection

RADIATION

ELECTROMAGNETIC RADIATION

"THERMAL RADIATION"

ALL BODIES RADIATE E & M WAVES.

RATE AT WHICH A BODY RADIATES $\propto A$ & T^4

P_R power radiated.. energy per unit time.

$P_R \propto (\text{details of surface})\, A T^4$

$P_R = \sigma \varepsilon A T^4$ Stefan-Boltzmann Law

σ: Stefan-Boltzmann constant

$\sigma = 5.6703 \times 10^{-8} \frac{W}{m^2 K^4}$

ε is "emissivity" of the surface

$0 \leq \varepsilon \leq 1$

$\varepsilon = 1$ called a Blackbody radiator

surface can reflect

$\varepsilon = 1$ means no reflection, only absorption

all attempts failed

There were a number of attempts at an explanation:

a relatively ad hoc suggestion by Wein, which had a shape which could be fit to data with unphysical parameters that had to come from the data...reasonable, except at long wavelengths

experiments were very precise by 1900...

$$u(T,\lambda) = (c_1/\lambda^{\alpha})e^{\left(-\frac{c_2}{\lambda T}\right)}$$

Raleigh and Jeans - the most physically motivated model:

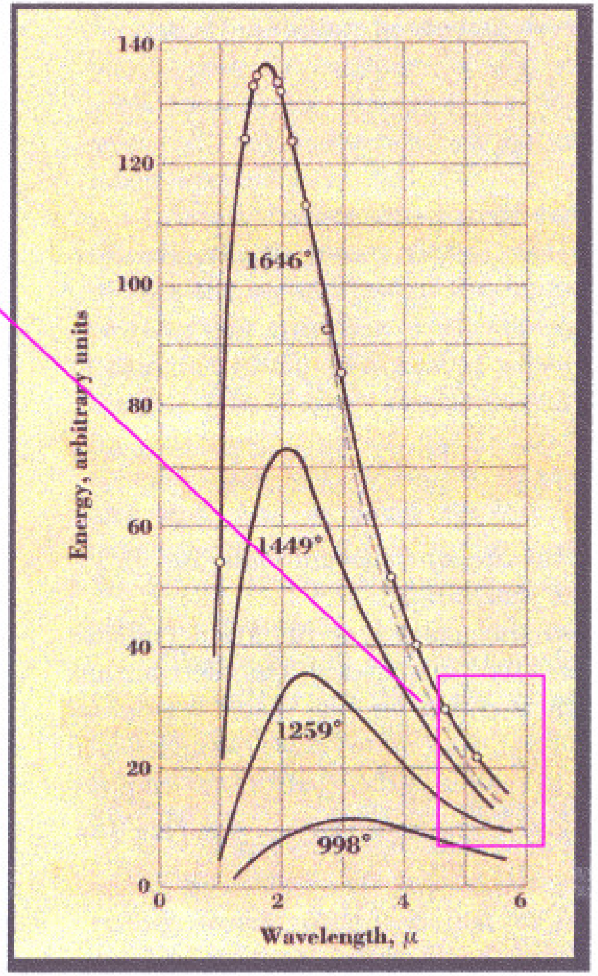
...oscillators in the wall of a black body absorb and emit E&M radiation

Each oscillator has its own characteristic frequency, which when they are close together appear continuously distributed

$U = 8\pi kT/\lambda^4$ ...was their prediction.

nobody could see anything wrong with the reasoning

the only problem was that it didn't fit at all - notice that at small wavelengths this formula blows up: the Ultraviolet Catastrophe was what this disaster was called - after all, there's no limit to the frequencies at which these oscillators may vibrate.



stay tuned

Surprise #9

a black eye

There were other EM issues

in particular, there was a lack of understanding of thermal radiation

a “blackbody” is an object which has reached an equilibrium in temperature

the first consideration of this sort of radiation was by Kirchhoff who named it…

imagine an oven, heated from the outside…

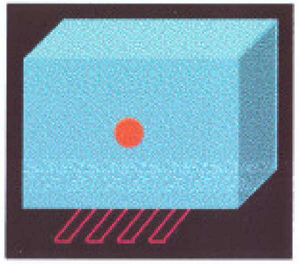
radiation which is continuous (not discrete) rattles around inside continuously absorbed and re-emitted from the interior walls - at all wavelengths

Suppose a small hole is made…any EM waves that are incident on the hole will be absorbed, not to be re-emitted - that’s why he called it a blackbody

However, radiation is emitted…and the intensity of the wavelengths was found experimentally to depend **only on the temperature**, *not the material*, nor the way it was heated

