ASTR 421

Stellar Observations and Theory

Lecture 06
Opacity: II

Prof. James Davenport (UW)

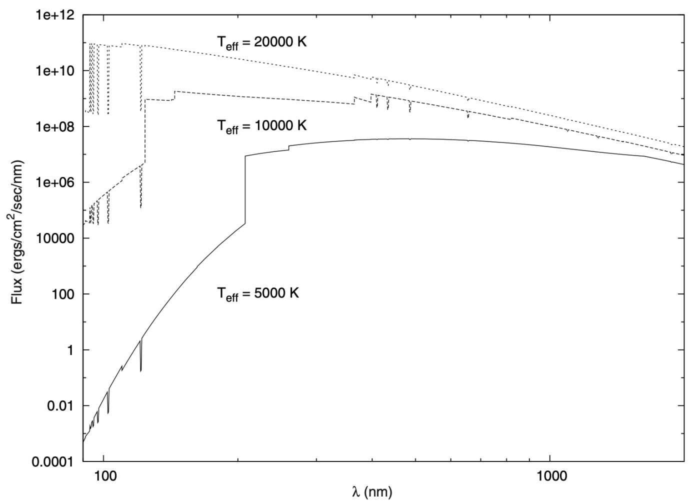
This area reserved for webcam overlay

Last time…

- Sources of opacity: **absorption** and **scattering**
- Mean free path (l), opacity (κ)
- Optical Depth (τ): “thick” vs “thin”

Continuum Opacity

- Continuous sources of opacity are those that work over a wide range of λ
  - e.g. bound-free & free-free transitions
  - e.g. Remember our friend the Balmer Break



Cardona+2009

H- Ion (aka H anion)

- The single e- only partially shields the nucleus, so H *can* attract a **second** e-
- This second e- is weakly bound, $\chi_{ion} \sim 0.75$ ev, rather than 13.6 ev for neutral H
- Thus photons with $\lambda < 1.6\,\mu m$ can ionize the extra e-, called “photodetachment”
- Important for stars with $T_{eff} < 6000$ K (hotter stars destroy H- too easily)
- **Main continuous opacity source in solar photosphere!**

Total Opacity

- In practice, need to consider *all* forms of opacity in the atmosphere simultaneously. Some terms depending on T, density, metallicity:

$$\kappa_\lambda(\rho, T, X_i) = \kappa_{\lambda,bb} + \kappa_{\lambda,bf} + \kappa_{\lambda,ff} + \kappa_{es} + \kappa_{H-}$$

bound-bound

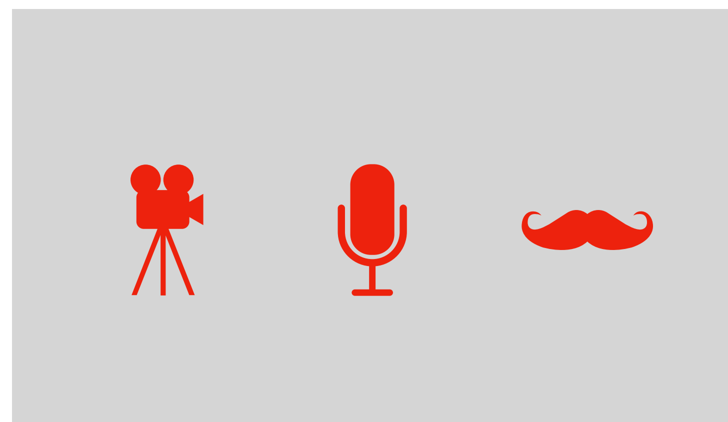
bound-free

free-free

electron scattering

- e- density, excitation/ionization states, other factors for the atmosphere are computed from the total opacity

- Important for estimating the Eddington Luminosity



Total Opacity

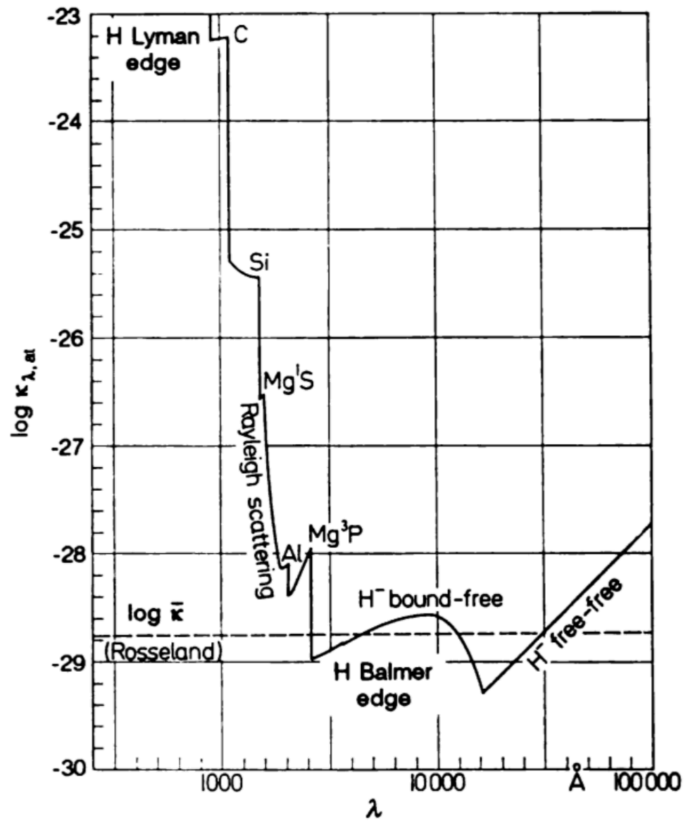


Fig. 4.8.2. The continuous absorption coefficient $\kappa_{\lambda,\mathrm{at}}$ per nucleus in [m^2] in the solar atmosphere (G2V) at $\tau_0 \simeq 0.1$ (τ_0 for $\lambda = 500$ nm), i.e. $T = 5040$ K, $P_e \simeq 0.32$ Pa, $P_g \simeq 5.8 \cdot 10^3$ Pa

