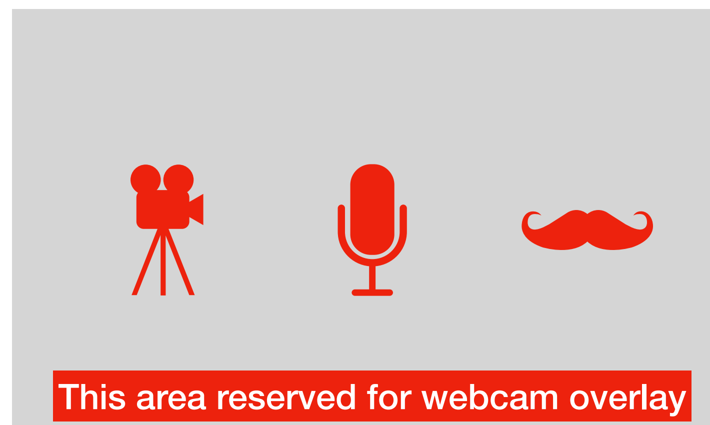
ASTR 421

Stellar Observations and Theory

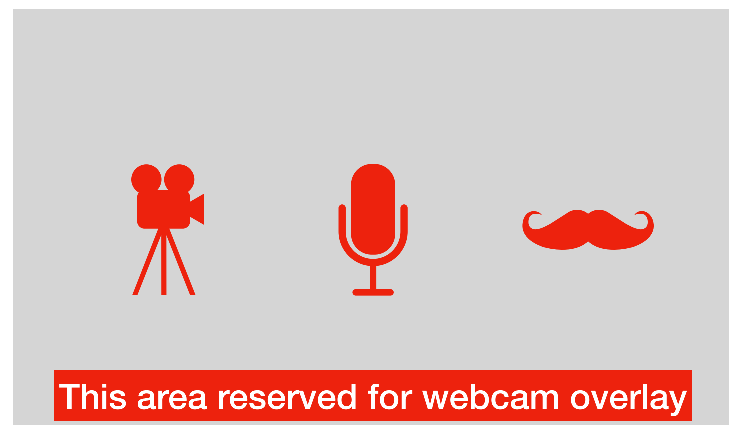
Lecture 08
Line Profiles

Prof. James Davenport (UW)



Last time…

- Introduction to "radiative transfer", which helps us understand how opacity works in stars, and thus how *lines* are formed



Source Function

$$S_\lambda \equiv \frac{j_\lambda}{\kappa_\lambda}$$

- Has units of intensity.
- Special case for optically thick material in Thermodynamic Equilibrium, $S_\lambda = B_\lambda$

$$B_\lambda(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k_B T}} - 1}$$

- Special case for pure scattering

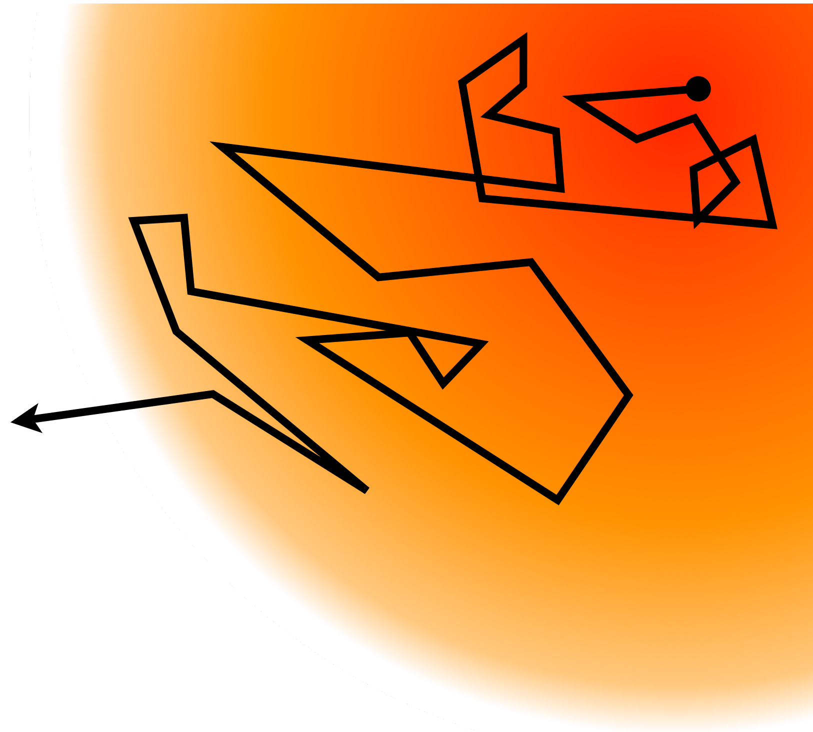
$$S_\lambda = \frac{1}{4\pi} \oint I_\lambda \, d\omega = J_\lambda$$

This area reserved for webcam overlay

How do photons reach us?

- **Both emission and absorption are happening within a volume of gas!**

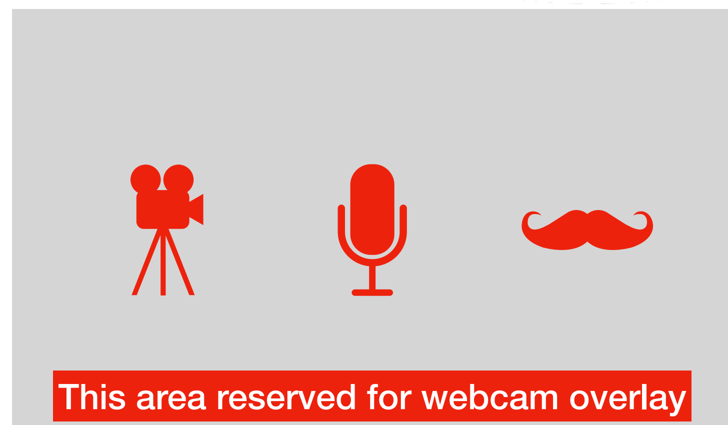
$$dI_\lambda = j_\lambda \, \rho \, ds \qquad dI_\lambda = -\, \kappa_\lambda \, \rho \, I_\lambda ds$$



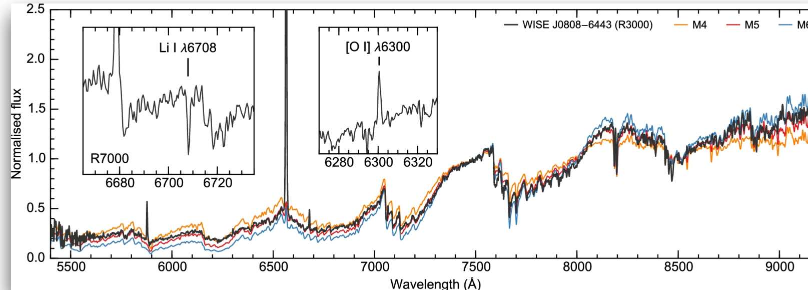
- Simplest solution to the radiative transfer eqn:

$$\frac{dI_\lambda}{d\tau_\lambda} = I_\lambda - S_\lambda$$

$$I_\lambda \, = \, I_{\lambda,0} \, e^{-\tau_\lambda} \, + S_\lambda \, (1 - e^{-\tau_\lambda})$$



On Emission

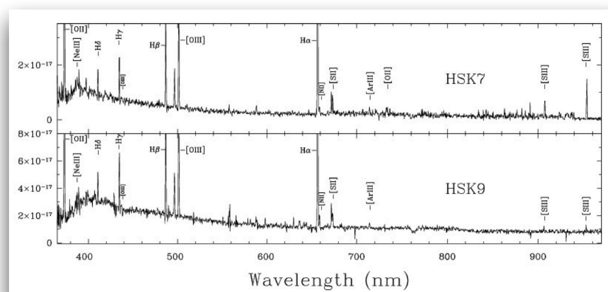


- For optically thick scenario:
  $I_\lambda(\tau_\lambda) \approx B_\lambda(T_{in}) + \tau_\lambda[B_\lambda(T_{out}) - B_\lambda(T_{in})]$

- So in "normal" scenario, $T_{out} < T_{in}$, resulting intensity is lower i.e. absorption lines

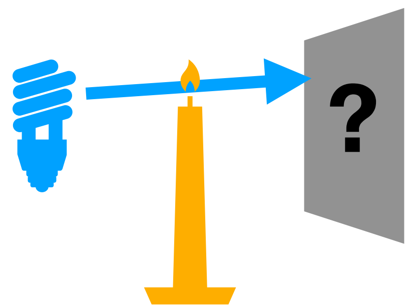
- BUT, if $T_{out} > T_{in}$, you see higher intensity (i.e. emission)
  - This happens e.g. in the solar Transition/Corona regions, where density decreases but temperature increases

Optically thin gas for very strong emission lines:



This area reserved for webcam overlay

Does a candle flame cast a shadow?

