# Photons

**Astronomy is based on observing photons from celestial bodies.**

*Annular solar eclipse*
*2005 Oct. 3rd (Spain)*

**Astronomy is based on observing photons from celestial bodies.**

We obtain information on temperature,<br>density,<br>chemical composition<br>....

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 $\sim 10^7$ yrs:

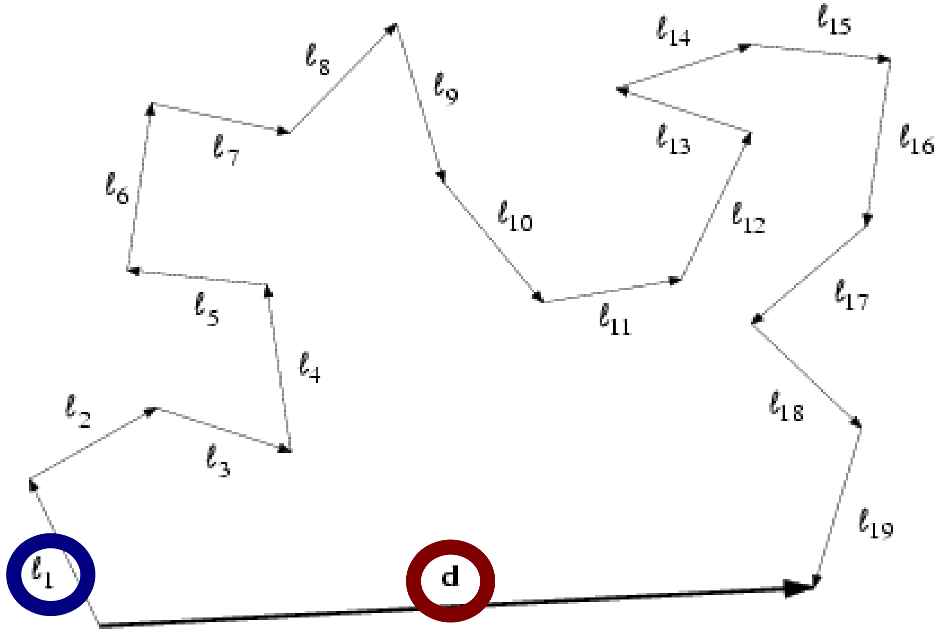
On the way, photons encounter many obstacles;
this causes them to lose energy (downgrade in frequency)
& to multiply in number, and it takes a **long** time to get out
Centre: keV photons surface: eV photons

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*




$$|\boldsymbol{l}_i| = l_{mfp} \qquad \boldsymbol{d} = \sum_{i=1}^{N} \boldsymbol{l}_i$$

$$\boldsymbol{d}\cdot\boldsymbol{d} = \sum_{i=1}^{N} \boldsymbol{l}_i\cdot\boldsymbol{l}_i + \sum_{i\neq j} \boldsymbol{l}_i\cdot\boldsymbol{l}_j$$

$$d^2 = N\,l_{mfp}^{\;2} + l_{mfp}^{\;2}\left(\cos\theta_{12} + \cos\theta_{13} + ....\right)$$
$$= \left(N + N(N-1)\langle\cos\theta\rangle\right) l_{mfp}^{\;2} \approx N\,l_{mfp}^{\;2}$$

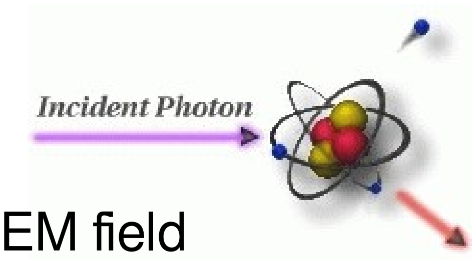
$$\rightarrow \boxed{d \approx \sqrt{N}\;\; l_{mfp}}$$

