ASTR 421

Stellar Observations and Theory

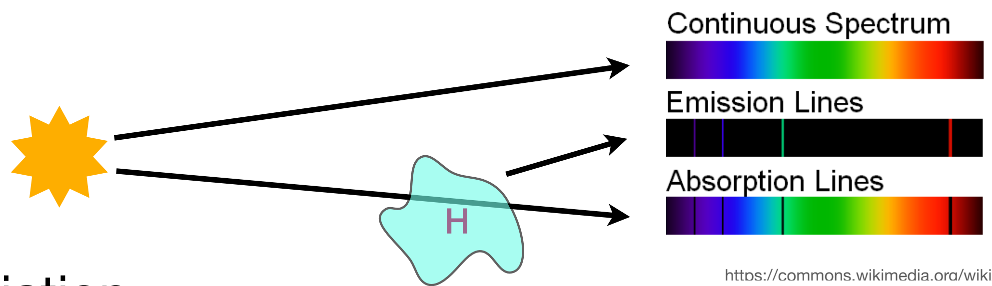
Lecture 05
Opacity

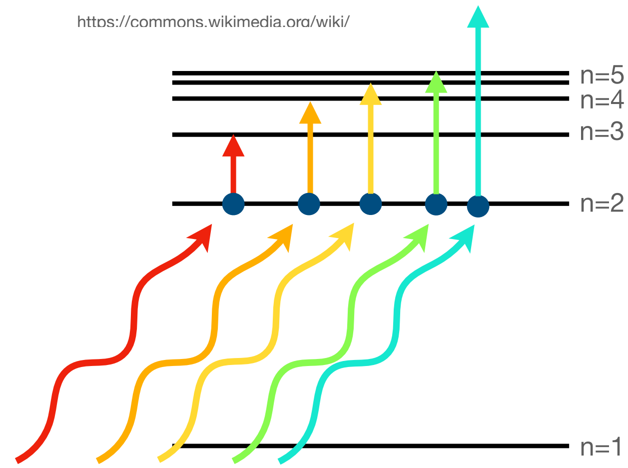
Prof. James Davenport (UW)

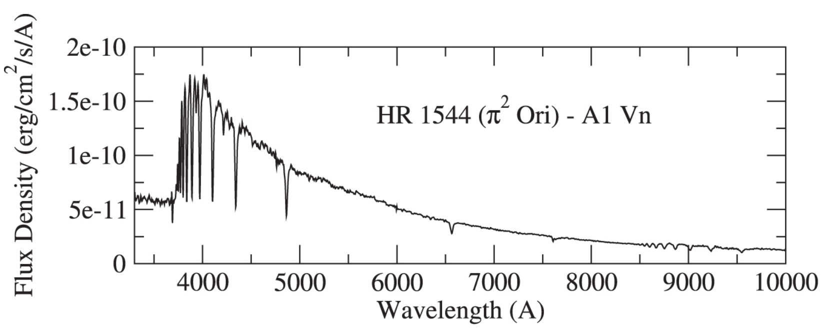
This area reserved for webcam overlay

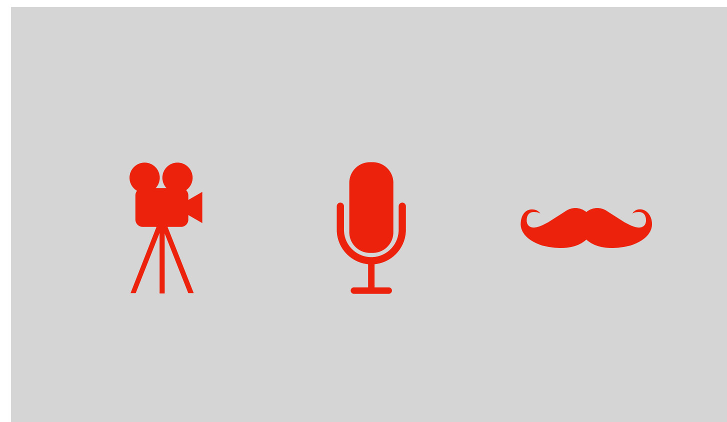
Last week…

- Thermal (blackbody) radiation
- Boltzmann & Saha Eqns
- Properties of real spectra
(e.g. continuum, lines, jumps/breaks)