Unsold & Baschek "The New Cosmos"

Mean Opacity

- Opacity often averaged over all λ (or ν), written as $\bar{\kappa}$
- Important for describing the *total* opacity of a medium to all photons

$$\kappa_\lambda(\rho, T, X_i) = \kappa_{\lambda,bb} + \kappa_{\lambda,bf} + \kappa_{\lambda,ff} + \kappa_{es} + \kappa_{H-}$$

- Take average as a function of λ
- Typically $\bar{\kappa}$ is called "Rosseland mean opacity", closely related to the "Planck mean opacity"

Mean Opacity

- Rosseland mean opacity:

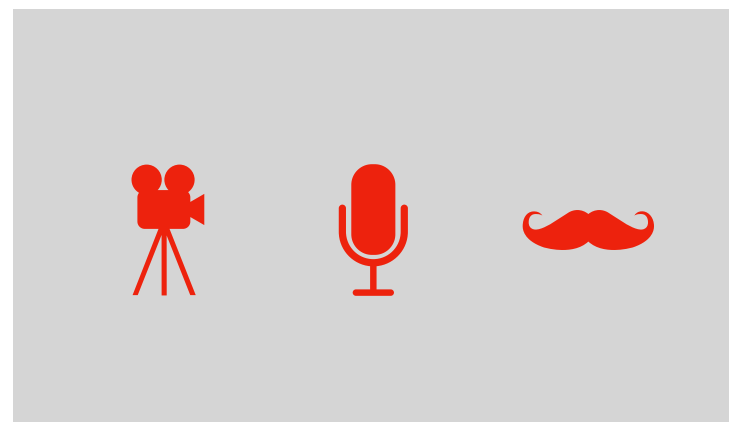
$$\frac{1}{\bar{\kappa}} = \frac{\int_0^\infty \kappa_\nu^{-1} u(\nu, T) d\nu}{\int_0^\infty u(\nu, T) d\nu}$$

$$u(\nu, T) = \partial B_\nu(T) / \partial T$$

Derivative of the Planck (blackbody) function wrt Temperature

$$l = \frac{1}{n\sigma} = \frac{1}{\kappa\rho}$$

Mean opacity -> typical path length!



Mass Fractions

BOB: Ch 9.2

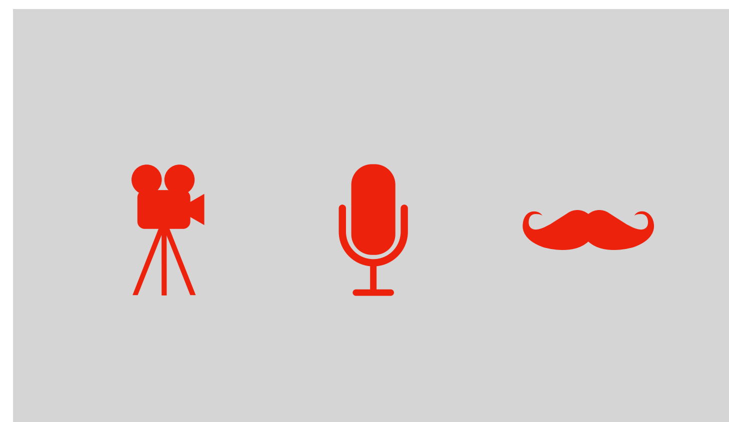
- Kind of non-sequitur… but it's mentioned here, and is *classic* astronomer shenanigans
- **X + Y + Z = 1**
- X = total fraction of mass in H
- Y = total fraction of mass in He
- Z = total fraction of mass in "metals"
- Sometimes stellar metallicity described with Z, rather than [Fe/H]

$$[M/H] = \log(Z/X) - \log(Z/X)_\odot$$

PARSEC isochrones
http://stev.oapd.inaf.it/cgi-bin/cmd

[Fe/H]=[Z/H] , solar Z=0.0142.

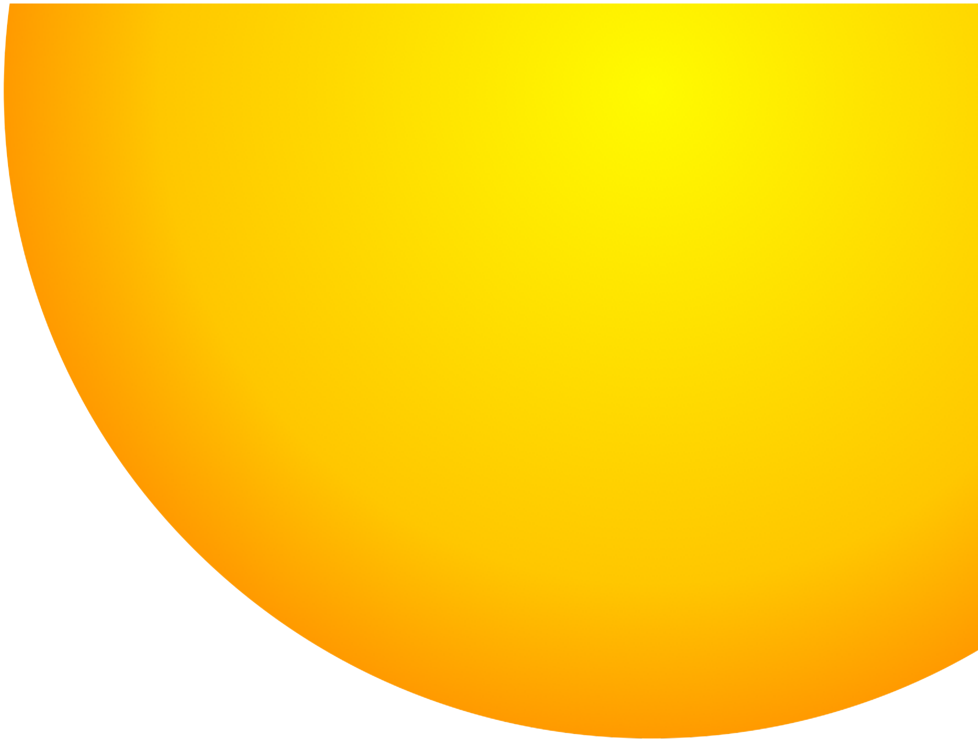
MIST isochrones
http://waps.cfa.harvard.edu/MIST/