So the travel time for the distance d is

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

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

## 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

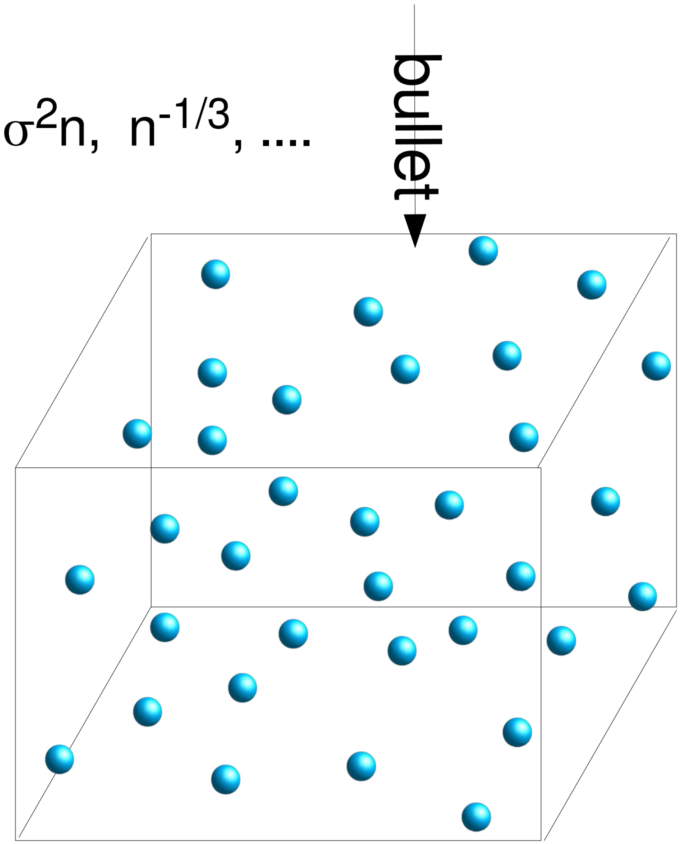
| | |
|---|---|
| Scattering | A & B are equal in frequency but differ in direction<br>--- matter absorbs momentum but hardly any energy ($h\nu/m_ec^2$)<br>--- photon loses hardly any energy but changes in direction |
| Absorption | no B is radiated<br>--- matter absorbs energy, something happens to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

Suppose each obstacle has a cross-sectional area of $\sigma$ ($m^2$)
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?
   $\sigma$ 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/m$^3$
   $l_{mfp}$ $\sim 10^{-10}$ m – $10^{-2}$ m ($\ll R_\odot \sim 10^9$ m)
   If $l_{mfp} \sim 10^{-2}$ m ---> $t_{\mathrm{diffusion}} \sim R_\odot^2/l_{mfp}c \sim$ 5000 years [$N \sim (R_\odot/l_{mfp})^2 \sim 10^{22}$]
   If $l_{mfp} \sim 10^{-10}$ m ---> $t_{\mathrm{diffusion}} \sim R_\odot^2/l_{mfp}c \sim 5\times10^{11}$ 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.

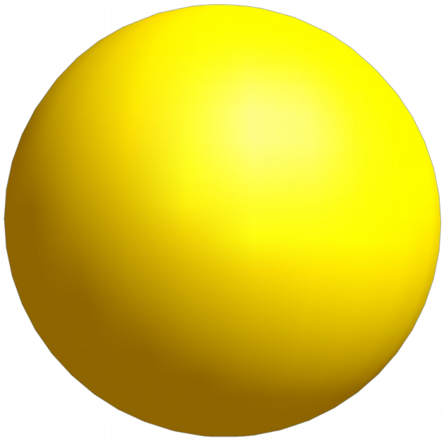
# What is 'temperature' of radiation?