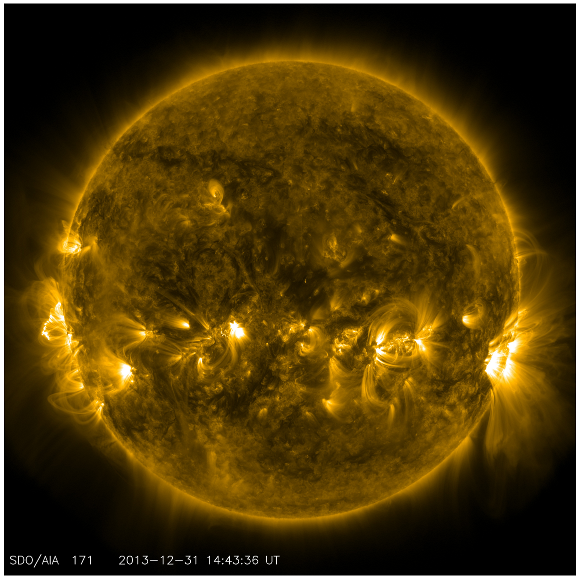






Today’s Goal: Understanding Opacity

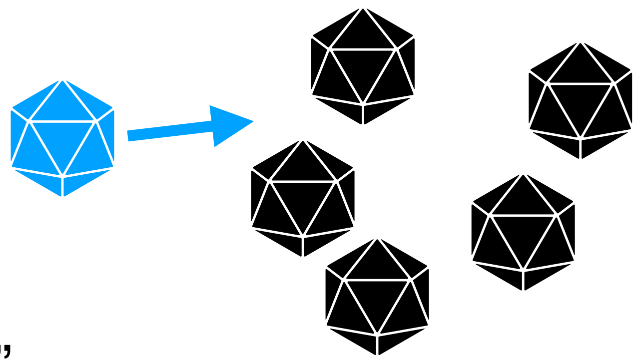
- How is opacity defined?
- How do we define the “surface” of a star
- Types of opacity in a star



Mean Free Path

- How far can a particle travel before colliding with another?

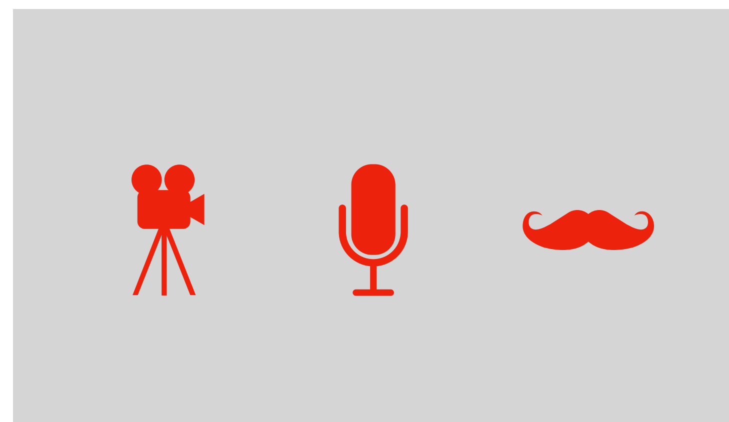
$$l = \frac{1}{n\sigma}$$



- n is the "number density" [1/cm^3]
- σ is the "collisional cross section" [cm^2]
- Important concept for gas dynamics (e.g. Maxwell-Boltzmann velocity distribution) and for "opacity" (i.e. photons interacting with things)

Opacity…

- Definition: ability for material to **absorb or scatter** a photon
    - Relatedly: how far can a photon travel in a material before it is absorbed/scattered