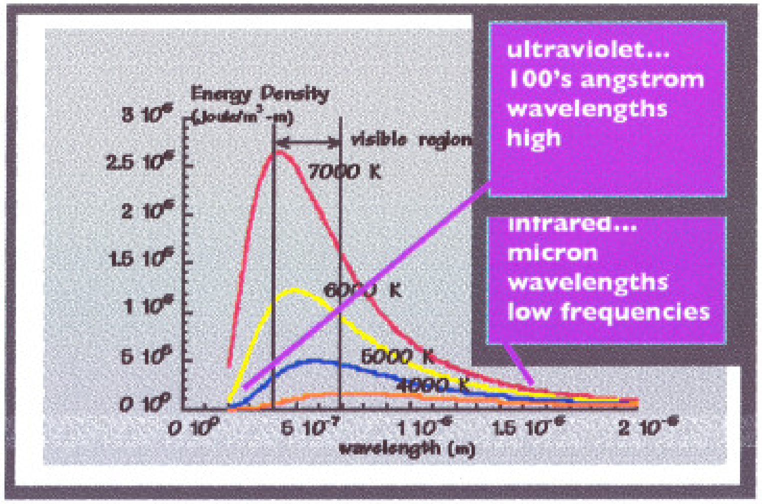
makers of china and fine knives and swords knew this - Wedgewood had a calibrated “thermometer” based on color

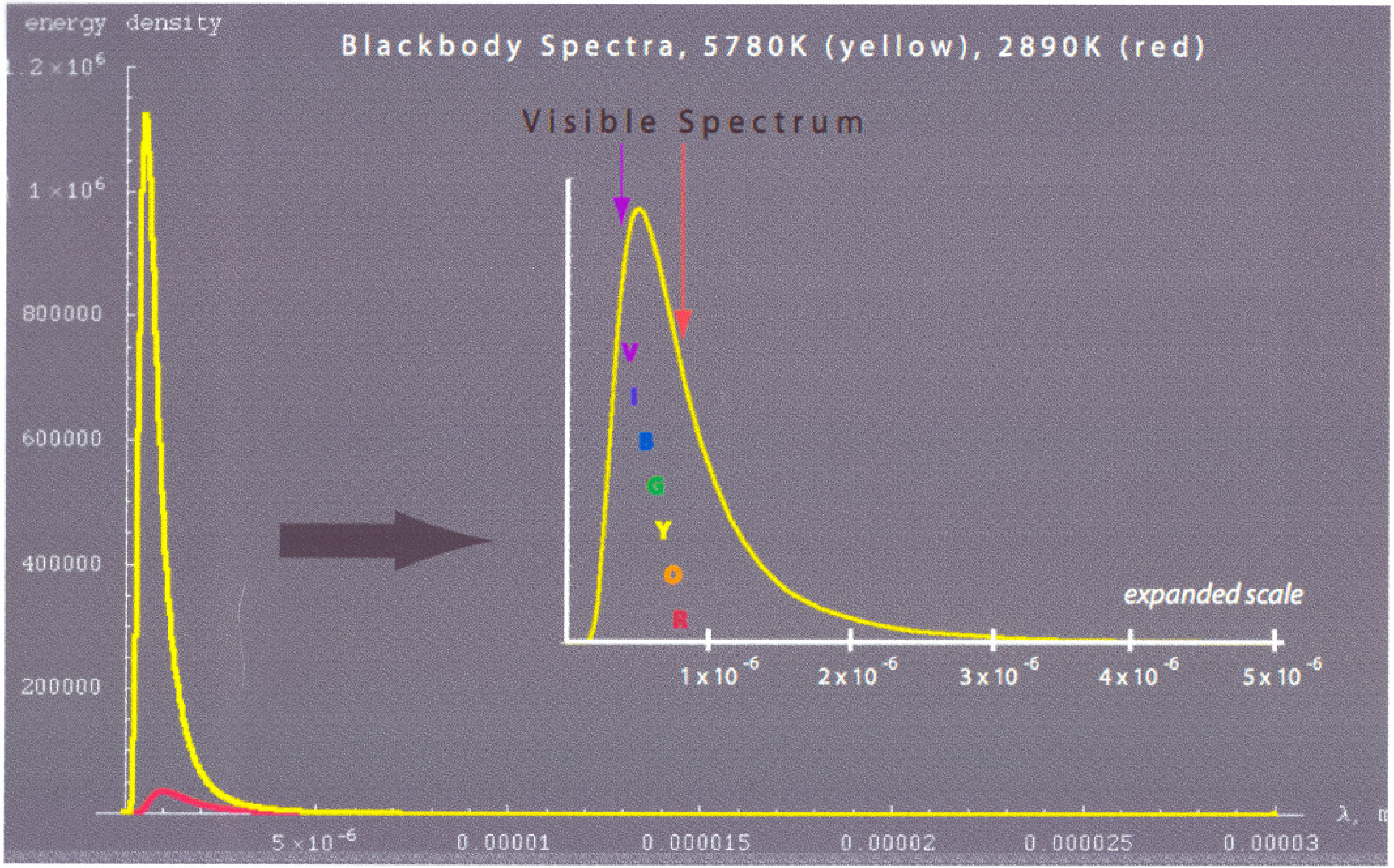
This, then, was a universal phenomenon - there must be a significant physical explanation…but nobody could find one