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"*

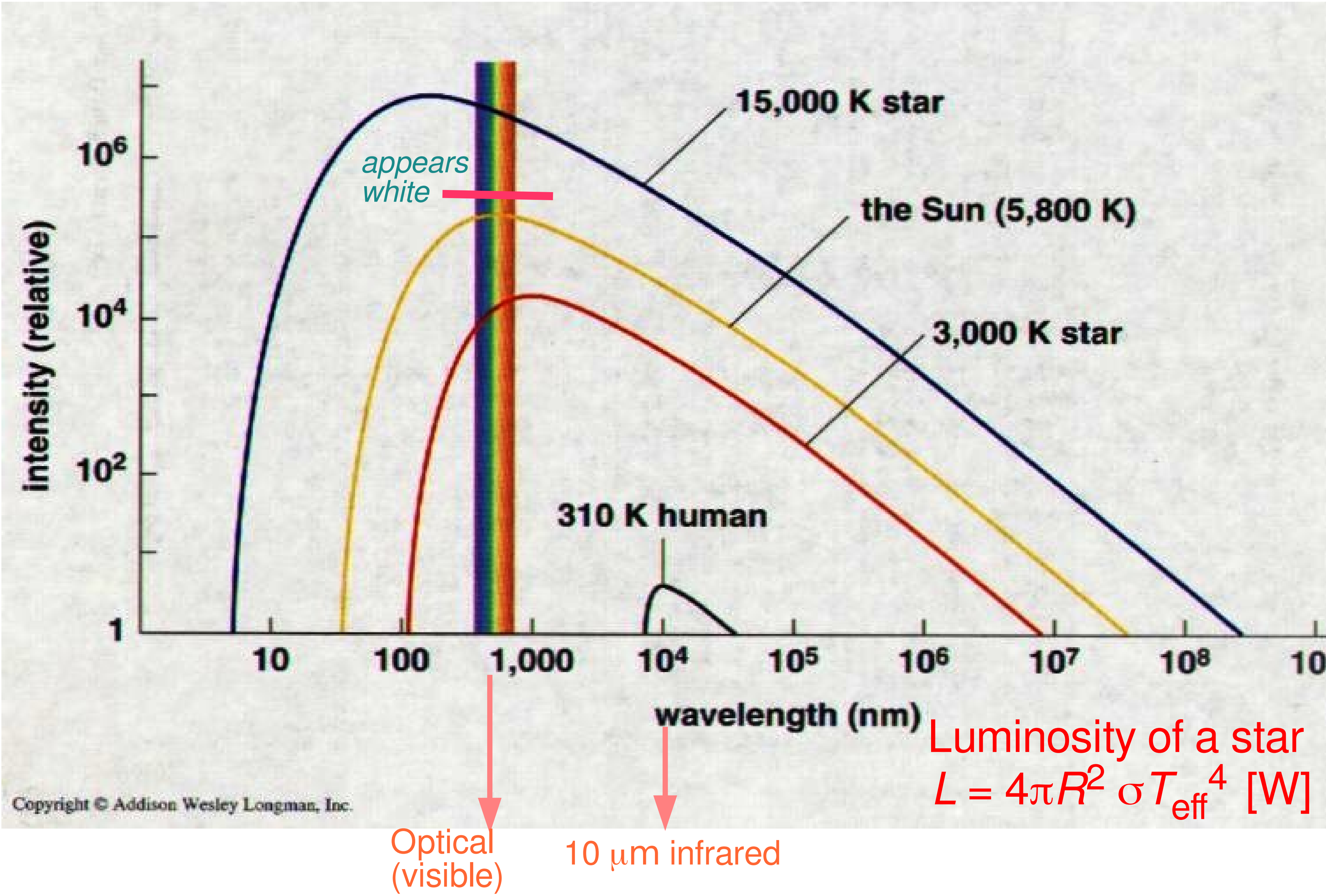
but its own radiation
has a 'color'



## Universal Radiation of a blackbody (only depends on $T$)

1) blackbody peak at $\lambda = 0.0029/T$ [m], color of things..

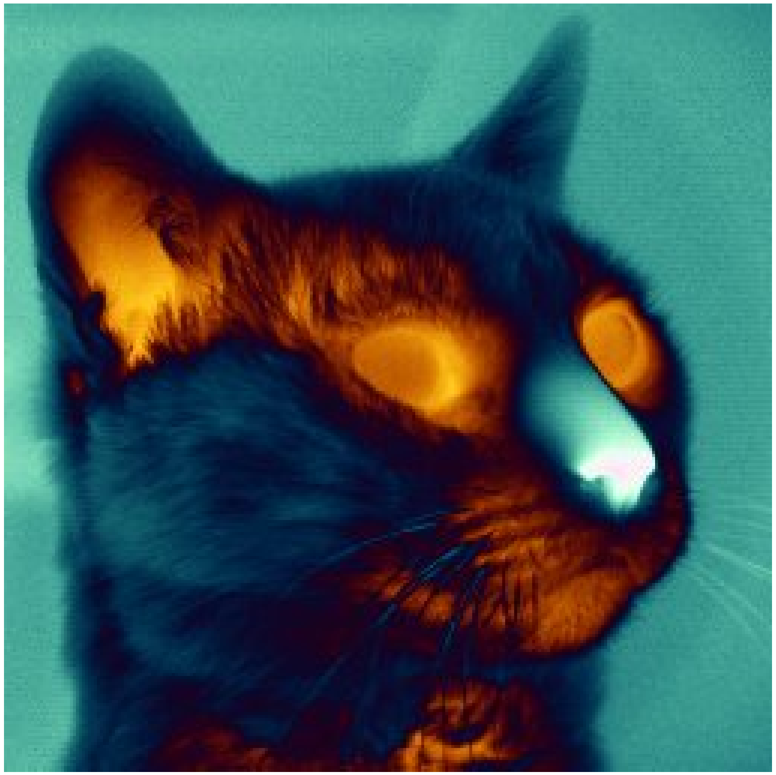
2) radiation flux $F = \sigma T^4$ [W/m²], brightness of things...