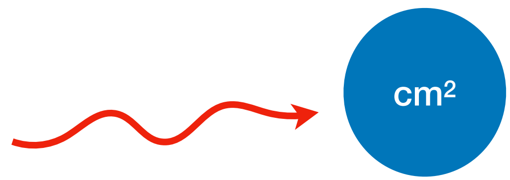


Opacity…

- Definition: ability for material to **absorb or scatter** a photon
    - Relatedly: how far can a photon travel in a material before it is absorbed/scattered
- High opacity (i.e. opaque), photons can’t make it through the object
- Low opacity (i.e. transparent), photons make it through w/ some absorption.
- Primarily due to: **density**
  (actually the “column density”)
- Also due to: **composition, temperature**

Opacity…

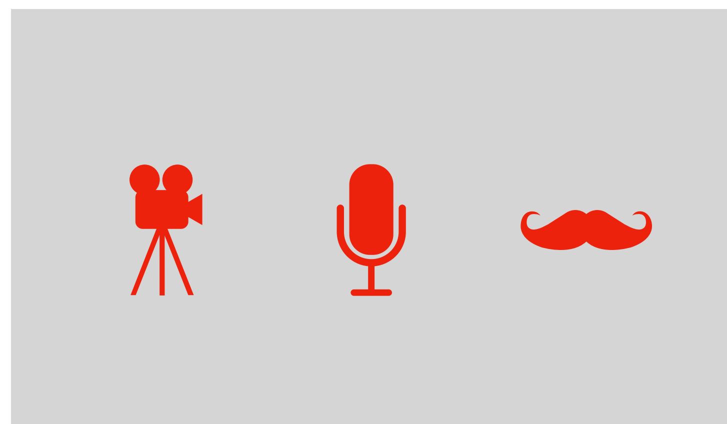
- Opacity, or absorption coefficient, usually written as: κ
- $[\kappa] = \mathrm{cm}^2/\mathrm{g}$



looks like:
(cross-section per particle) / (g of material)

Metals have high opacity!

- This is why it's "column density" that determines observed opacity.

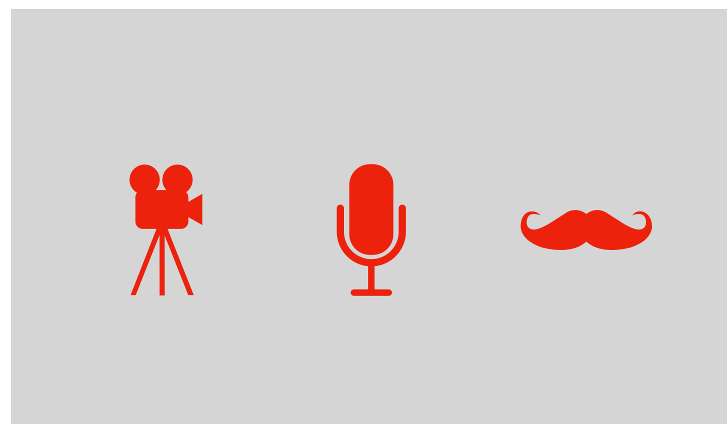


Opacity…

- Change of intensity over a distance (s) due to an opaque material is:
  $dI_\lambda = -\kappa_\lambda \rho \, I_\lambda ds$

- So, $I_\lambda = I_{(\lambda,0)} \, e^{-\kappa_\lambda \rho \, s}$
  - $\kappa\rho$ is like the “length scale” for absorption here
  - Recall mean free path for collisions