Physical/observational examples

- Let’s look at a few in a little more detail…

Surface of a Star



- $\tau \equiv 0$ at the surface
  (by definition, i.e. a boundary condition)

- We see light down to $\tau \sim 1$

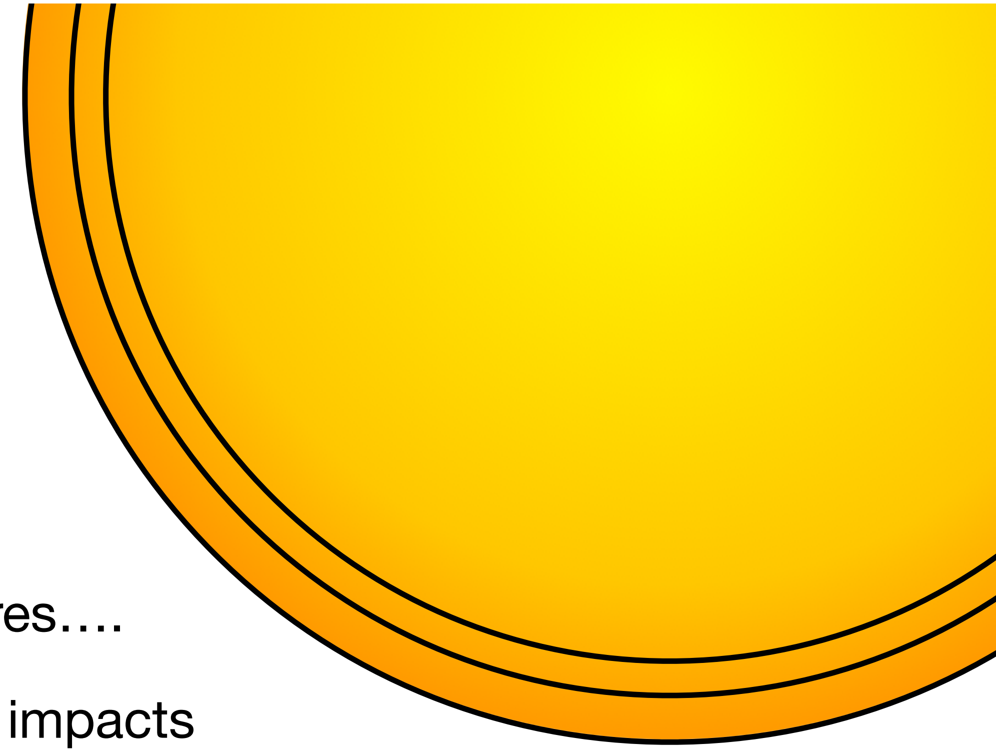
  - This is heavily wavelength dependent!
    (even in spectral lines themselves!)

- Photosphere is classically defined as: $\tau_\lambda \approx 2/3$

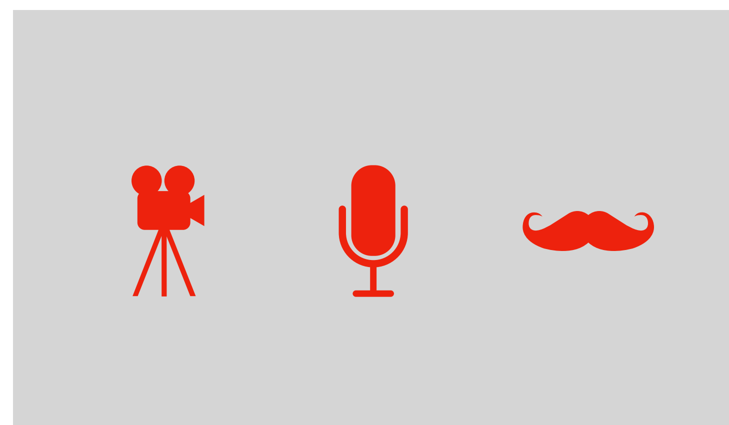
$$I_\lambda = I_{(\lambda,0)}\, e^{-\tau_\lambda}$$

