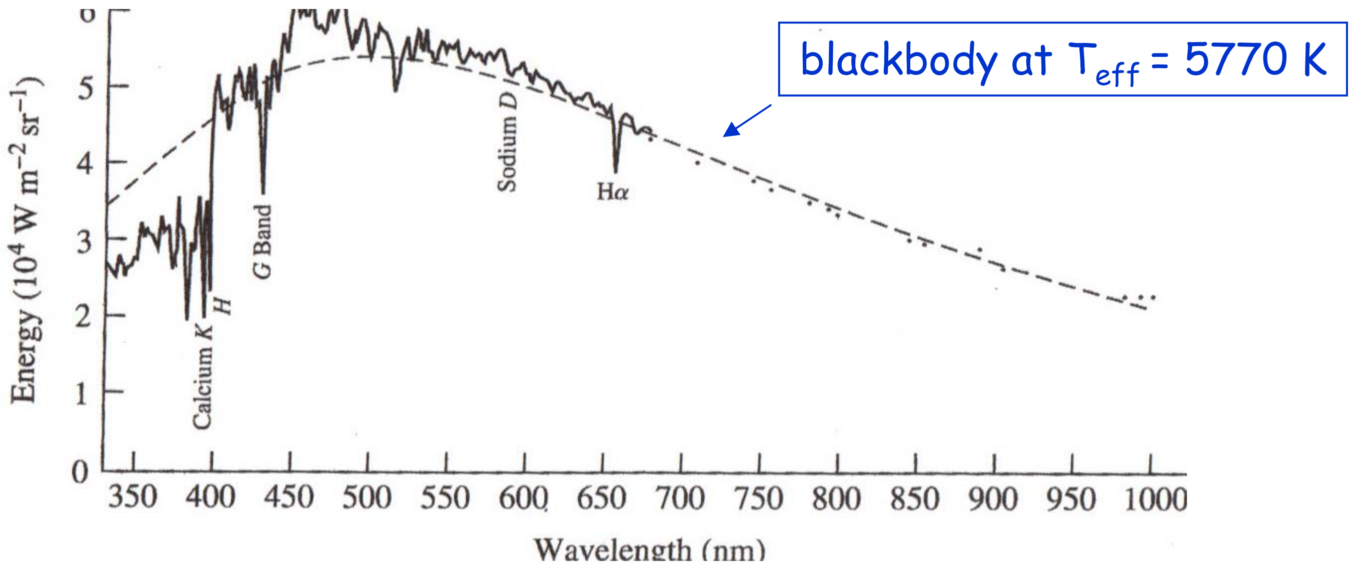
AY 20 Fall 2010

Stellar Atmospheres: Opacity

Reading: Carroll & Ostlie, Chapter 9.2

Stars are not blackbodies – e.g. Sun



atmosphere "opaque" at various wavelengths – no outward flux of photons at these wavelengths

$$L = 4\pi R^2 \sigma T^4_e$$

and $F_{surface} = L/4\pi R^2 = \sigma T^4_{eff}$

"surface layer" is region from which continuum radiation emerges

≡ photosphere

→ T_e based on reduced flux

→ surface temperature given by Te only for a blackbody

Local Thermodynamic Equilibrium (LTE)

When particles and radiation are in equilibrium at a single temperature $\rightarrow$thermal equilibrium

Overall, stellar atmospheres cannot be in thermal equilibrium

Define a local environment where thermal equilibrium holds

i.e. conditions can be described a single temperature

For LTE:

distance over which temperature changes significantly >> mean free path of particles/photons

Mean free path (very simplistically)

Any 2 atoms in an ensemble of number density n "collide" if they pass within $2a_0$ of one another (a_0 =Bohr radius)

Instead, suppose 1 atom, radius $2a_0$, moving at velocity $\underline{v}$:

in time t, it sweeps out volume $V = \pi(2a_0)^2 vt = \sigma vt$

σ = collision cross-section = $\pi(2a_0)^2$

$\therefore$ number of collisions = $n\sigma vt$

mean free path = average distance between collisions = ℓ

ℓ = distance / # of collisions = $vt/n\sigma vt$

$\therefore$ mean free path = $1/n\sigma$

For Sun*, at ~ 5650K, $\ell \sim 2 \times 10^{-2}$ cm

$H_T \sim 700$ km $= 7\times 10^7$ cm $\rightarrow H_T/\ell \sim 2.5 \times 10^9$

$\therefore H_T \gg \ell$

$\therefore$ For atoms, environment between collisions looks to be at constant T_{kin}

Stellar opacity

Absorption – any process that removes photons from beam

$\equiv$ true absorption (due to excitation to higher excited states)

+ scattering due to photon-free electron "collisions"

Decrease in intensity of beam at wavelength λ = dI_λ

decrease $\propto$ I_λ, gas density ρ, and distance traversed, ds

$\therefore dI_\lambda = -\kappa_\lambda I_\lambda \rho ds$, κ_λ = absorption coefficient = opacity

opacity = cross-section per unit mass of material for absorbing wavelength λ photons (c^2/gm)