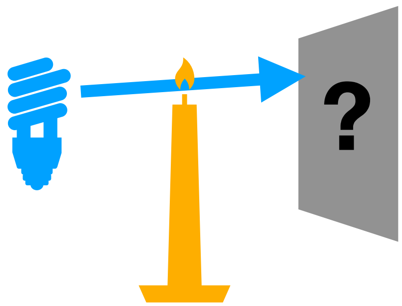


This area reserved for webcam overlay

Does a candle flame cast a shadow?

- It certainly CAN… The answer depends on the transfer equation!

$$I_\lambda = I_{\lambda,0}\, e^{-\tau_\lambda} + S_\lambda\,(1 - e^{-\tau_\lambda})$$



- Soot particles *do* cast shadows

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

- But they are burning too, and add intensity with a Source Function (brightness)

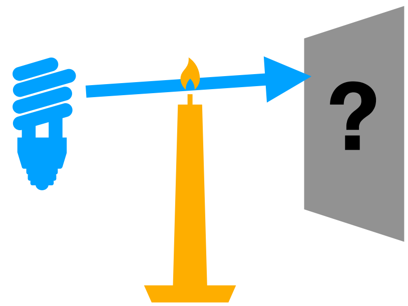
$$S_\lambda\,(1 - e^{-\tau_\lambda})$$

http://www-star.st-and.ac.uk/~kw25/teaching/nebulae/lecture03_radtrans.pdf

Does a candle flame cast a shadow?

- NO shadow if $T_{soot} > T_{bulb}$ (i.e. $S > I_0$)

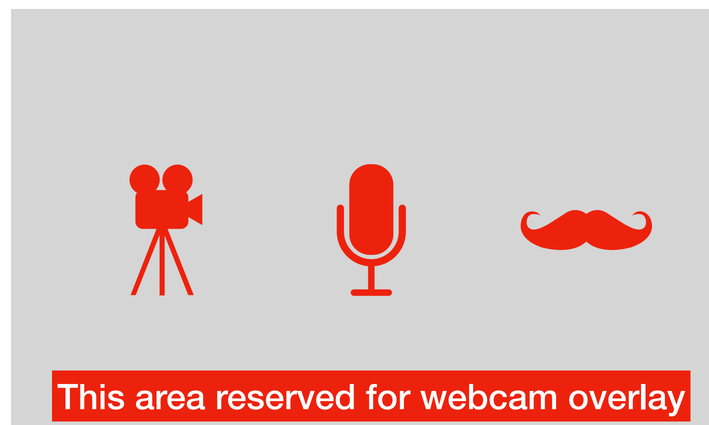
$$I_\lambda = I_{\lambda,0}\, e^{-\tau_\lambda} + S_\lambda\, (1 - e^{-\tau_\lambda})$$



- YES shadow if $T_{soot} \leq T_{bulb}$

- You can try this w/ the Sun (carefully)

- $T_\odot = 5800K$, while $T_{candle} \sim 1200K$



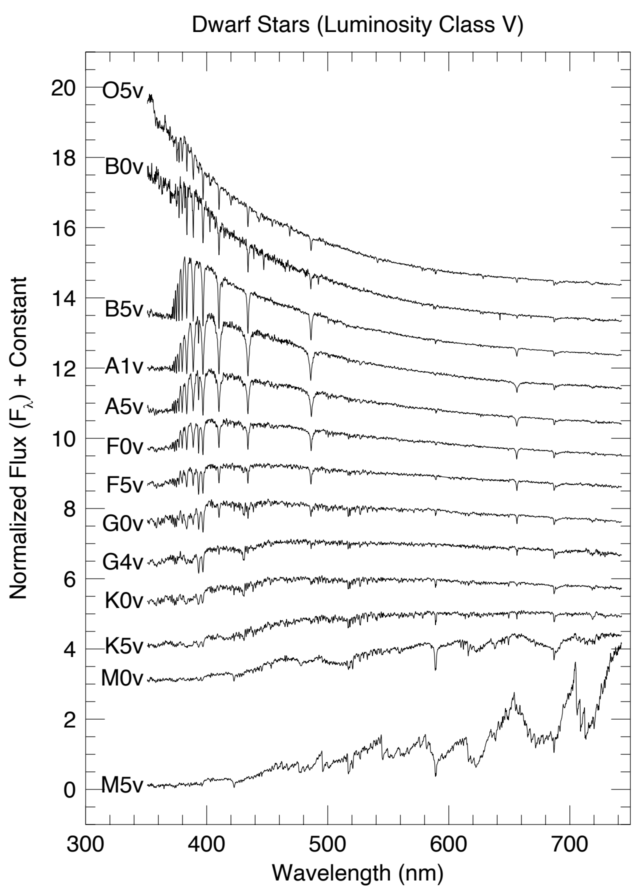
http://www-star.st-and.ac.uk/~kw25/teaching/nebulae/lecture03_radtrans.pdf

Our goal this week is to study line profiles

- Where light travels through the atmosphere determines the line profile (since Temp, pressure, etc are different)
- Overview of types of “line broadening”
- Notable lines/profiles
- (Simple) solutions to the Radiative Transfer Eqn. in action…. (Homework 3!)

This area reserved for webcam overlay

Lets look at a few lines to just discuss what we see…

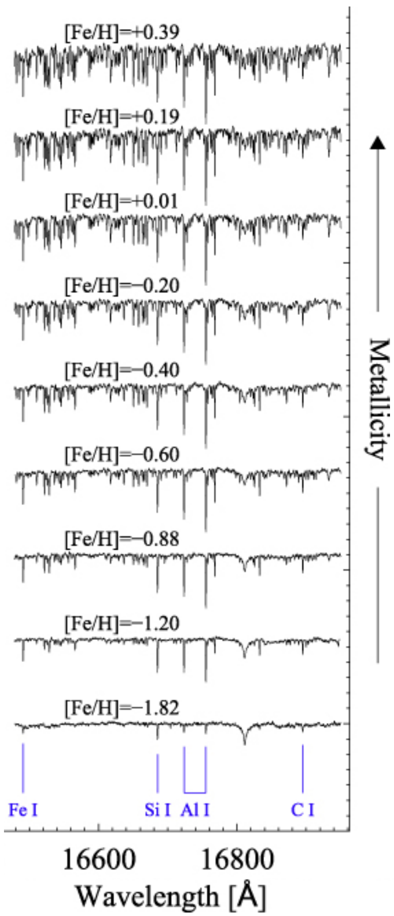


Line strength (τ_λ) has to do with local properties of gas near the “surface”

e.g. Temperature

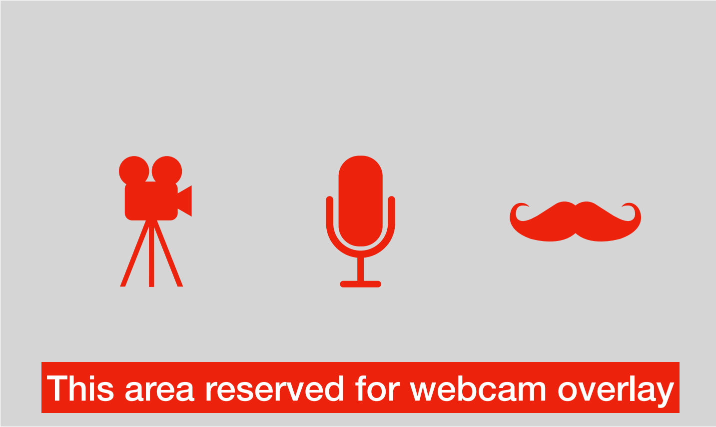
This area reserved for webcam overlay

Lets look at a few lines to just discuss what we see…

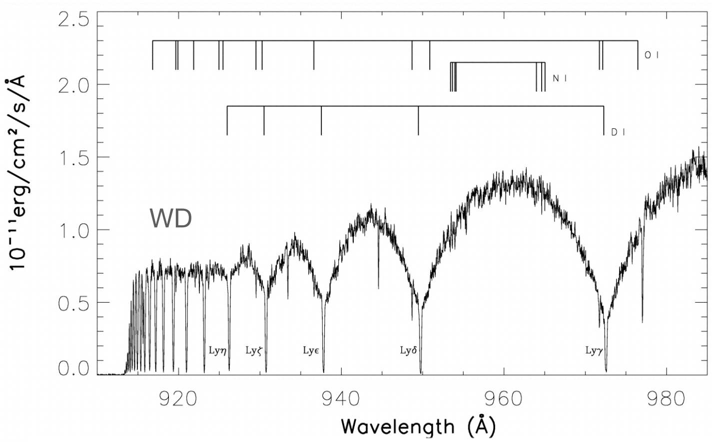


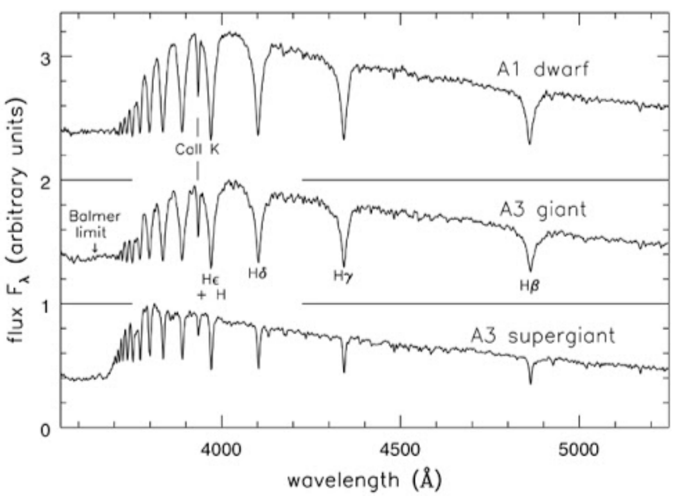
Line strength (τ_λ) has to do with
local properties of gas near the “surface”