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



Optical Depth

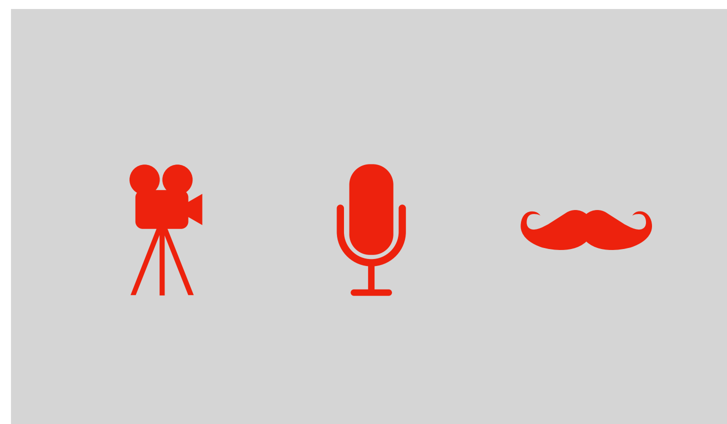
- *Not* the same as the characteristic length!
- Important concept for stars, defining where emission comes from

$$dI_\lambda = -\,\kappa_\lambda \rho \; I_\lambda ds$$

$$d\tau_\lambda = -\,\kappa_\lambda \rho \; ds$$

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

- Where τ (the optical depth) is the number of mean free paths along a line of sight, or the "thickness" of a gas
- τ >>1: optically thick, τ<<1: optically thin



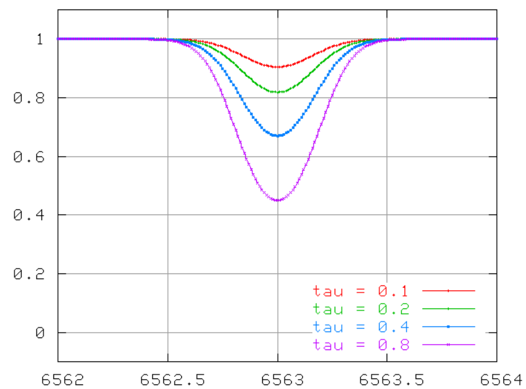
Optical Depth

- In simplest case, weak lines give you direct map of optical depth for the optically thin absorbing material

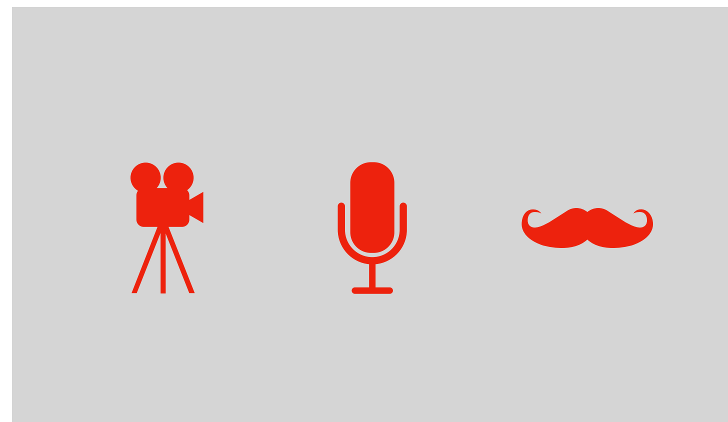
$$dI_\lambda = -\,\kappa_\lambda \rho \, I_\lambda ds$$

$$d\tau_\lambda = -\,\kappa_\lambda \rho \; ds$$

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



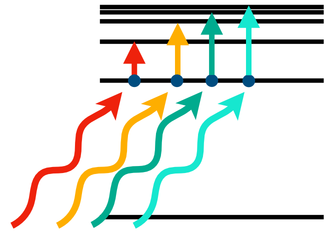
http://spiff.rit.edu/classes/phys440/lectures/curve/curve.html



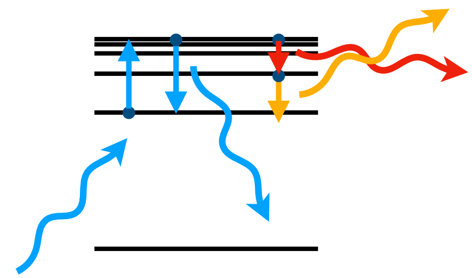
Surface of a Star

- $\tau \equiv 0$ at the surface
- We see light down to $\tau = 1$
  - This is heavily wavelength dependent! (even in spectral lines themselves!)
- Photosphere is classically defined as: $\tau_\lambda \approx 2/3$
  - Photosphere is wavelength dependent!