$e^{-2/3} \sim 0.5$, i.e. half the light attenuated

Surface of a Star

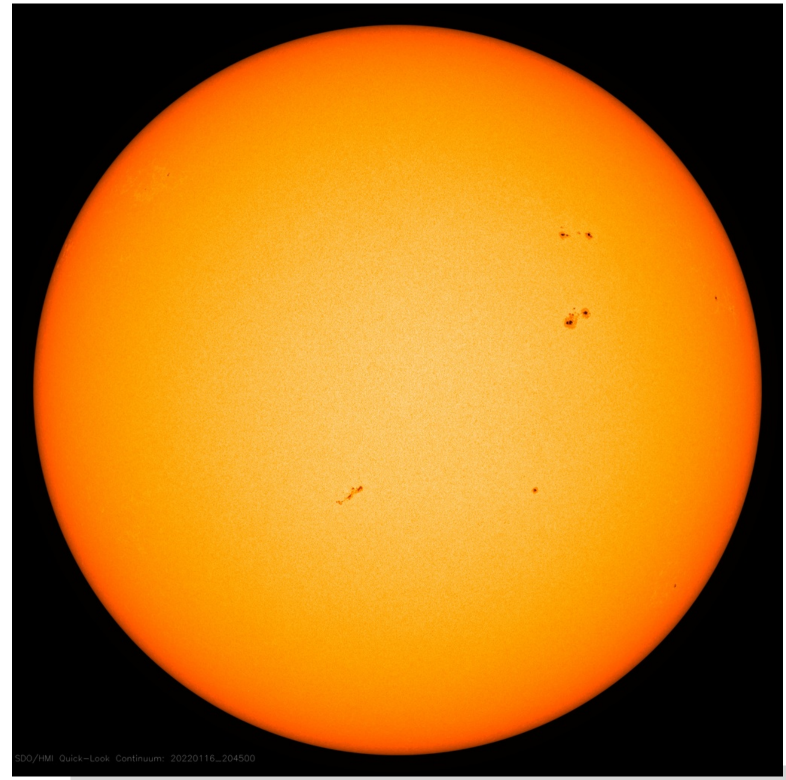


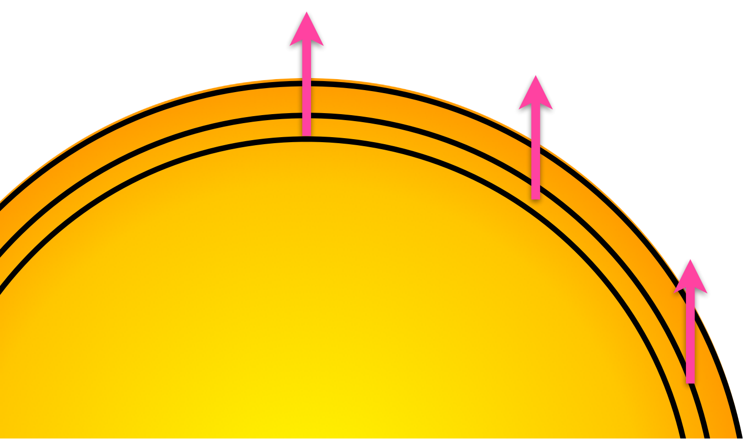
- **Photosphere is wavelength dependent!**
- “radius” of star is wavelength dependent
  - This also true for (exo)planet atmospheres….
- This means e.g. metallicity & composition impacts the stellar radius, since it changes opacity
  - More metals = higher opacity, increased absorption & photon pressure on gas, increased radius, lower T_{eff}



Limb Darkening

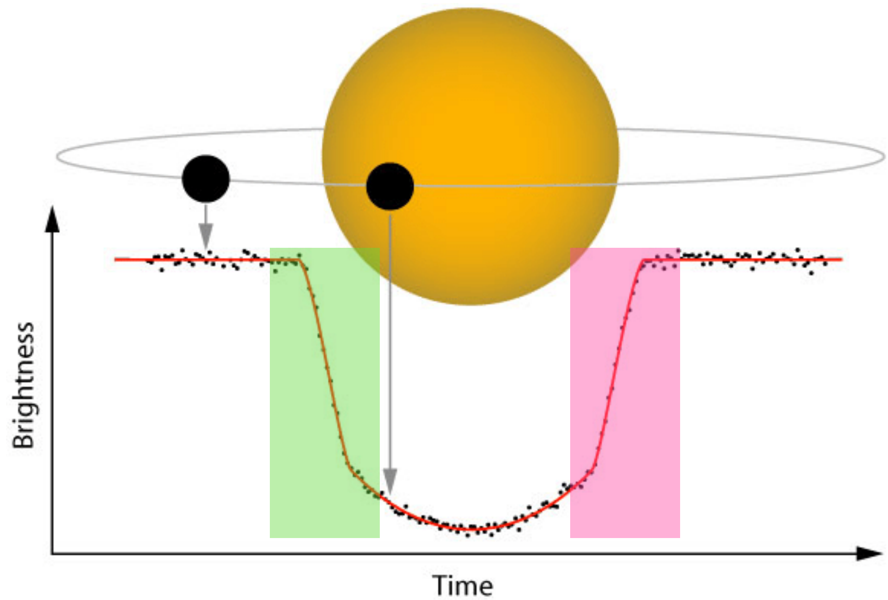
- Star (or Sun) does not *appear* to have uniform brightness across the surface (disk)
- e.g. see this actual photograph!
- Temp of gas reaching $\tau = 1$ is *lower* near limb, causing star to appear and fainter near limb, brighter in center