e.g. Composition



Lets look at a few lines to just discuss what we see…



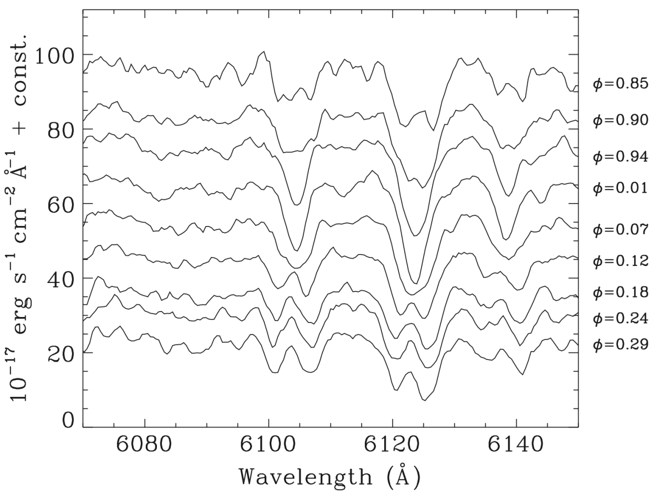


Line strength (τ_λ) has to do with
local properties of gas near the "surface"

e.g. Surface Gravity

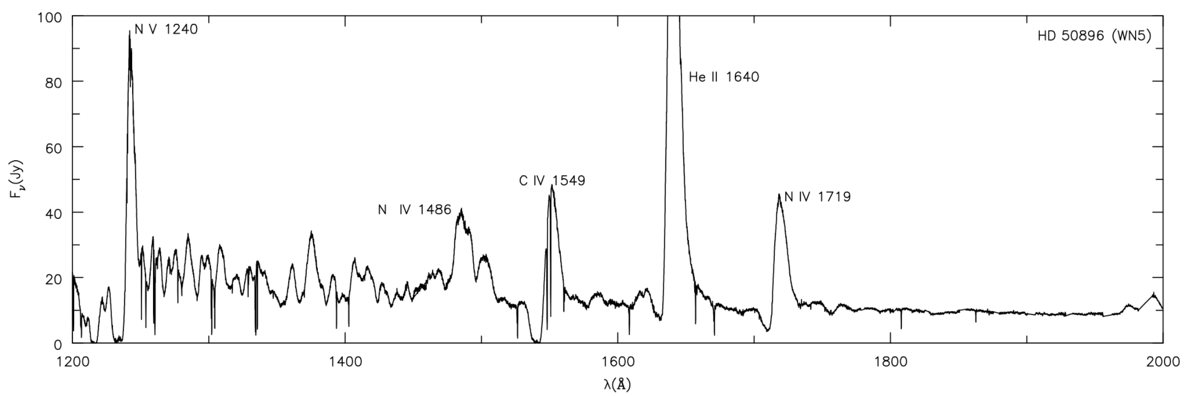
This area reserved for webcam overlay

Lets look at a few lines to just discuss what we see…



Line strength (τ_λ) has to do with local properties of gas near the "surface"

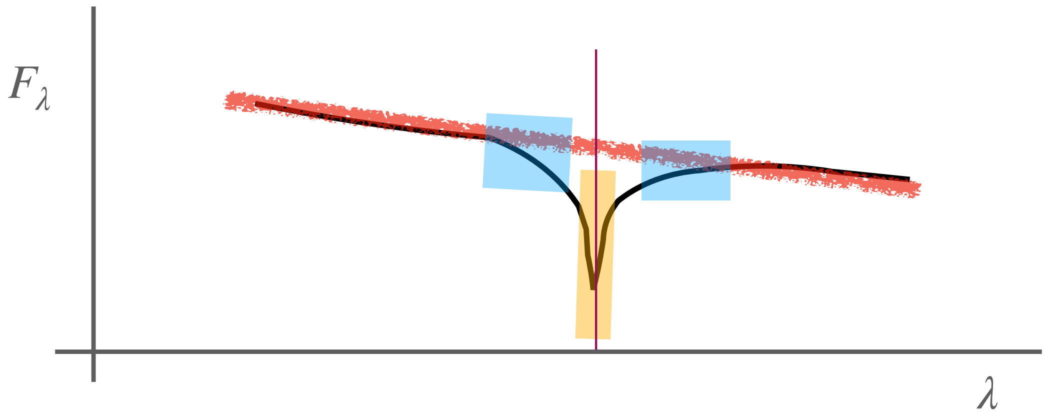
e.g. Velocity

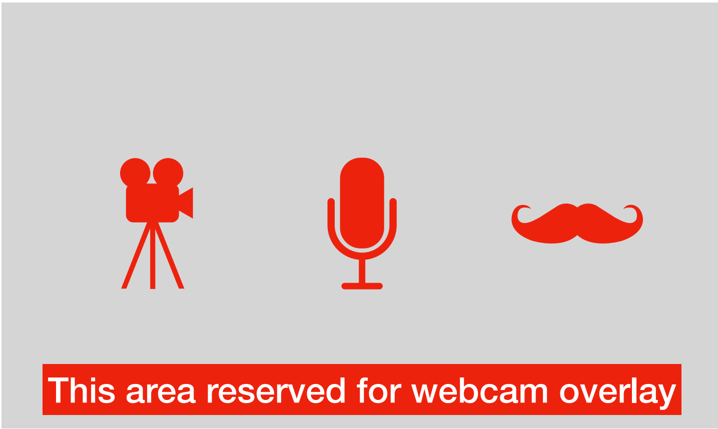


This area reserved for webcam overlay

Where do lines form?

- First, some terminology:
  - Spectrum $\equiv (\tau = 2/3)$
  - Continuum (blackbody)
  - Wings (both sides)
  - Core (center)
  - λ_{lab} (note: vac or air wavelengths)