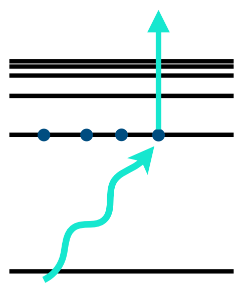
Sources of Opacity

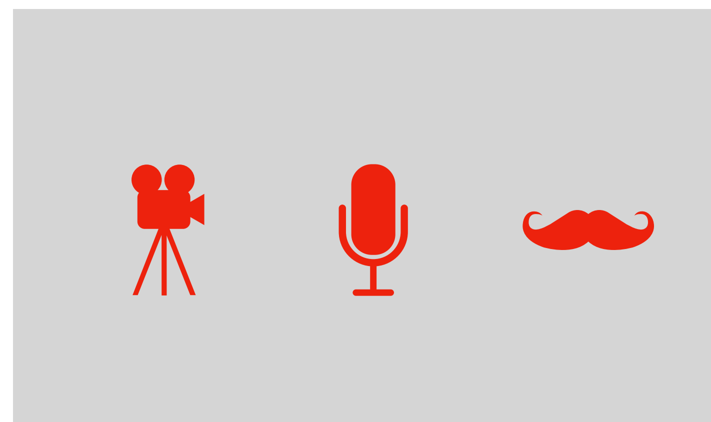


- Absorption: photon is removed (for a while)
  - Bound-Bound, at discrete wavelengths, forms absorption lines, as discussed.
    If quickly re-emits, acts like scattering, & can change the λ
    Sometimes called “line scattering”

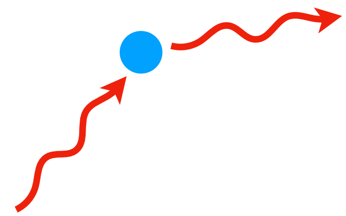


  - Bound-Free, above a wavelength threshold, *photoionization*

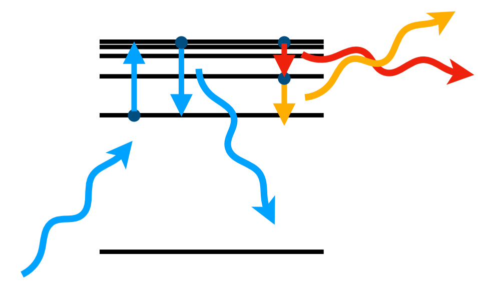




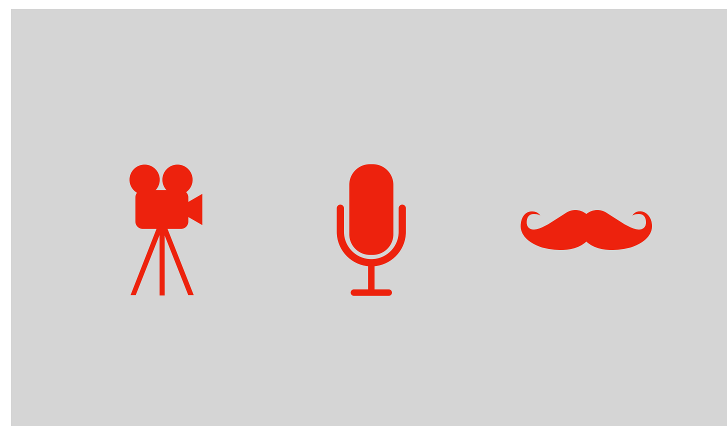
Sources of Opacity



- Scattering: photon is redirected
- Acts as absorption in one direction & emission in another