- dependent on gas composition, density, and temperature

We have $dI_\lambda = -\kappa_\lambda I_\lambda \rho ds$ = change (decrease) in intensity

Suppose initial intensity = I_0 at $s=0$

Final intensity after light has travelled distance s = $I_{\lambda,f}$

so
$$\int_{I_{\lambda,0}}^{I_{\lambda,f}} \frac{dI_\lambda}{I_\lambda} = -\int_0^s \kappa_\lambda \rho ds$$

$$\therefore \quad I_{\lambda,f} = I_{\lambda,0} e^{-\int \kappa_\lambda \rho ds}$$

$\therefore$ for uniform gas with constant κ_λ, ρ: $I_\lambda = I_{\lambda,0} e^{-\kappa_\lambda \rho ds}$

For pure absorption, intensity falls off exponentially i.e. by factor e^{-1} at characteristic distance $\ell = 1/\kappa_\lambda \rho$

For Sun* at 5000 Å, ℓ = 160 km; scale height H_T = 677 km

LTE not strictly applicable!

for scattered photons:

characteristic distance ℓ = photon mean free path

and $\ell = 1/n\sigma_\lambda = 1/\kappa_\lambda\rho$

$n\sigma_\lambda$ and $\kappa_\lambda\rho$ inversely proportional to ℓ

$\equiv$ fraction of photons scattered /meter of distance

Recall $I_\lambda = I_{\lambda,0}e^{-\kappa_\lambda\rho ds}$

Define optical depth, τ_λ, *back* along light ray:

$d\tau_\lambda = -\kappa_\lambda\rho ds$ (s measured in direction of photon's motion i.e. at stellar surface $\tau_\lambda = 0$)*

$$\therefore \quad \tau_\lambda = -\int_0^s \kappa_\lambda \rho ds$$

$$\text{and } \mathrm{I}_\lambda = I_{\lambda,0} e^{-\int_o^s \kappa_\lambda \rho ds} = I_{\lambda,0} e^{-\tau_\lambda}$$

Optical depth continued

Since $I_\lambda = I_{\lambda,0} e^{-\tau_\lambda}$

if $\tau_\lambda = 1$ at ray's start point, at surface of star it will have decreased by factor of e^{-1}

Typically see (in line of sight) into atmosphere only to $\tau_\lambda \approx 1$

(for pure absorption intensity declines exponentially for any ray direction)

Optical depth = number of mean free paths from original position to surface

since $\ell = 1/\kappa_\lambda\rho$, $\tau_\lambda = \kappa_\lambda\rho\int ds = \int ds/\ell$

Usage: gas through which light passes optically thick if $\tau_\lambda \gg 1$

gas through which light passes optically thin if $\tau_\lambda \ll 1$

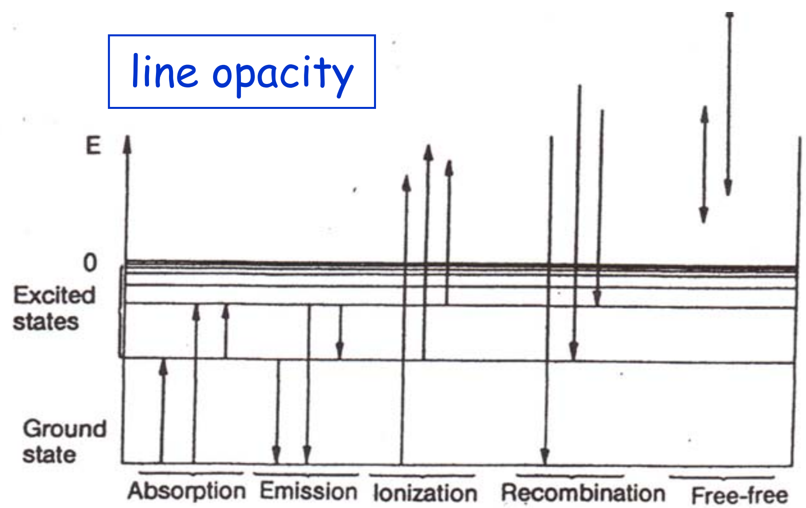
e.g. optical depth of earth's atmosphere at different wavelengths*

Sources of Opacity: slowly varying affects continuum; rapid variations → dark spectral lines

1. bound-bound transitions: photons "lost" to beam at discrete λs
2. free-free transitions: absorption & bremsstrahlung – no preferred λ
3. bound-free transitions: photoionization* – any photon w. $\lambda < hc/\chi$
4. electron scattering: Thompson scattering at high T, ρ; also Compton or Rayleigh scattering

* photoionization of H^- ions important continuum opacity source in stars cooler than F0
B and A stars: continuum opacity from photoioniz. of H atoms or free-free absorption
O stars: electron scattering and photoionization of He

Fig. 5.2. Different kinds of transitions between energy levels. Absorption and emission occur between two bound states, whereas ionization and recombination occur between a bound and a free state. Interaction of an atom with an free electron can result in a free-free transition



continuum opacity

5.2

the H above)