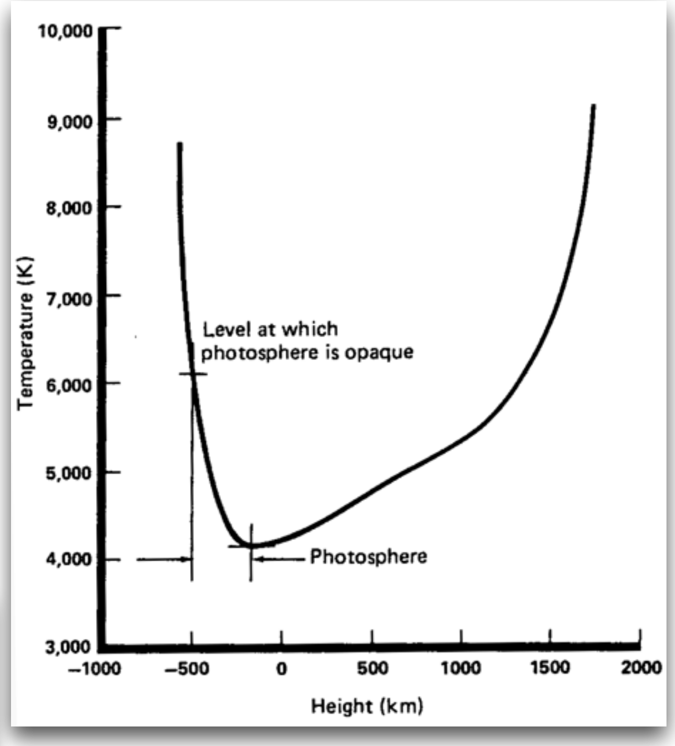


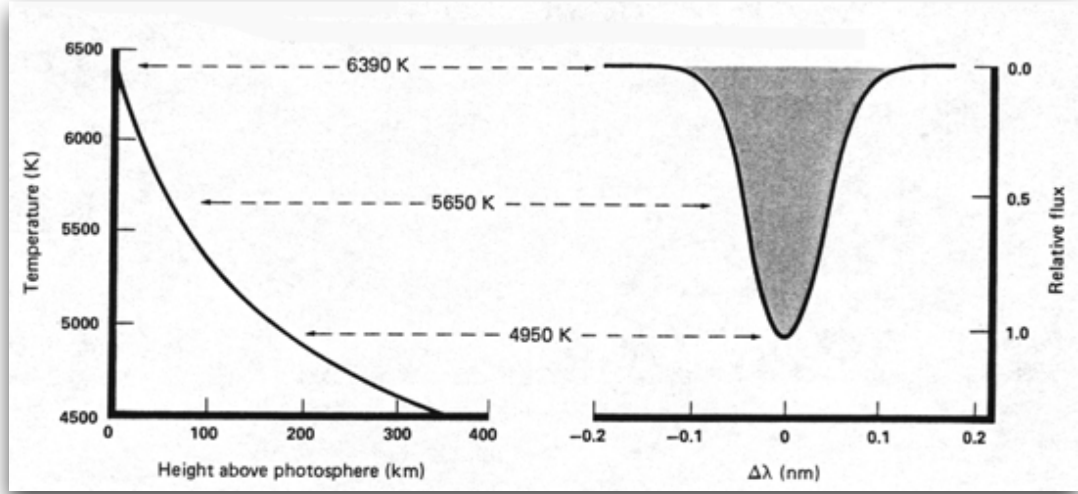


Where do lines form?

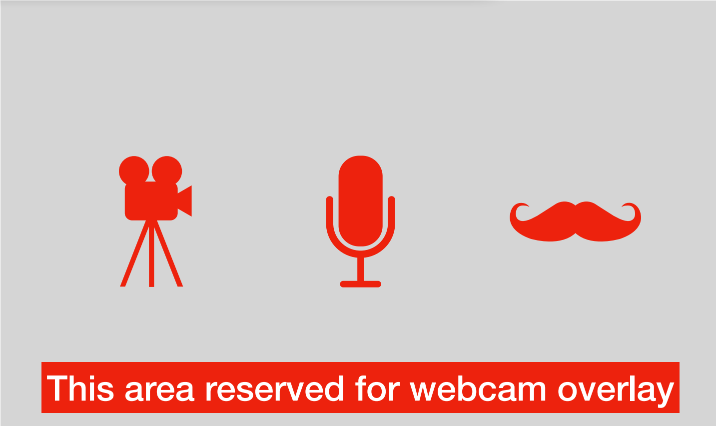
- Cores of lines typically form *higher*, in cooler region of atmosphere.

  Wings typically form *lower* (hotter)





http://ircamera.as.arizona.edu/astr_250/Lectures/Lecture_14.htm

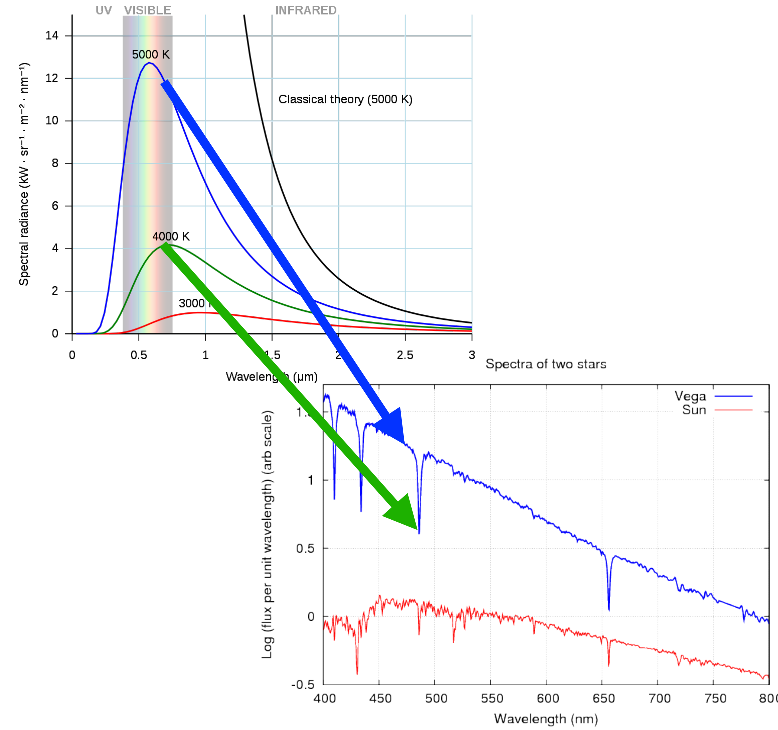


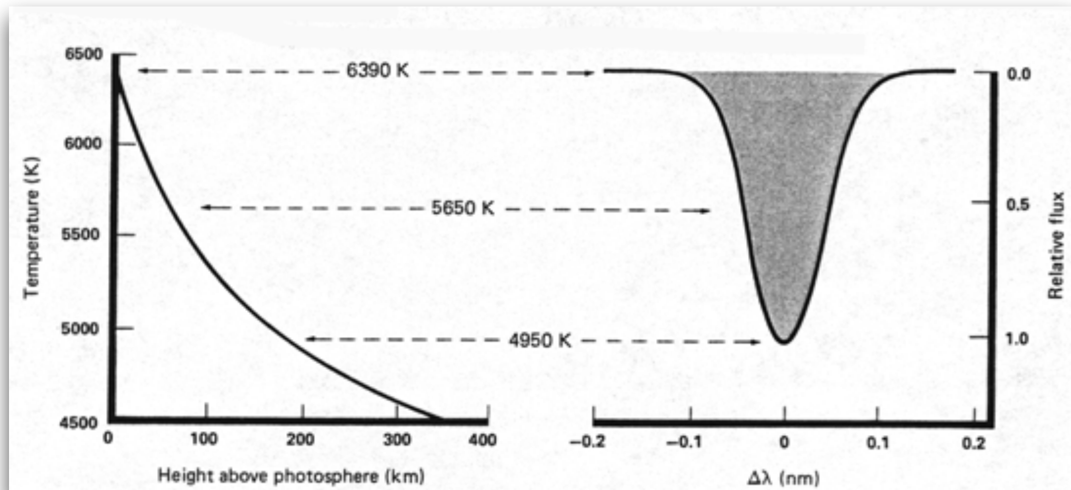
Line depth = $\tau(\lambda)$

This is why lines don't (usually) go to Flux=0.

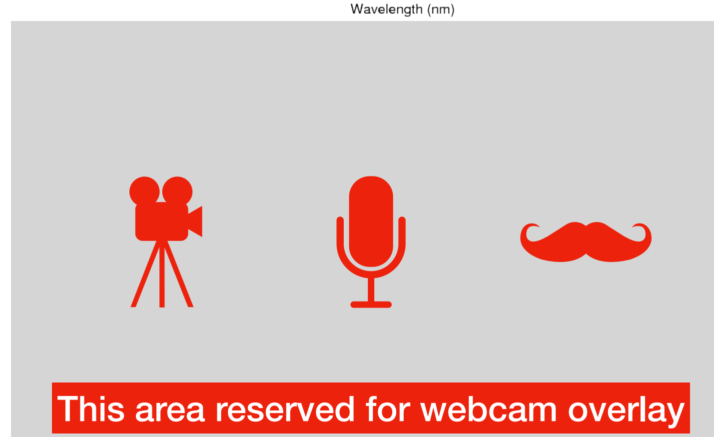
The star isn't *opaque* at the line wavelength, it's super bright!