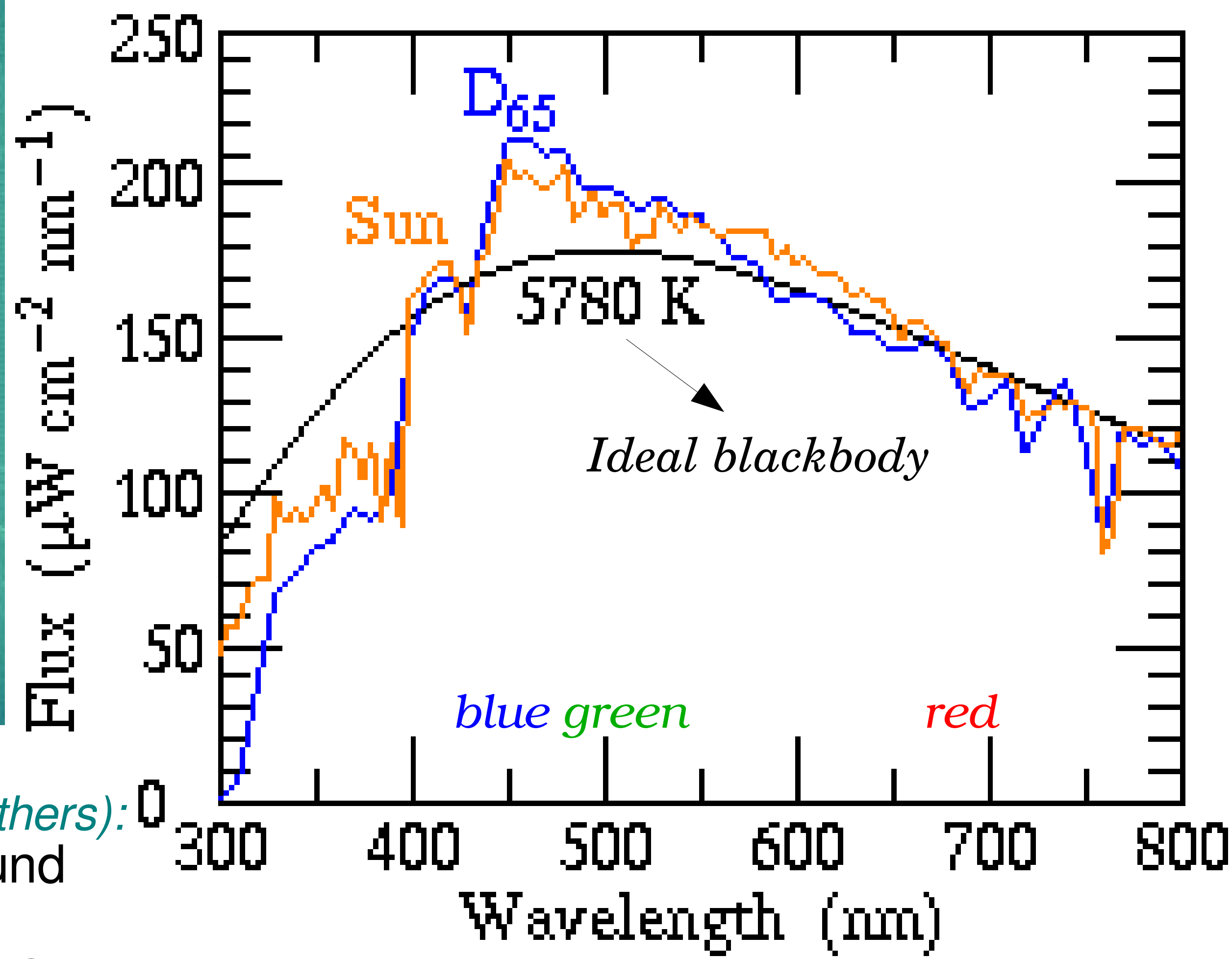

Luminosity of a star

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

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



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




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...

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

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

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

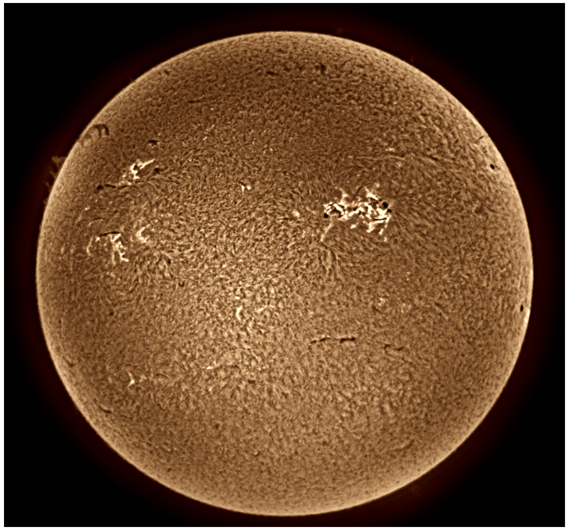
$$\textit{where } n = \frac{\rho}{\mu m_H}, \quad (\rho \textit{ is gas density})$$

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

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

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

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



Photosphere of the Sun in Hα