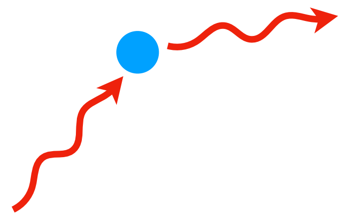


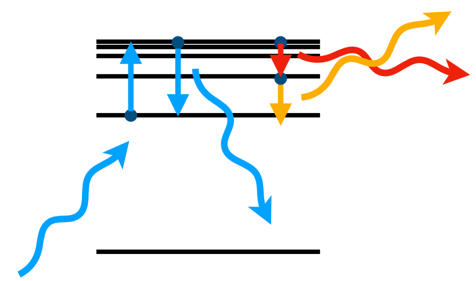
- Many kinds of scattering (names can be confusing) work in a similar way:
    - Photon approaches electron
    - Electron "vibrates" due to photon's **B** field
    - Photon leaves in another direction

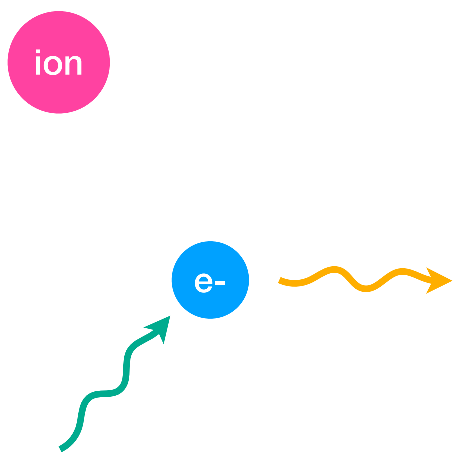


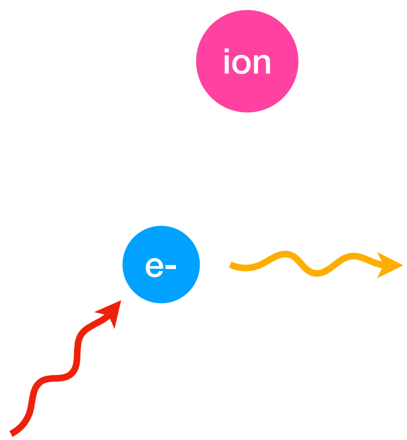
Sources of Opacity

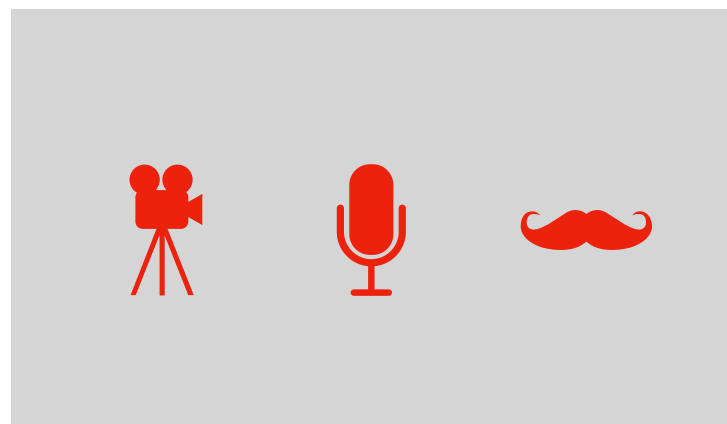
- <u>Scattering</u>: Many configurations