https://commons.wikimedia.org/wiki/File:Black_body.svg

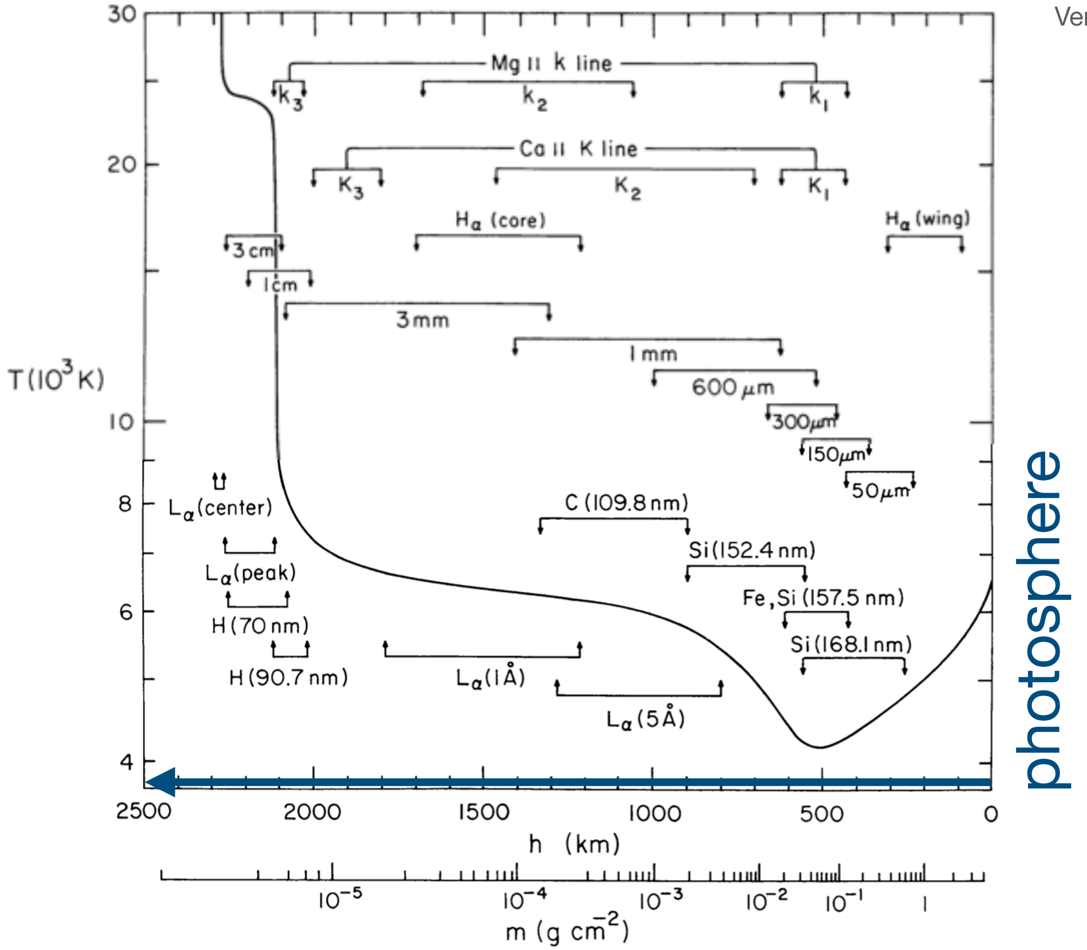




http://ircamera.as.arizona.edu/astr_250/Lectures/Lecture_14.htm



Line depth = $\tau(\lambda)$



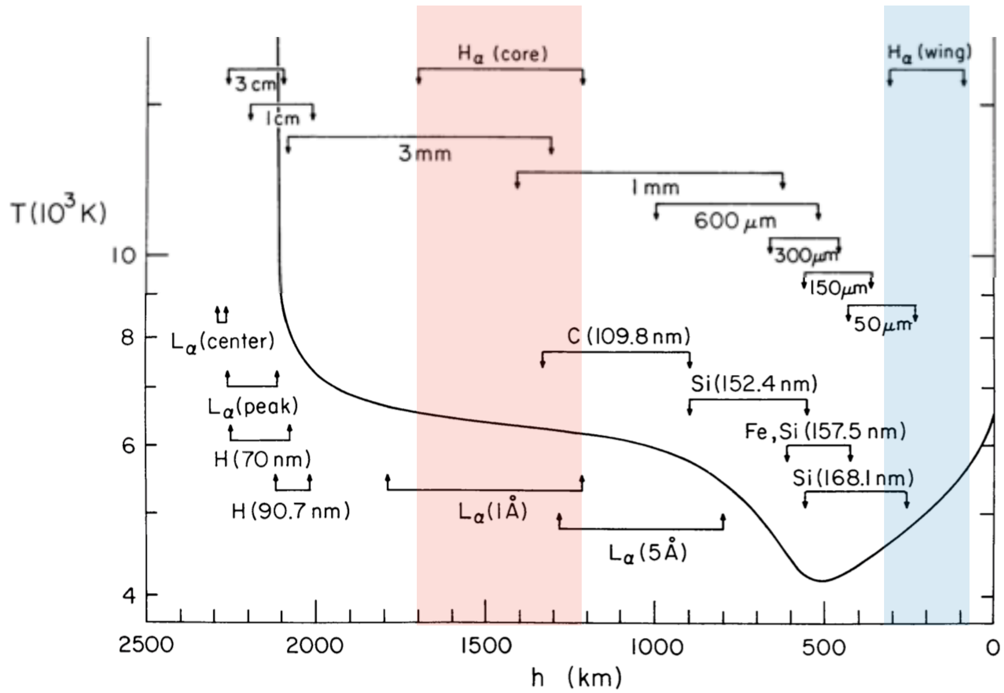
Vernazza+1981

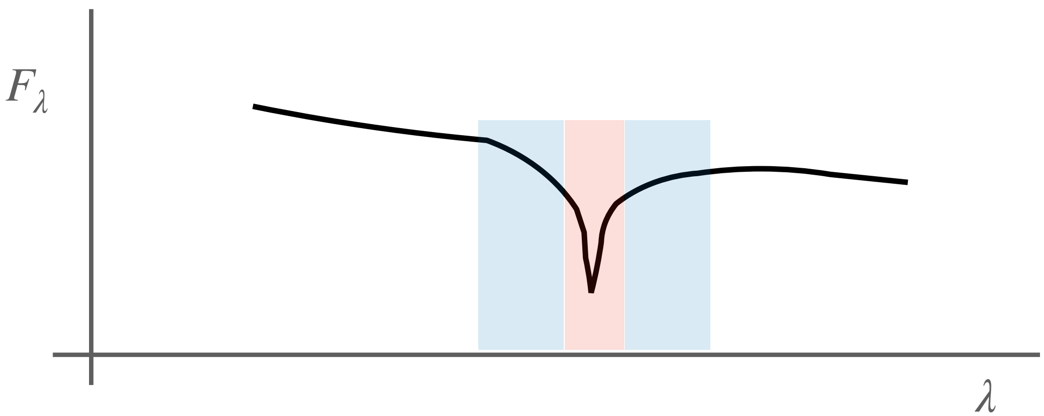
Need to model:
non-LTE, optically thick behavior
many transitions of many elements

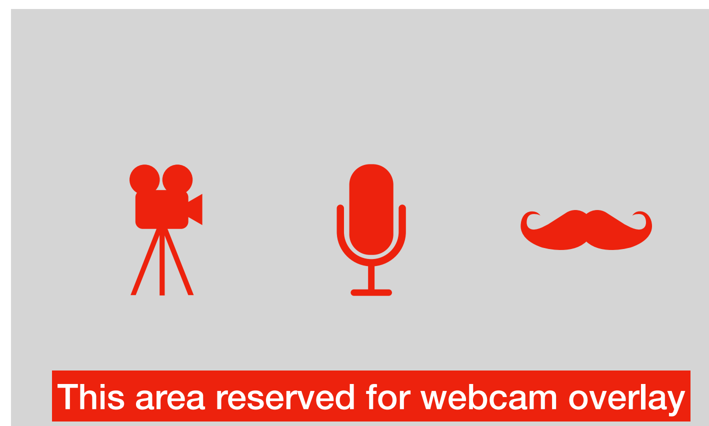
This area reserved for webcam overlay

$H\alpha$

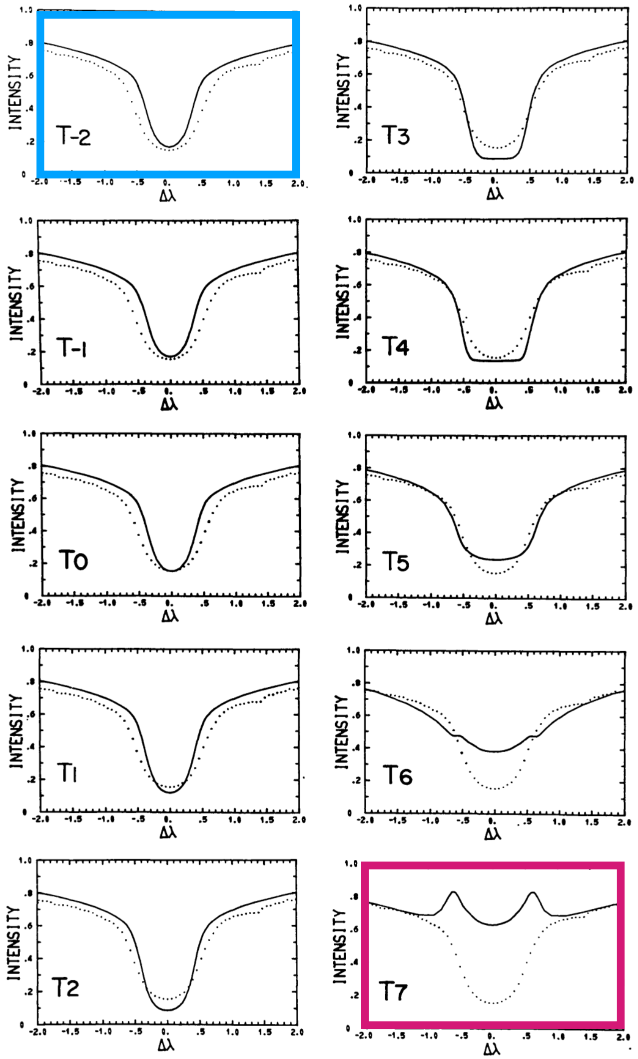
- Absorption at places where κ_{total} is high, just the *right* mix of temperature, density…





