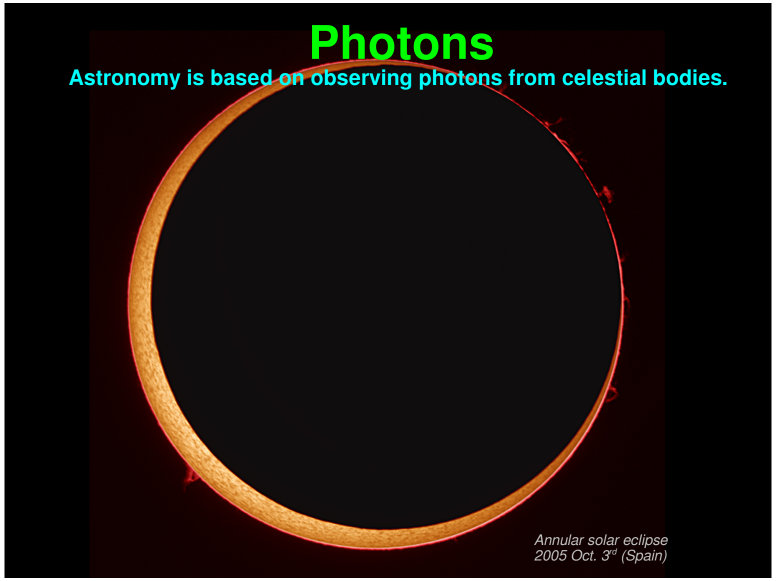


Astronomy is based on observing photons from celestial bodies.

We obtain information on temperature,
density,
chemical composition
....

How?

This lecture
1) diffusion and random walk
2) blackbody and temperature
3) Photosphere of the Sun

next lecture
4) stellar spectrum
5) atomic & molecular transitions
6) equation of radiative transport

1) Heat escapes from the Sun as photons

2) The journey from the centre to the surface

---- What happens if photons can travel freely from solar center to us?
$t_{cross} \sim R_\odot/c \sim 2$ sec? (neutrinos do...)

---- Actual travelling time ~ 10^7 yrs:

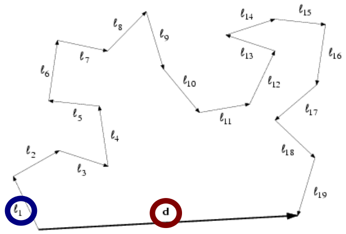
On the way, photons encounter many obstacles;
this causes them to lose energy (downgrade in frequency)
& to multiply in number, and it takes a **long** time to get out
Centre: keV photons surface: eV photons

random walk

Random Walk

'photon mean free path' l_{mfp}

1) l_{mfp} --- distance between obstacles;
2) Photon changes direction randomly after encountering an obstacle;
3) d: net distance traveled



$$|l_i| = l_{mfp} \qquad d = \sum_{i=1}^{N} l_i$$

$$d \cdot d = \sum_{i=1}^{N} l_i \cdot l_i + \sum_{i \neq j} l_i \cdot l_j$$

$$d^2 = N l_{mfp}^2 + l_{mfp}^2 (\cos\theta_{12} + \cos\theta_{13} + ...)$$

$$= (N + N(N-1)\langle\cos\theta\rangle) l_{mfp}^2 \approx N l_{mfp}^2$$

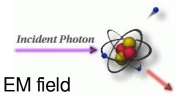
$$\rightarrow d \approx \sqrt{N}\ l_{mfp}$$

So the travel time for the distance d is

$$= \frac{d}{c} \qquad \text{if } l_{mfp} \geq d$$

$$= N\frac{l_{mfp}}{c} = \frac{d^2}{l_{mfp} c} \qquad \text{if } l_{mfp} < d$$

What is an obstacle
(Or: how does a photon interact with matter)?



1) Photon A (an electro-magnetic wave) generates an oscillating EM field
2) matter (e^-, ions, atoms, molecules) is shaken by this fluctuating EM field (absorption of the photon A)
3) Their shaking is itself an fluctuating field, and this radiates EM wave – photon B

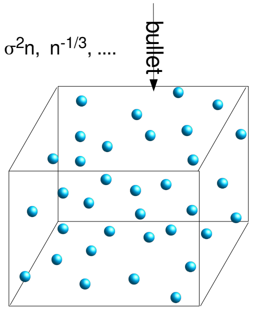
3 types of obstacles

Scattering	A & B are equal in frequency but differ in direction --- matter absorbs momentum but hardly any energy ($h\nu/m_e c^2$) --- photon loses hardly any energy but changes in direction
Absorption	no B is radiated --- matter absorbs energy, something happens to it
Emission	sometimes matter decides to emit B (when or when not A) --- reverse of absorption

Suppose each obstacle has a cross-sectional area of σ (m^2)
number density n (m^{-3})

How large is l_{mfp}?