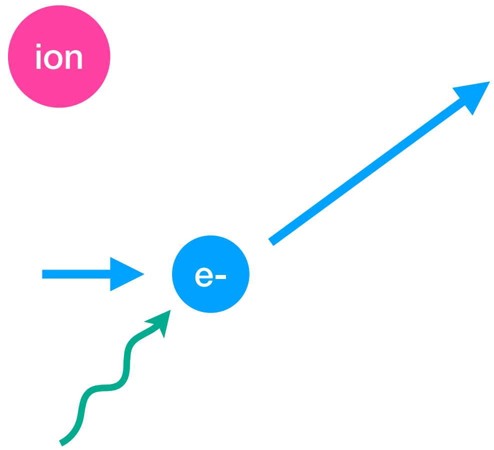




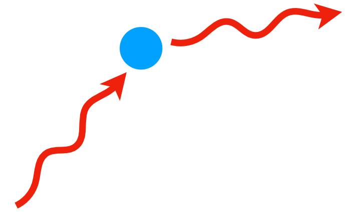


Sources of Opacity

- Scattering:
- **Free-Free**: absorption by a "free" electron in the presence of (but not bound to) an ion
- Can occur from any wavelength photon, acts as a "continuous" opacity
- The opposite scenario: an e- loses energy passing by an ion, emits a photon, called "Bremsstrahlung" radiation.
  - This includes both "synchrotron" & "cyclotron" radiation, but we won't discuss here



Sources of Opacity



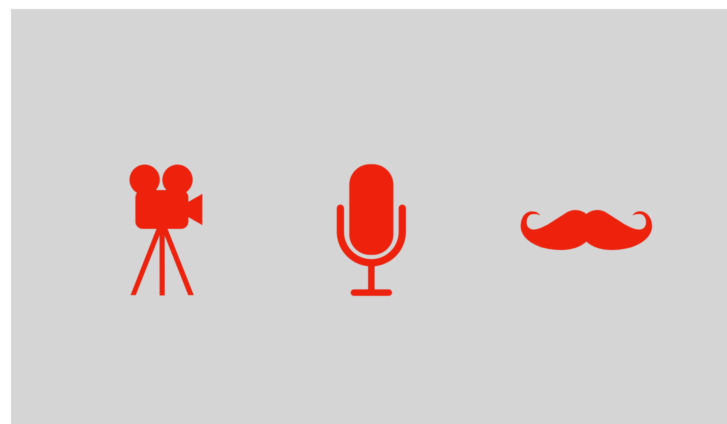
- <u>Scattering:</u>

- Pure (elastic) electron scattering is called **Thompson Scattering**

- Cross-section is related to the classical radius of the electron!
  $\sigma_T = \frac{8\pi}{3} r_e^2 \approx$ 6.65e-29 m^2

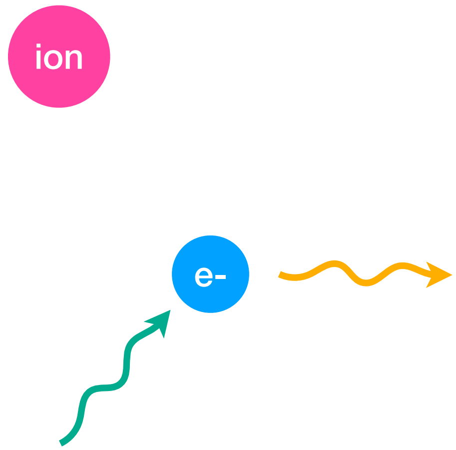
- Not wavelength dependent, so only depends on *electron density*

- Important for very hot (ionized, lots of e-) and dense gas: deep in stellar interiors!



Sources of Opacity

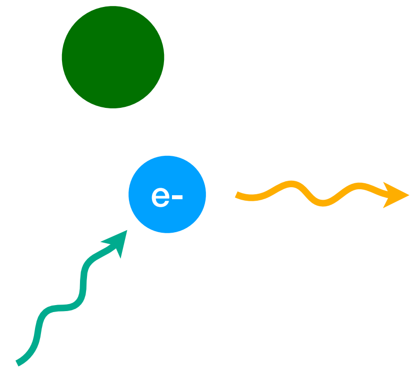
- <u>Scattering:</u>
- **Compton Scattering**: inelastic
- If the e- is in the presence of an ion, the e- can exchange momentum from the photon
- This usually results in heating of the e- (lower energy photon)
- Can also impart energy to the photon, called the *inverse* Compton effect
- Relativistic effects are important for detailed calc.