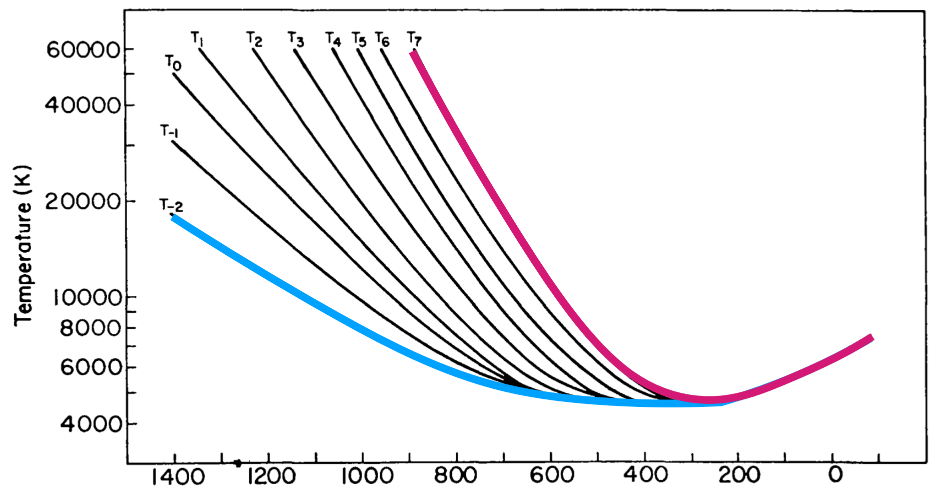


$H\alpha$

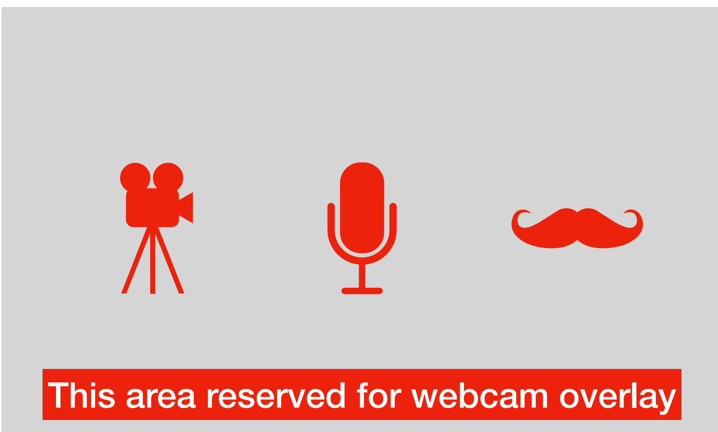


Core almost in emission!

Chromosphere temperature models

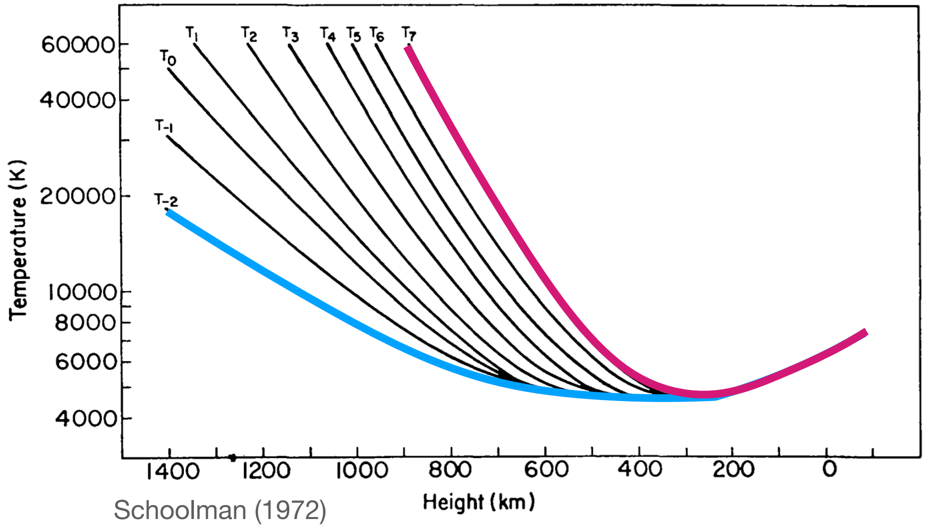


Schoolman (1972)



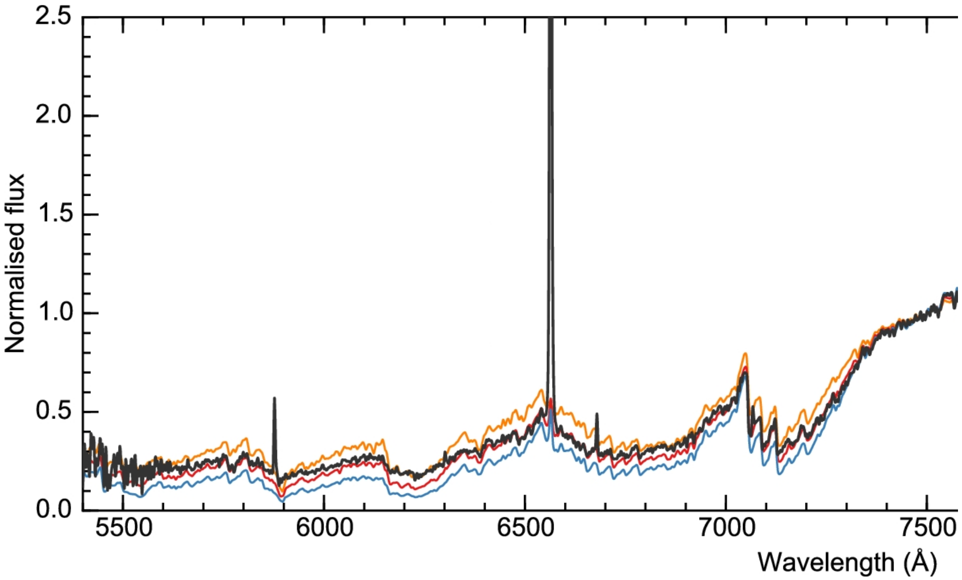
$H\alpha$

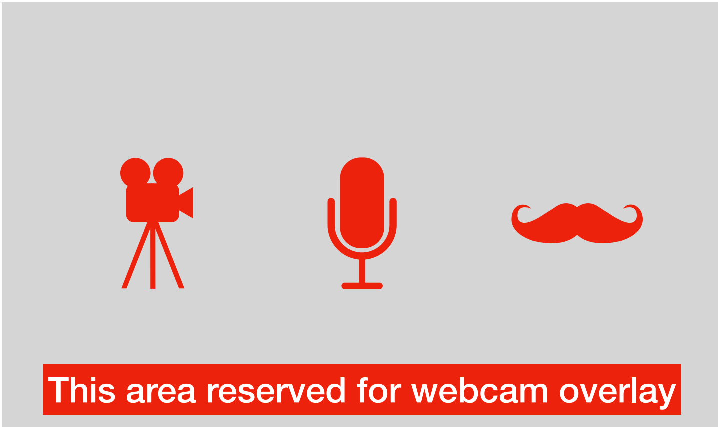
Chromosphere temperature models



Schoolman (1972)

Strong emission: Hot chromosphere!

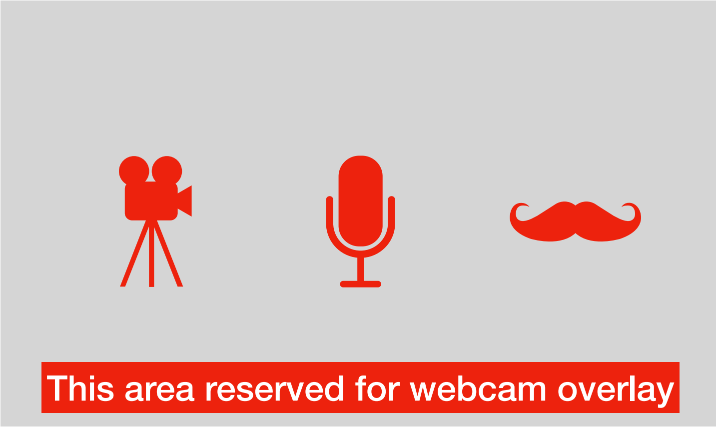




Overview of Line Broadening

- Line profile shapes can be influenced by many local effects in the atmosphere
    - Many can act simultaneously, and look similar.