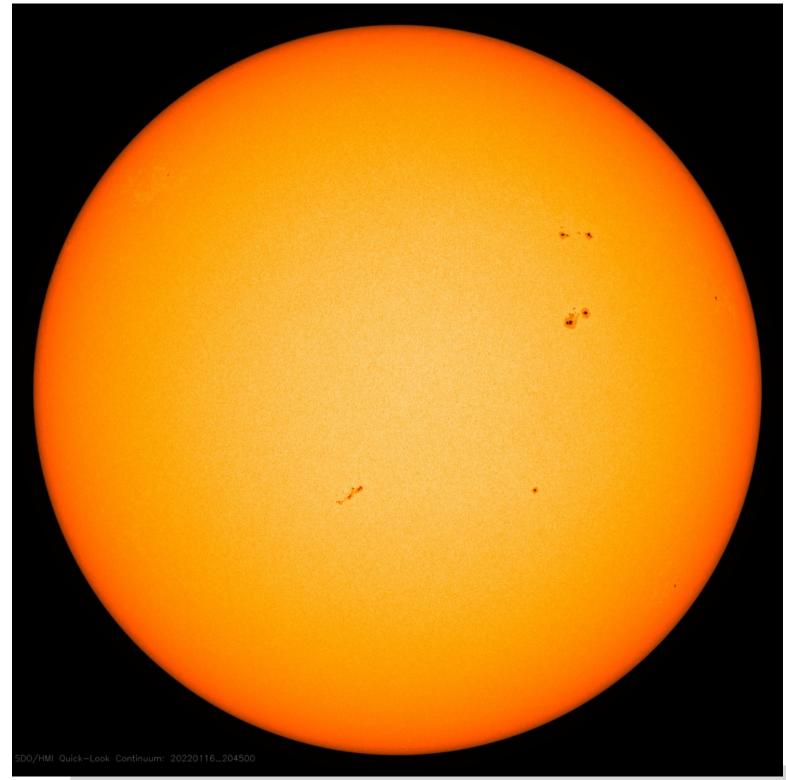




Limb Darkening

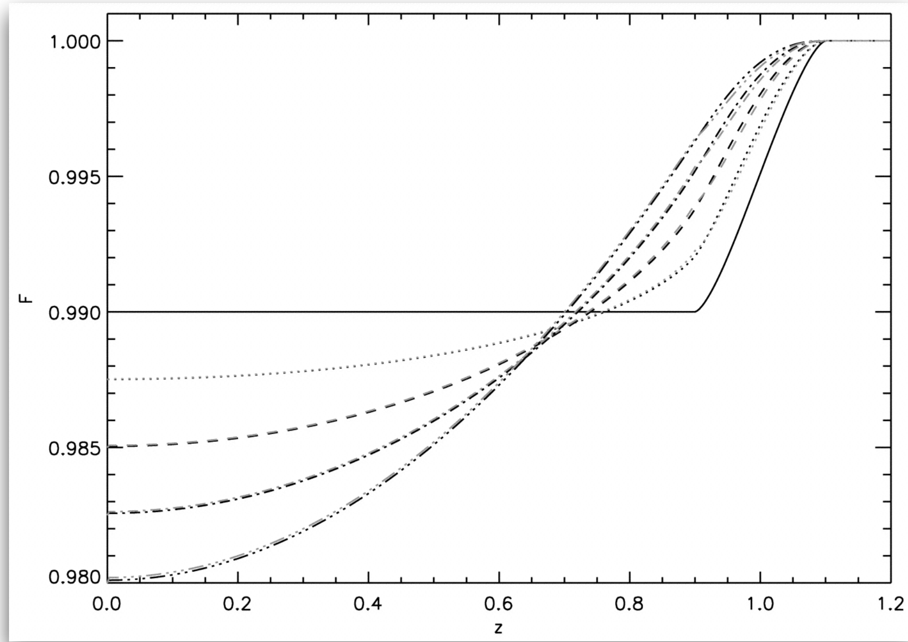
- One place this is SUPER important: transits!
- Planet is opaque (to 1st order)
- Limb darkening determines shape of transit esp. **ingress** and **egress**

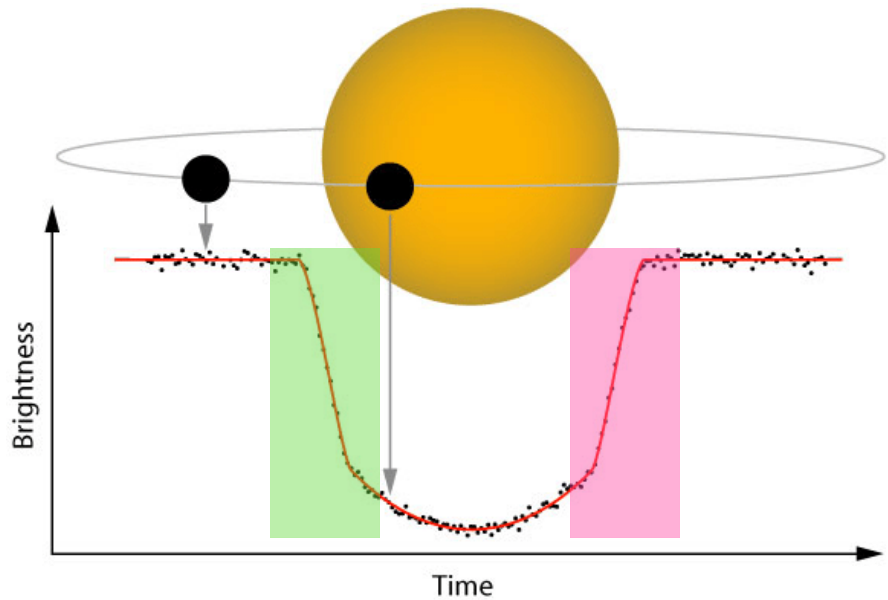




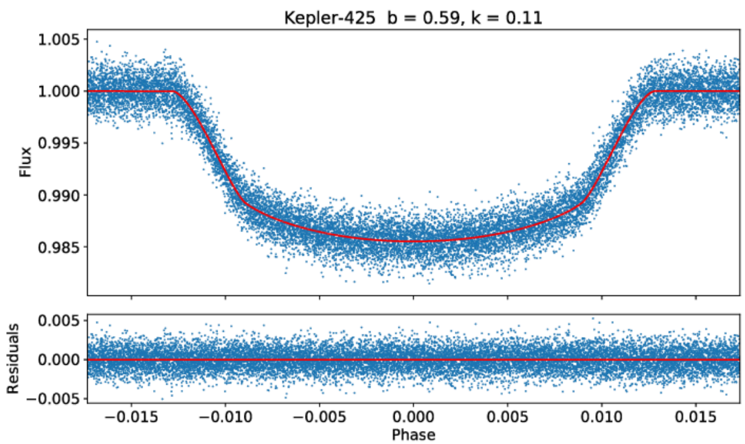
Limb Darkening

- The industry standard for describing limb darkening for transits is: **Mandal & Agol (2002)**