1) Dimensional analysis: l_{mfp} [m]: $1/(n\sigma)$, $\sigma^2 n$, $n^{-1/3}$, ...
2) Physical argument:
   photon = bullet
   obstacles = balloons on a wall
   wall has area A, will hit one
   if $N\sigma = A$, where $N = n\,l\,A$
   so $l_{mfp} = 1/(n\sigma)$



3) How big are the balloons inside a star?
   σ lies between 10^{-28} m^2 (size of e^-)
   and 10^{-20} m^2 (size of H atom)
   $n \sim 10^{30}$ m^{-3} if $\rho = 10^3$ kg/m³
   l_{mfp} ~10^{-10} m – 10^{-2} m (<< $R_\odot \sim 10^9$ m)
   If l_{mfp} ~10^{-2} m ---> $t_{diffusion} \sim R_\odot^2/l_{mfp}c \sim 5000$ years [$N \sim (R_\odot/l_{mfp})^2 \sim 10^{22}$]
   If l_{mfp} ~10^{-10} m ---> $t_{diffusion} \sim R_\odot^2/l_{mfp}c \sim 5\times10^{11}$ years [$N \sim (R_\odot/l_{mfp})^2 \sim 10^{38}$]

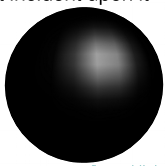
Actual diffusion time across the Sun ~ 10^7 yr

Note: if diffusion is too slow, strong temperature gradients build up, which lead to convection.

What is 'temperature' of radiation?

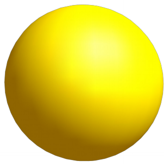
Temperature is defined for an ideal body (black body):
which radiates a universal spectrum of light
– blackbody radiation –
that depends only on the 'temperature'
(independent of material property, environment,...)

To do so, it must absorb all light incident upon it --- 'black'



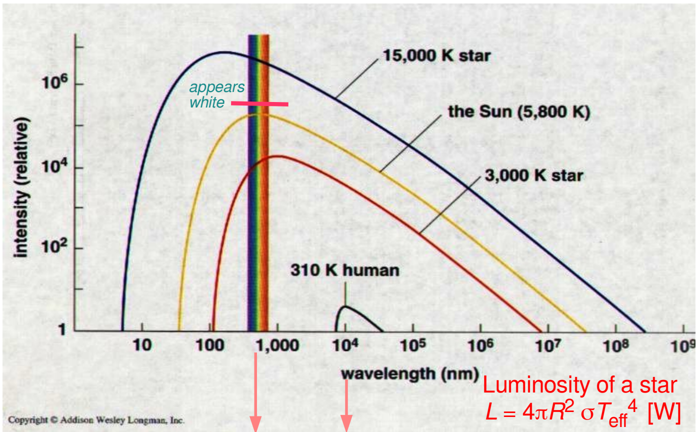
"guarantee no reflected light pollutes the blackbody signal"

but its own radiation has a 'color'



Universal Radiation of a blackbody (only depends on T)

1) blackbody peak at $\lambda = 0.0029/T$ [m], color of things..
2) radiation flux $F = \sigma T^4$ [W/m²], brightness of things...

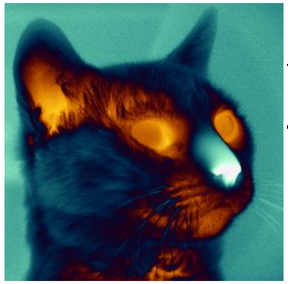


Luminosity of a star
$L = 4\pi R^2 \sigma T_{eff}^4$ [W]

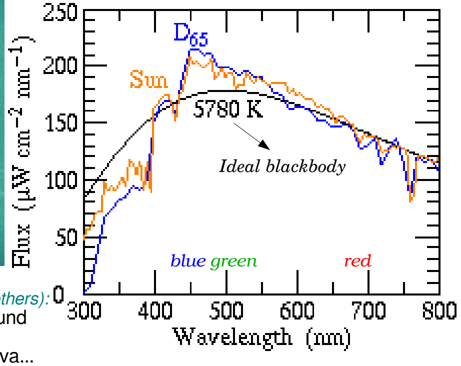
Optical (visible)

10 μm infrared

A cat as a black-body
(seen in infrared)



The solar surface as a blackbody (visible)
Effective temperature T_{eff} = 5780 K



http://casa.colorado.edu/~ajsh/colour/Tspectrum.html

Examples *(some more perfect than others)*:
- 3K cosmic microwave background
- surface/interior of a star,
- human skin, candle, volcanic lava...

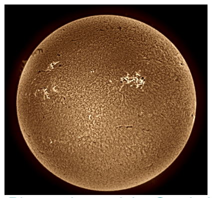
counter-examples:
- neon lights, fluorescent bulbs...


NGC 2266 star cluster

Where is the "surface" of a star at which we measure T_{eff}?

The **photosphere**

--> Outermost layer where photons can escape freely without further interaction (photons have just one last mean-free-path)
This is the layer where stellar conditions are last imprinted on the photons


Photosphere of the Sun in Hα

$$l_{mfp} \sim \frac{1}{n\sigma} \sim \text{ pressure scale height } H$$

$$\text{where } n = \frac{\rho}{\mu m_H}, \quad (\rho \text{ is gas density})$$

$$\text{Hydrostatic equilibrium: } \frac{dP}{dr} = -g\rho$$

$$H \sim \left(\frac{1}{P}\frac{dP}{dr}\right)^{-1} \sim \frac{P}{g\rho}$$

$$\text{At photosphere: } P \sim g\rho H \sim \frac{g\rho}{n\sigma} \sim \frac{g\mu m_H}{\sigma}$$

$$P \sim 10^7\, N\, m^{-2} \quad \text{for the Sun}$$