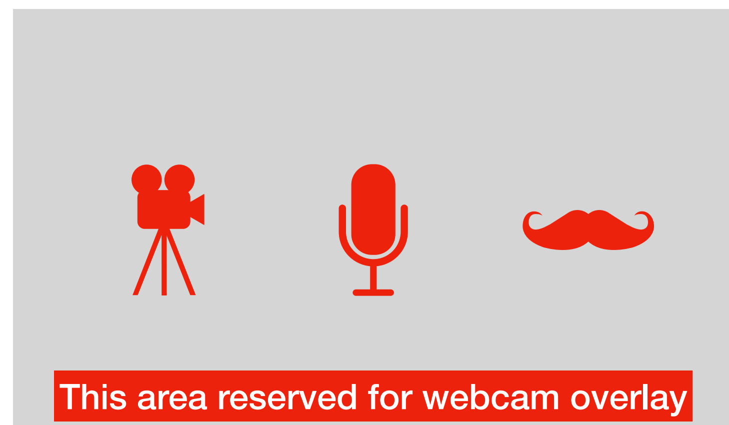
- **Doppler broadening** (thermal motions)
- **Natural broadening** (Heisenberg uncertainty)
- **Pressure broadening** (a few kinds)



Overview of Line Broadening

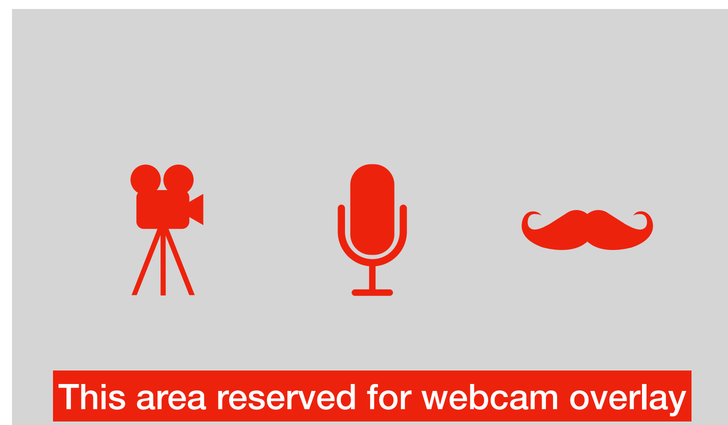
- Line profile shapes can be influenced by many local effects in the atmosphere
    - Many can act simultaneously, and look similar.

- **Doppler broadening** (thermal motions) — **Gaussian profile**
- **Natural broadening** (Heisenberg uncertainty)
- **Pressure broadening** (a few kinds) — **Lorentzian profile**



Line profile shapes

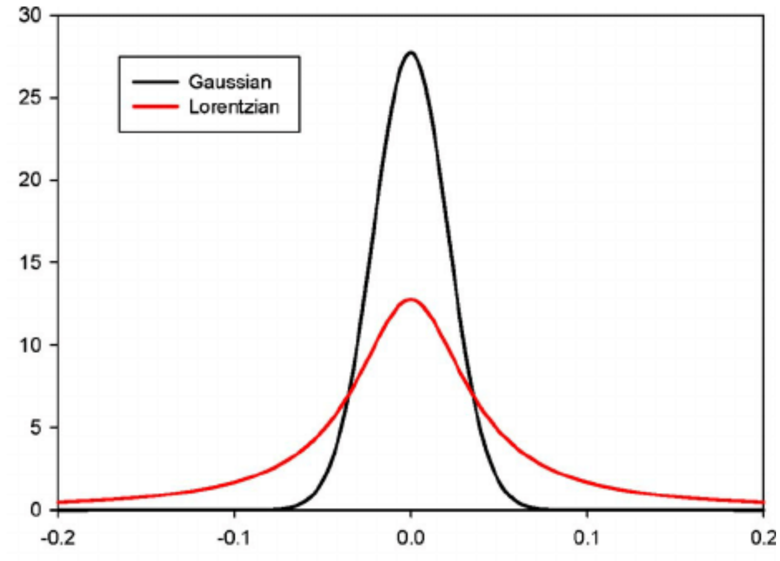
- Primarily 3 functions we care about
- (Math for homework 3!)

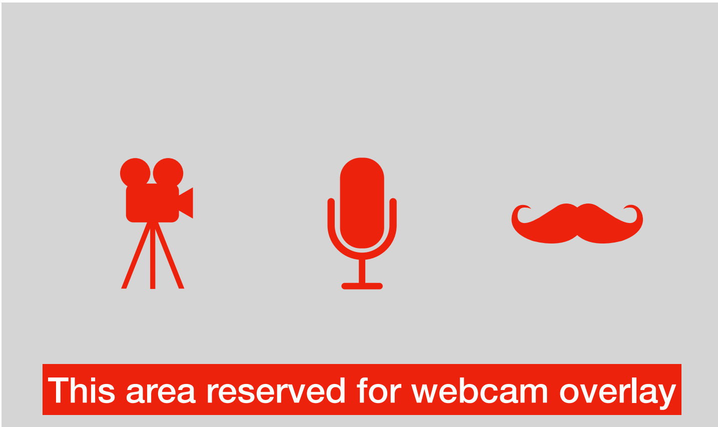


Gaussian

- Classic line shape for thermal broadening
- Arrises because of Maxwell-Boltzmann velocity distribution of gas
- Width a function of local temperature

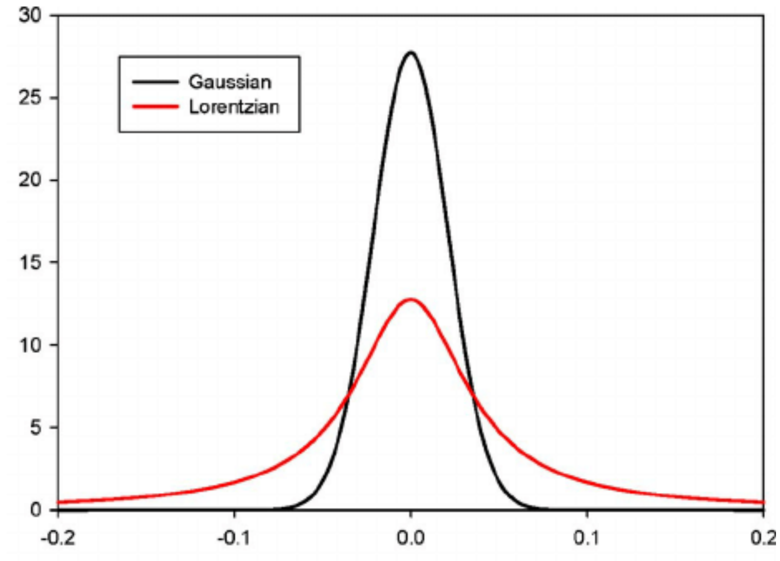
$$G = e^{-(x-\mu)^2/\sigma^2}$$

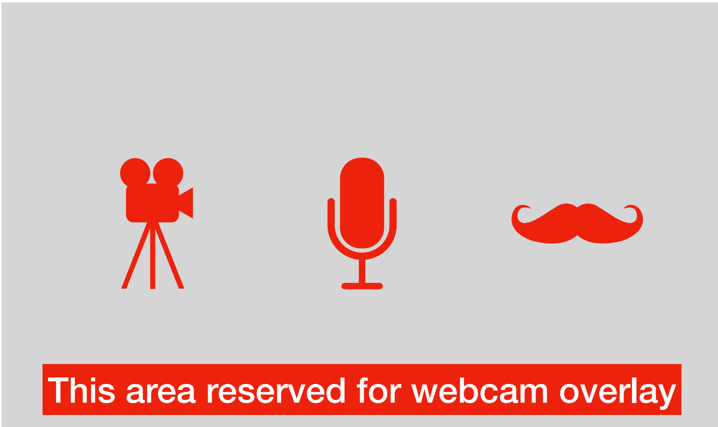




Lorentzian

- aka “Cauchy distribution”
- Especially useful for surface gravity or pressure
- $$L = \frac{1}{1+x^2}, \qquad x = \frac{p - p_0}{w/2}$$