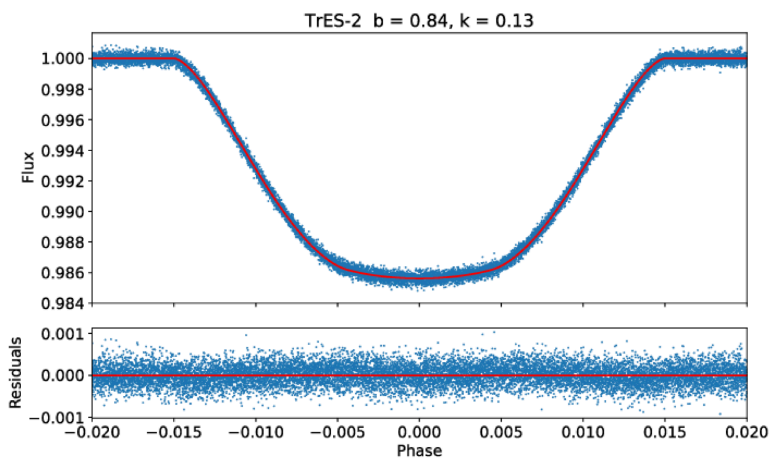




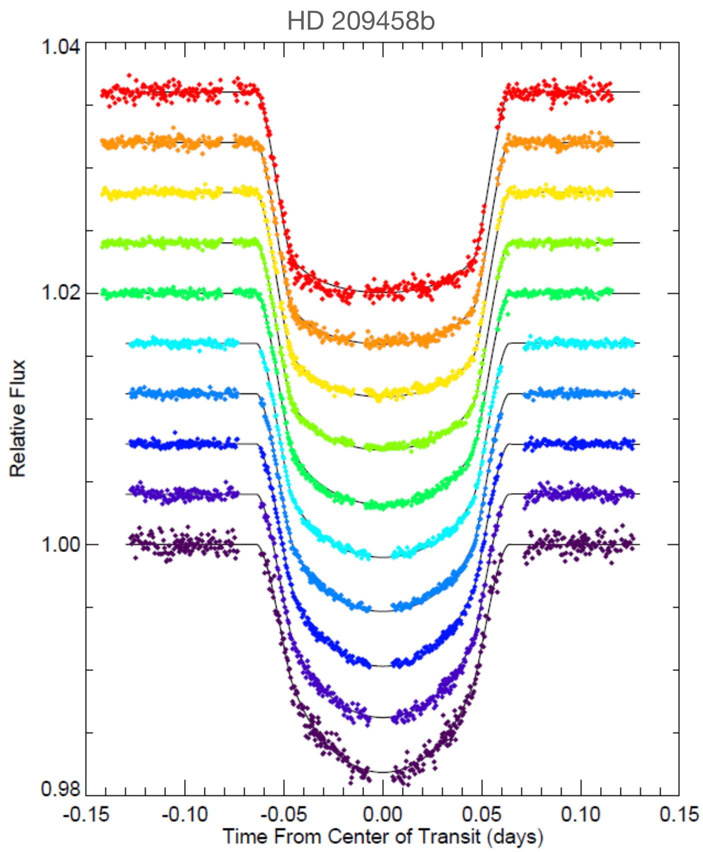
Limb Darkening

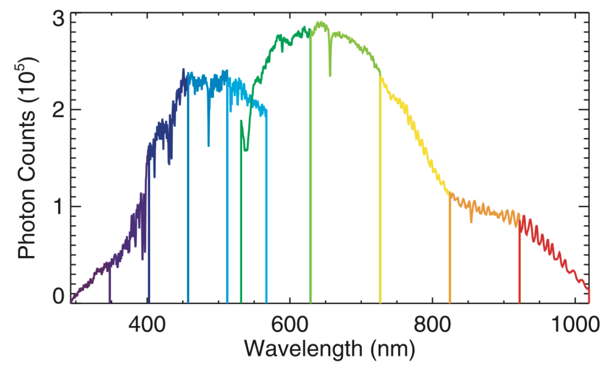


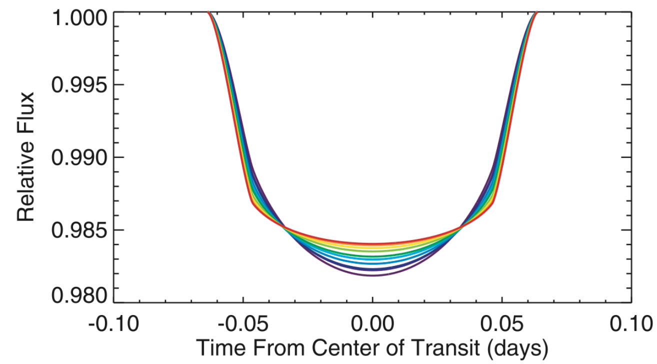
Maxted (208)



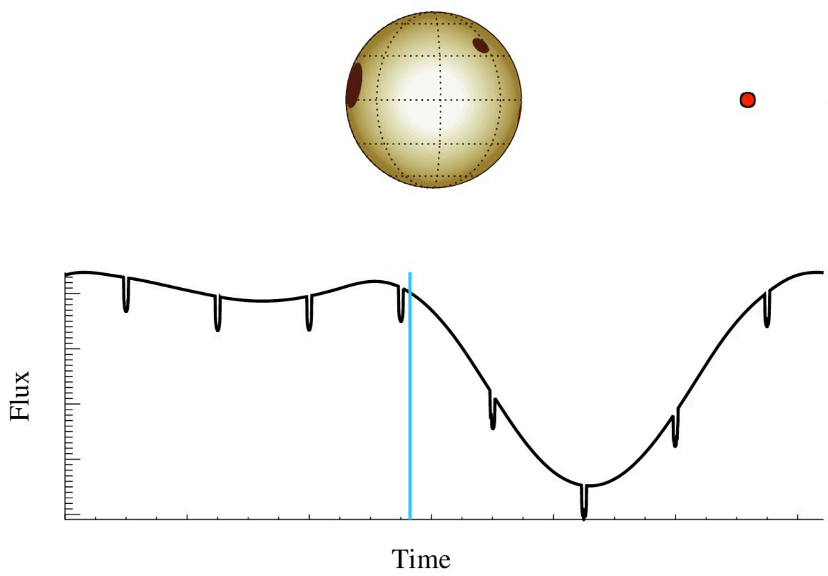
Limb Darkening







Knutsen+2007



Davenport, Hebb, & Hawley (2015)

Examples of scattering and absorption

Mie scattering
Like Rayleigh scattering , but for big particles!
(DUST)

