energy density @ center of galaxy

isotropic emitter - light bulb. emits same brightness everywhere

isotropic radiation

emission of isotropic emitter is not isotropic radiation

need to surround w/ isotropic emission to have isotropic radiation

Planck's Function

didn't believe for 16 years

temperature Einstein: ayo fax! quanta gang

Einstein time

ground level $\xrightarrow{\text{photon}}$ 1^{st} level

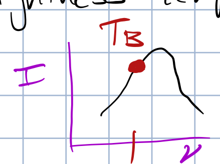
↳ high end of Planck's f^n

1^{st} level $\xrightarrow{\text{stimulated emission}}$ ground level

↳ gang. everything works out

Characteristics of Temp

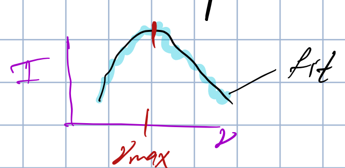
(1) Brightness temp.



$I_\nu = B_\nu(T_B)$

measurement of intensity @ frequency & match

(2) Color temp.



$h\nu_{max} = 2.82\, k \cdot T_c$

match ν_{max}

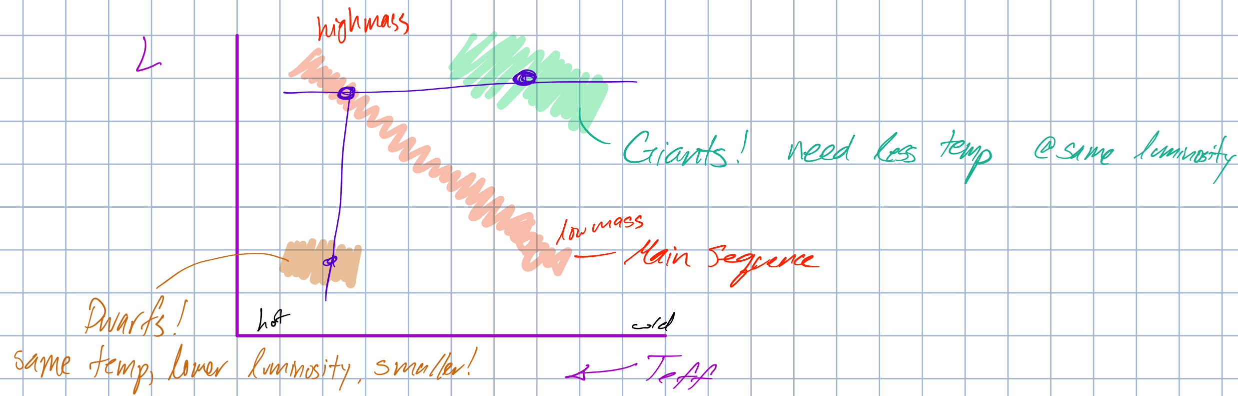
③ Effective temp.

assume blackbody radiation → $F = \sigma T_{eff}^4$ $\qquad \frac{E}{t \cdot A}$

Luminosity: energy / second nothing about measurers

surface of Sun

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



intrinsically different stars? or same in evolution?

why doesn't supernovae & CMB → H_0 agree?

Einstein's Derivation of Planck Law

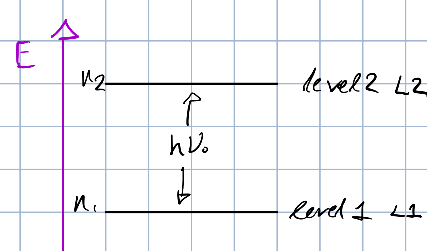
Kirchoff's Law: thermal radiation $j_\nu = \alpha_\nu B_\nu(T)$

needs to be some microscopic balance

simple model radiation in equilibrium w/a "two level" system

level 1: energy E statistical weight g_1

level 2: energy $E + h\nu_0$ statistical weight g_2



3 processes

① spontaneous emission

Bork!

transition when atom moves from L2 $\to$ L1

even in absence of radiation

A_{21} = transition probability of L2 $\to$ L1

② absorption

when photon is absorbed to move from L1 + photon $\to$ L2

transition probability is proportional to density of photons near ν_0

avg mean density near ν_0 "line width"

$B_{12} \bar{J}$, $\bar{J} = \int_0^\infty J_\nu \, \phi_\nu(\nu) \, d\nu$

③ stimulated emission

transitions when atom moves from L2 $\to$ L1 + photon

$B_{21} \bar{J}$

In equilibrium:

(in) = (out)

$$n_1 B_{12} \bar{J} = n_2 A_{21} + n_2 B_{21} \bar{J}$$

out of 1 by absorption

into 1 by emission

into 1 by stimulation

solve for $\bar{J}$

$$\bar{J} = \frac{n_2 A_{21}}{n_1 B_{12} - n_2 B_{21}} = \frac{A_{21}/B_{21}}{\left(\frac{n_1}{n_2}\right)\left(\frac{B_{12}}{B_{21}}\right) - 1}$$

$\to$ can use Boltzmann statistics for number density assuming thermodynamic equilibrium in TE $\left(\frac{n_1}{n_2}\right) = \frac{g_1}{g_2} \frac{e^{-E/kT}}{e^{-(E+h\nu_0)/kT}} = \frac{g_1}{g_2} e^{\frac{h\nu_0}{kT}}$

$$\bar{J} = \frac{A_{21}/B_{21}}{\frac{g_1 B_{12}}{g_2 B_{21}} \exp\left(\frac{h\nu_0}{kT}\right) - 1}$$

if $g_1 B_{12} = g_2 B_{21}$ & $A_{21} = \frac{2h\nu^3}{c^2} B_{21}$

$\longrightarrow$ Blackbody radiation

in absence of stimulated emission, recover Wien's Law

$\longrightarrow$ why? valid if $h\nu \gg kT$

b/c $n_2 \ll n_1$ & can be neglected

nothing about temperature!

Einstein's relations true w/o thermal equilibrium

can derive macroscopic properties from Einstein

can show $j_\nu = \frac{h\nu_0}{4\pi} n_2 A_{21} \phi(\nu)$ emmission

uncorrected (w/o stim)

$$\alpha_\nu = \frac{h\nu_0}{4\pi} n_1 B_{12} \phi(\nu)$$

corrected w/ stimulation

$$\alpha_\nu = \frac{h\nu_0}{4\pi} (n_1 B_{12} - \underline{n_2 B_{21}}) \phi(\nu)$$

$$\longrightarrow \alpha_\nu = \frac{h\nu_0}{4\pi} n_1 B_{12} \left(1 - \frac{g_1 n_2}{g_2 n_1}\right) \phi(\nu)$$

$$S_\nu = \frac{2h\nu^3}{c^2} \left(\frac{g_2 n_1}{g_1 n_2} - 1\right)^{-1}$$ (generalized Kirchhoff)