Sources of Opacity

- <u>Scattering:</u>

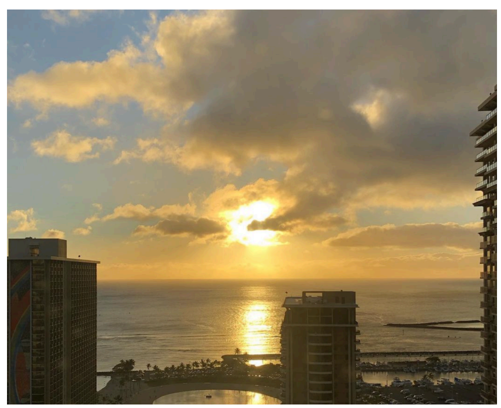
- Similar to Compton, **Rayleigh Scattering** happens often for electrons around molecules or atoms

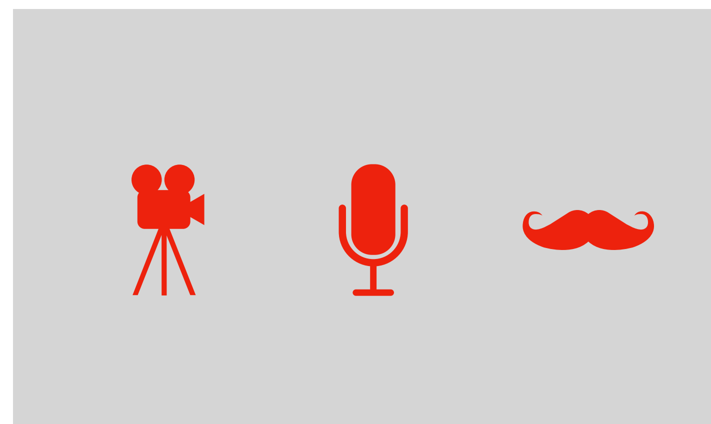


- Very wavelength dependent

$$\sigma \sim 1/\lambda^4$$

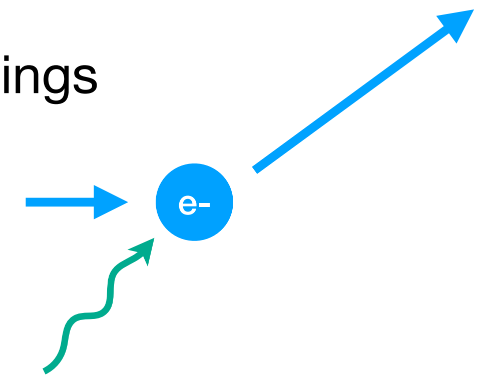
- This is broadly the cause of the blue sky, & the colors at sunset



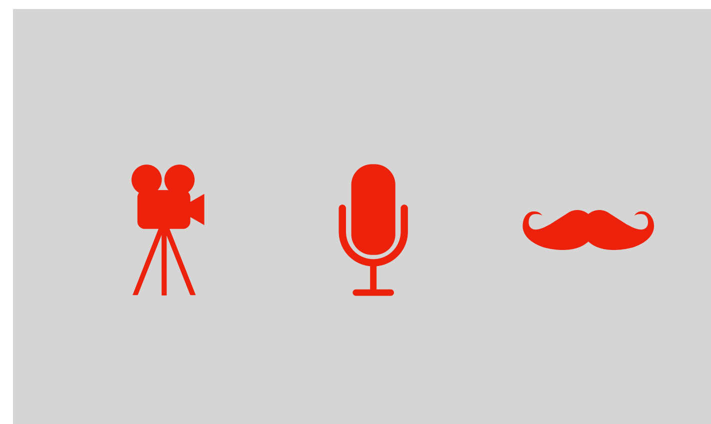


Radiation Pressure (Briefly)

- Photons have momentum, and so exert pressure on things (called radiation pressure)
  $p = h/\lambda$



- If you had TOO much light, this pressure would start launching material off a star
- This is known as the **Eddington Luminosity**
- More opacity, easier to impart pressure from radiation



Next time:

- Opacity of the H- ion in the Sun
- Limb Darkening
- Total Opacity
- Spectral Lines

- Reading: BOB Ch 9.1-9.2; LeBlanc Ch 3.1-3.3