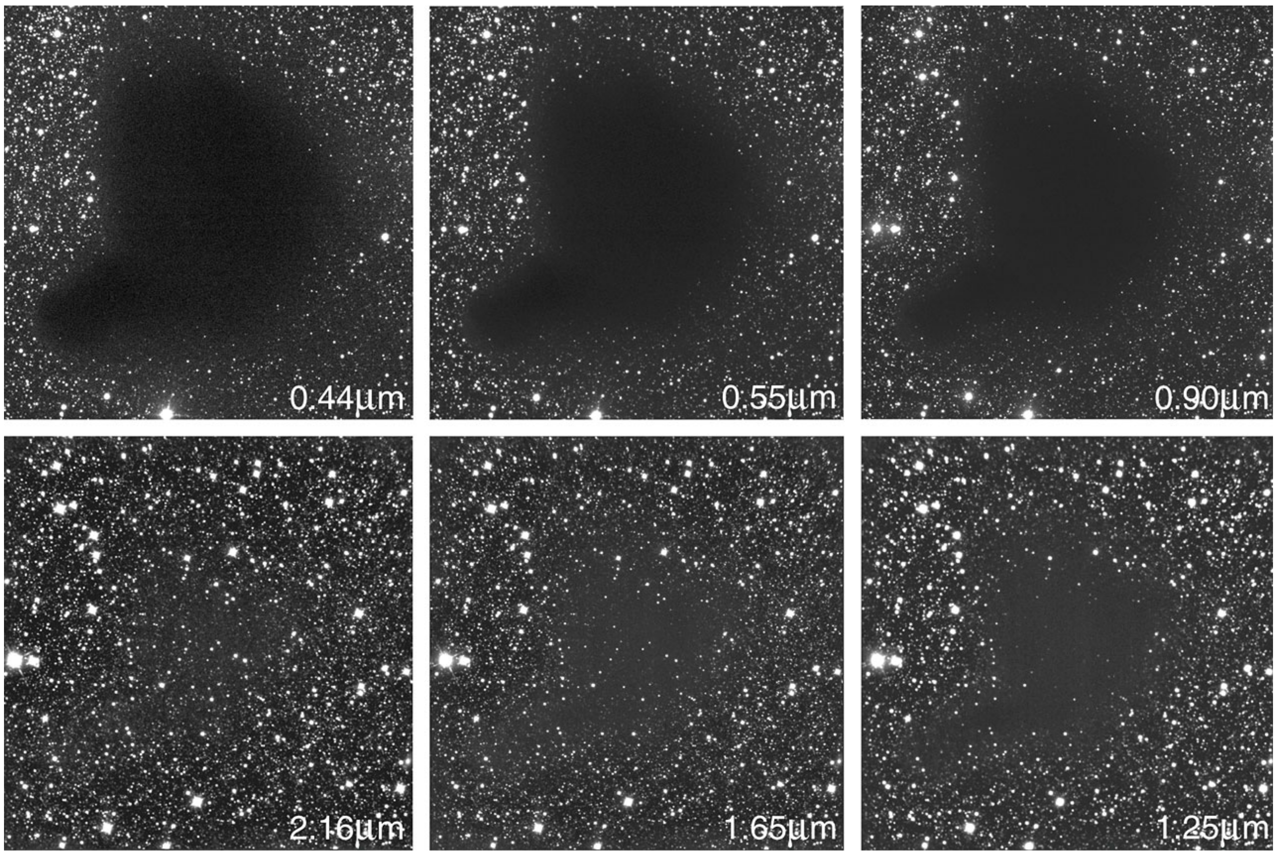
FUN FACT:
This dust is not part of the Pleiades, but is an interstellar cloud the cluster is moving through at 6-10km/s