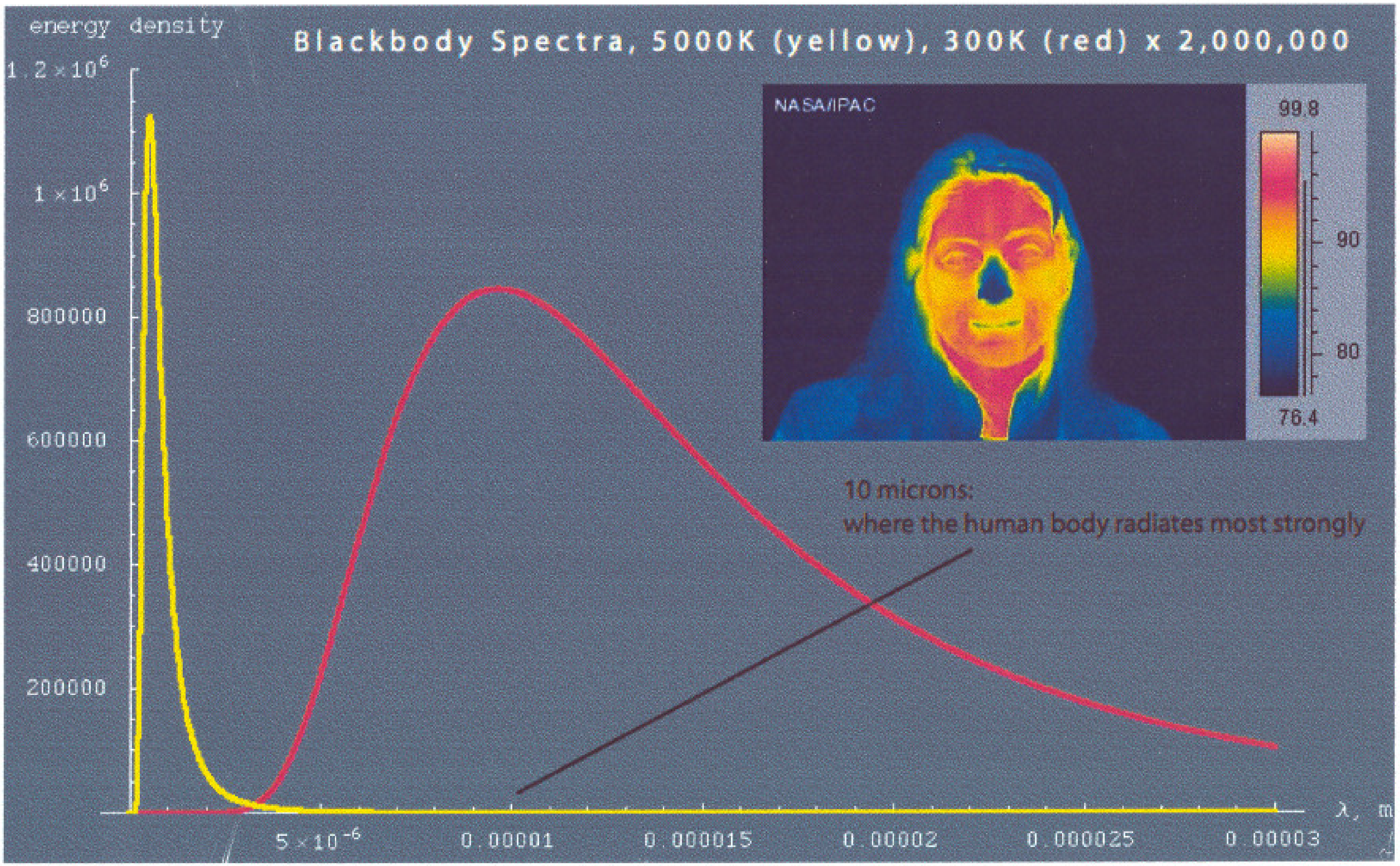


many common radiators are pretty good blackbodies…your body, for example.

The Sun, why is it yellow? Because its surface is about 6000K:




energy density
Blackbody Spectra, 5780K (yellow), 2890K (red)
Visible Spectrum
V
I
B
G
Y
O
R
expanded scale
1.2 × 10^6
1 × 10^6
800000
600000
400000
200000
5 × 10^-6
0.00001
0.000015
0.00002
0.000025
0.00003
λ, m
1 x 10^-6
2 x 10^-6
3 x 10^-6
4 x 10^-6
5 x 10^-6


Blackbody Spectra, 5000K (yellow), 300K (red) x 2,000,000
energy density
1.2 × 10^6
1 × 10^6
800000
600000
400000
200000
5 × 10^-6
0.00001
0.000015
0.00002
0.000025
0.00003
λ, m
NASA/IPAC
99.8
90
80
76.4
10 microns:
where the human body radiates most strongly