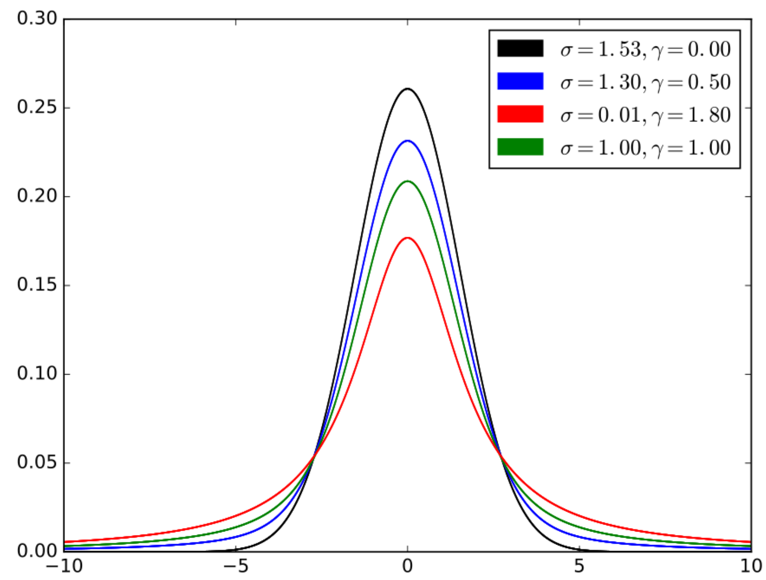


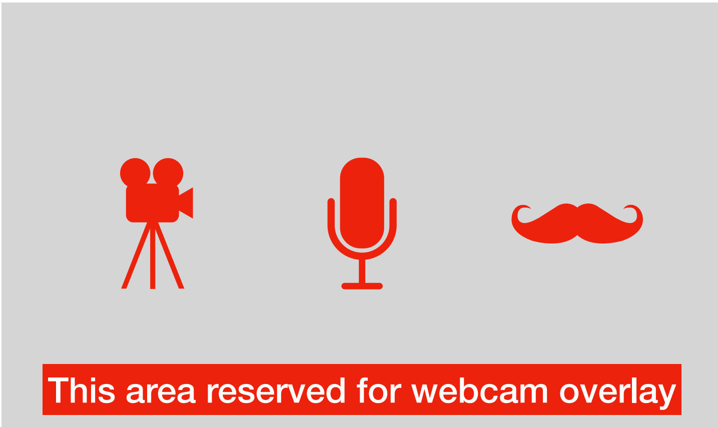


The Voigt Profile

- A *convolution* of Gaussian & Lorentzian profiles
- This the classic line profile equation we use in most cases
  - Core: mostly Gaussian shape
  - Wings: mostly Lorentz shape
- **Useful for constraining physics behind both thermal & pressure broadening in a line!**

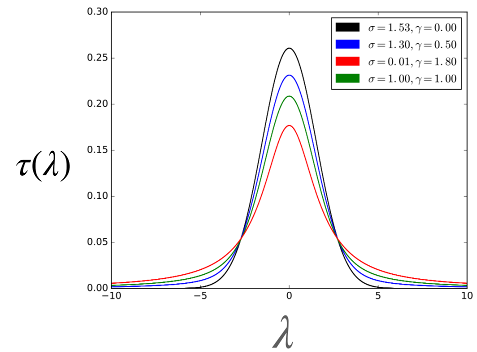
$$V(x;\sigma,\gamma) = \int_{-\infty}^{\infty} G(x';\sigma)L(x-x';\gamma)\,dx'$$

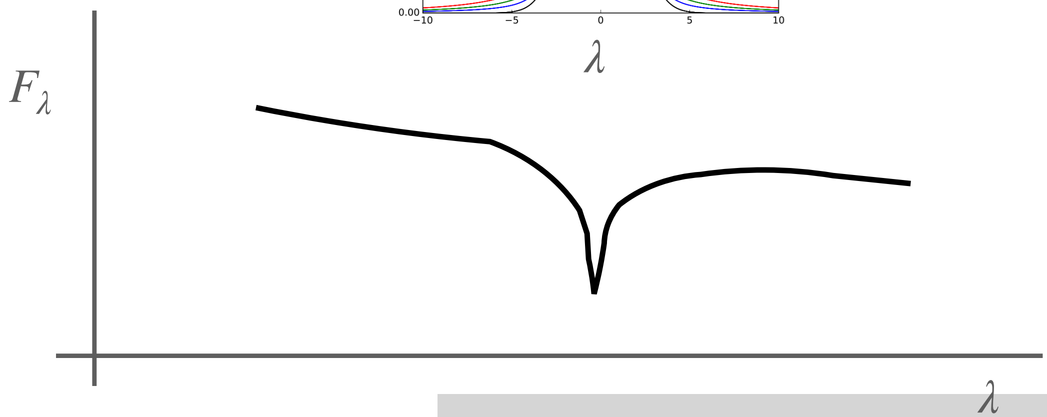




The Voigt Profile: $\sim \tau(\lambda)$

- Use this to profile to model opacity of material for a given spectral line!



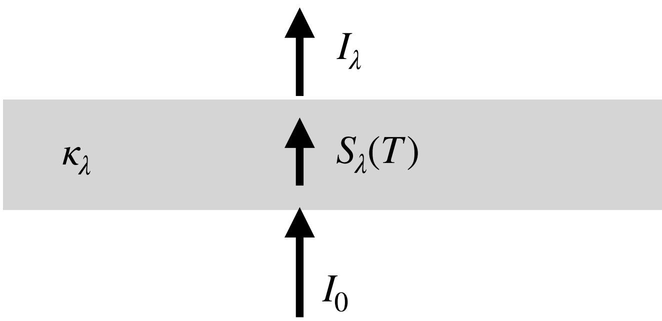


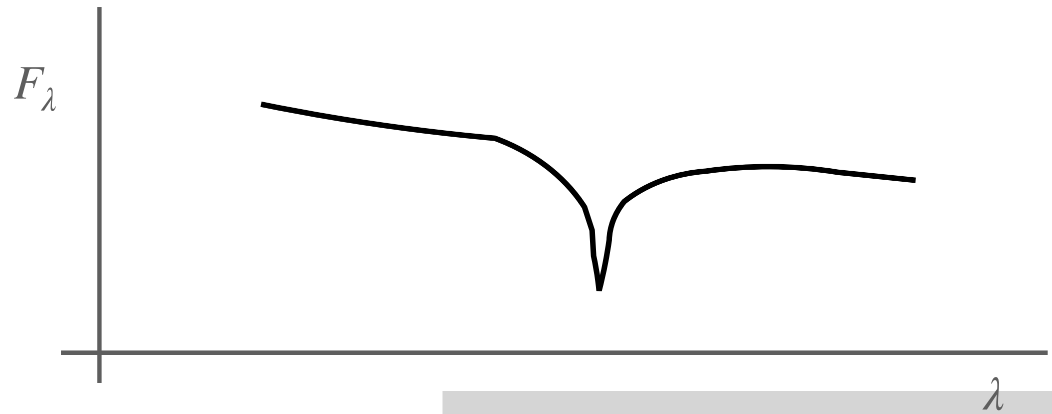
This area reserved for webcam overlay

The Voigt Profile: $\sim \tau(\lambda)$

- Consider a "slab" atmosphere, for a single spectral line…

$$I_\lambda = I_{\lambda,0}\, e^{-\tau_\lambda} + S_\lambda \left(1 - e^{-\tau_\lambda}\right)$$

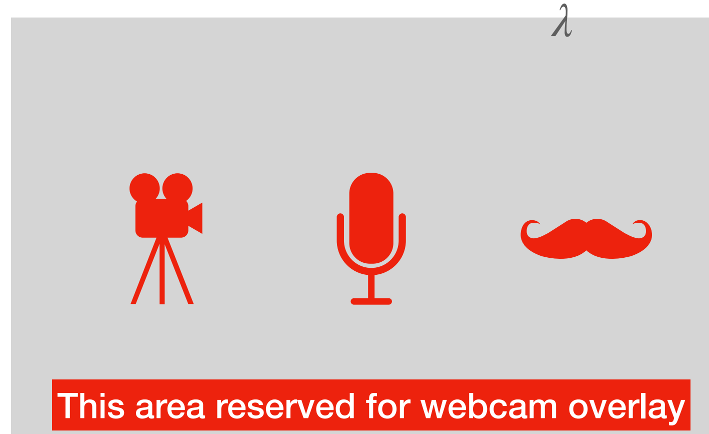




$$\tau(\lambda) = \tau_0\, V(\lambda, \sigma, \gamma)$$

Gaussian (σ)

Lorentzian (γ)



Next time:

- Details of the line broadening mechanisms
- Starting putting pieces together to understand line profiles more
- The Ca II HK lines!
- HW 3 is posted, due next week