Examples of scattering and absorption

"Bok Globules"
VERY effective absorption

Examples of scattering and absorption

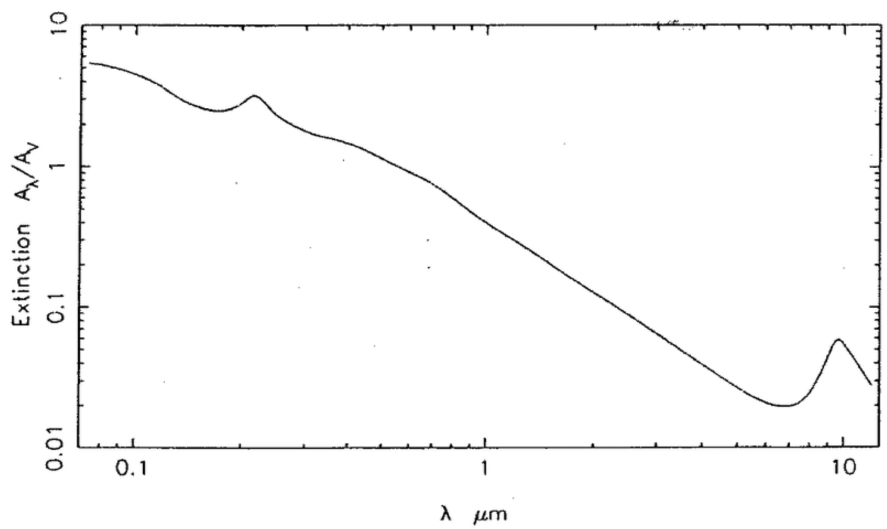
Barnard 68



https://www.eso.org/public/images/eso9934b/

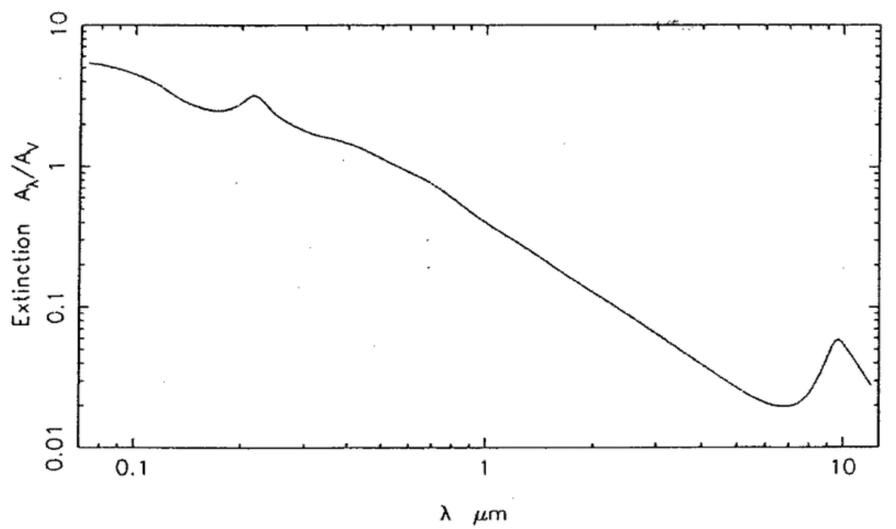
Dust extinction

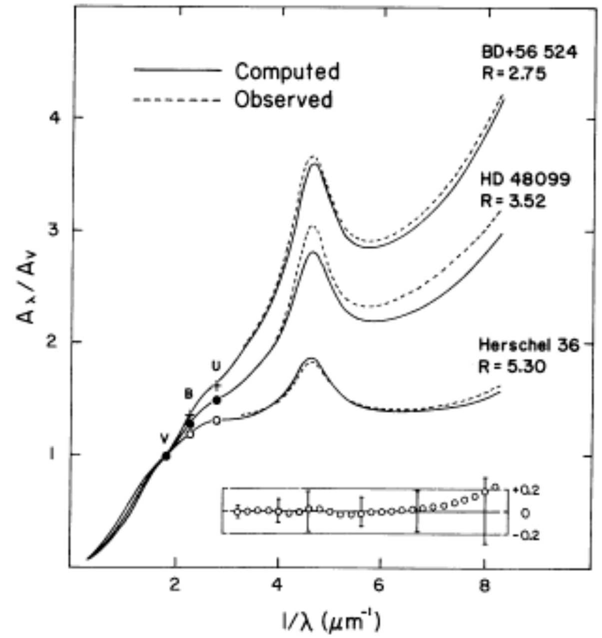
- Continuum scattering and absorption from molecules
- Silicates, hydrocarbons, PAH's… lots of complex molecules!



Dust extinction

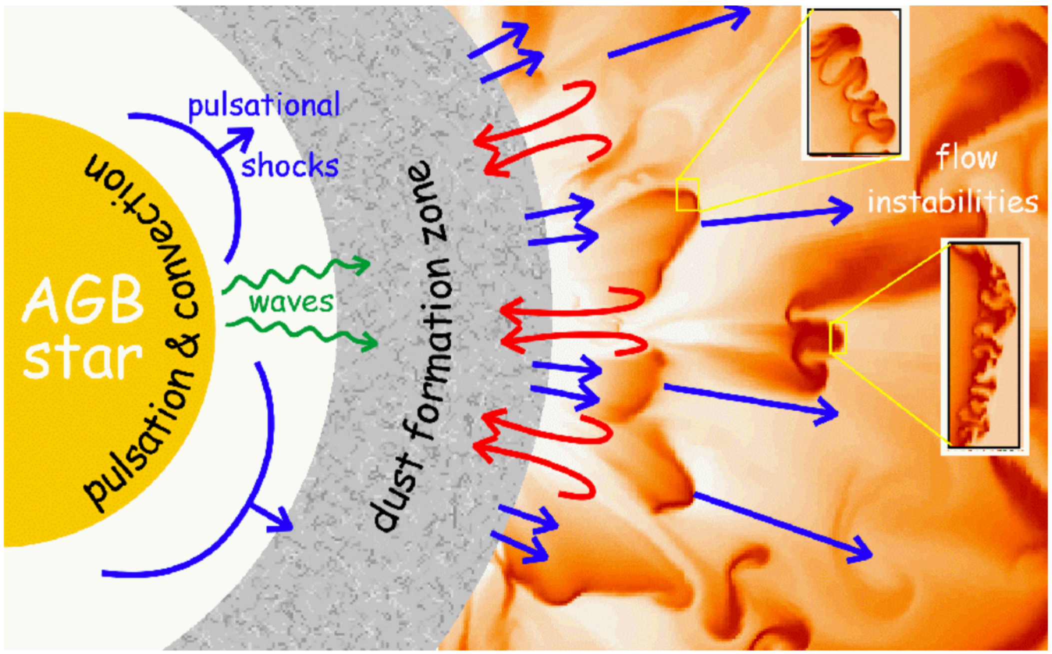
- Curve is smooth (continuum opacity at work)
- Very important at short λ





Opacity driven dust formation (e.g. AGB stars)

At *very* large radius, material cools, forms dust.



http://www-star.st-and.ac.uk/~pw31/AGB_popular.html

Dust has VERY high opacity,
blocks light from star well.

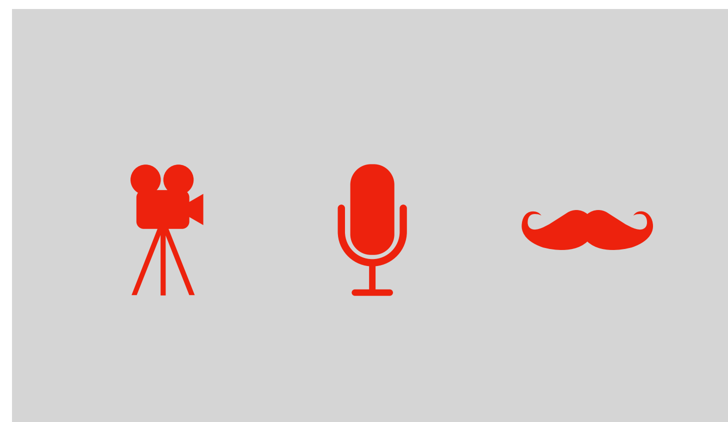
Radiation pressure ejects dust!

Kappa mechanism

- AKA the “Eddington Valve”
- Opacity driven pulsation (revisit this when we talk about pulsators in a few weeks)

This is opposite what we might expect, happens in ionization **shell** in atmosphere

  - Gas “falls”, heats up, *increases opacity*
  - This increases radiation pressure, pushes gas (atmosphere) out
  - Temperature decreases, opacity drops
  - Cycle repeats



Next time:

- Radiative Transfer!