Astronomía estelar

2024

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Clase 9

Atmósferas estelares - II

Chapter 9: Stellar Atmospheres

Why do we only see photons from the photosphere? By definition, this is the layer of the Sun where photons can escape freely into space.

Processes that remove photons from a parallel beam of light are collectively termed absorption.

- *Atomic absorption*
- *Compton scattering*
- *Molecular transitions*

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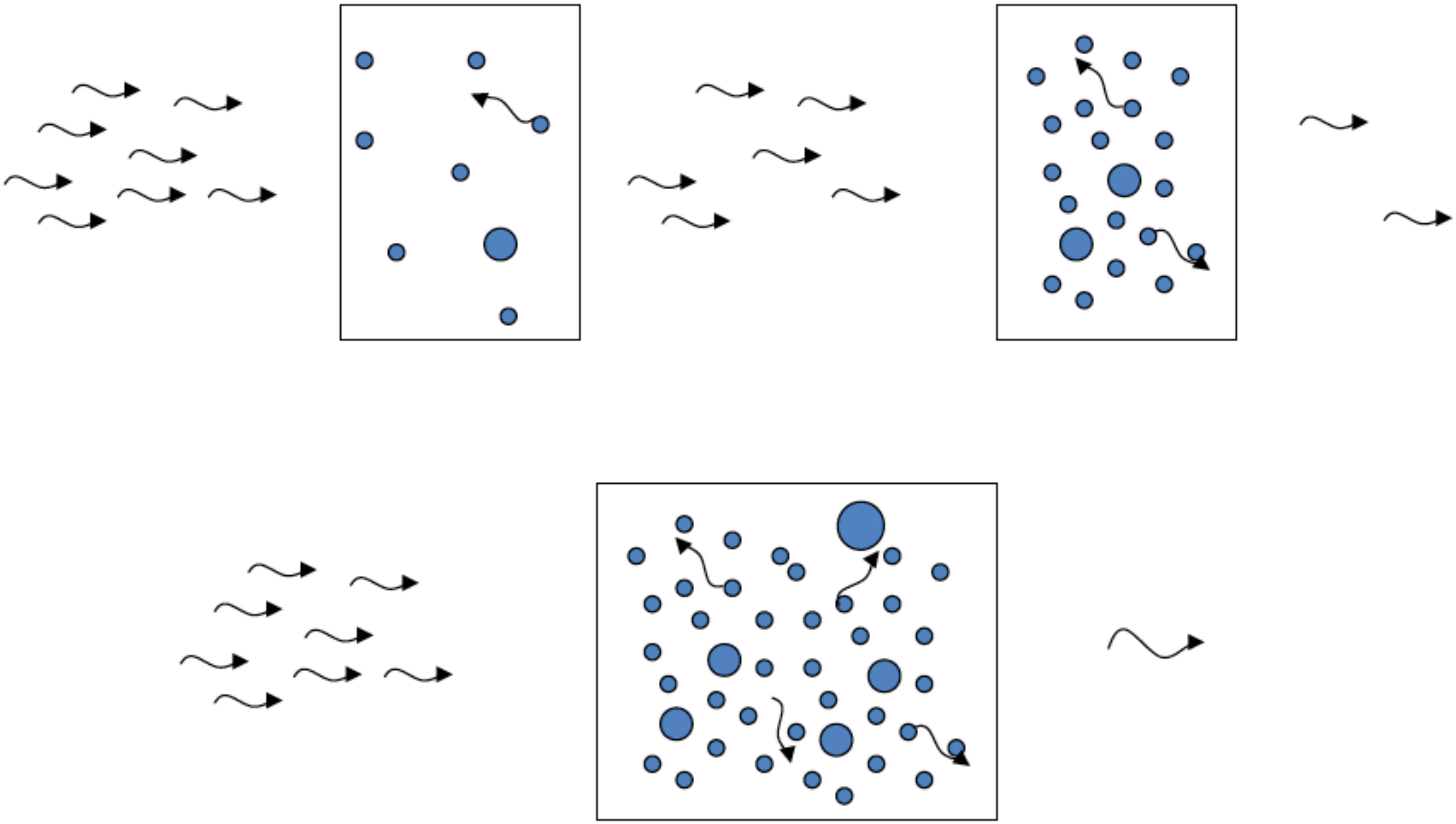

The number of incoming photons that make it through a gas depends on…?

distance traveled, density of the gas and cross-sectional area of intervening particles.

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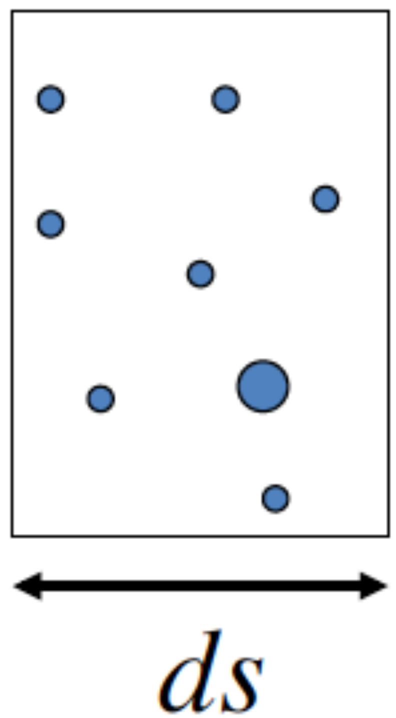

Opacity, κ_λ

cross-section for absorbing/removing photons of wavelength $\lambda + d\lambda$ per unit mass of stellar material.

κ_λ is also called the absorption coefficient and is wavelength dependent

The loss in photon intensity is proportional to $\kappa_\lambda \rho I_\lambda$, and ds:

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

Greater the absorption coefficient, κ_λ, the more photons removed.

Greater the particle density, ρ the more photons removed

Greater the incoming intensity, the more photons removed

Longer the path, ds, the more photons removed

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The final intensity of light through a gas:

$$\int_{I_{\lambda,init}}^{I_{\lambda,final}} \frac{dI_\lambda}{I_\lambda} = -\int_0^s \kappa_\lambda \rho \, ds$$

$$I_\lambda = I_{\lambda,init} e^{-\int_0^s \kappa_\lambda \rho \, ds} = I_{\lambda,init} e^{-\kappa_\lambda \rho s}$$

Intensity decreases exponentially, falling by a factor of e^{-1} over a characteristic distance, $\ell = 1/\kappa_\lambda \rho.$

In the solar atmosphere:

- $\rho = 2.1 \times 10^{-4}$ kg m^{-3}
- $\kappa_{500} = 0.03$ m^2 kg^{-1}

ℓ=160 km the typical distance traveled by photons before being removed from the light beam.

This distance is comparable to the temperature scale height, showing that photons do not see a constant temperature and the LTE approximation is not strictly valid.

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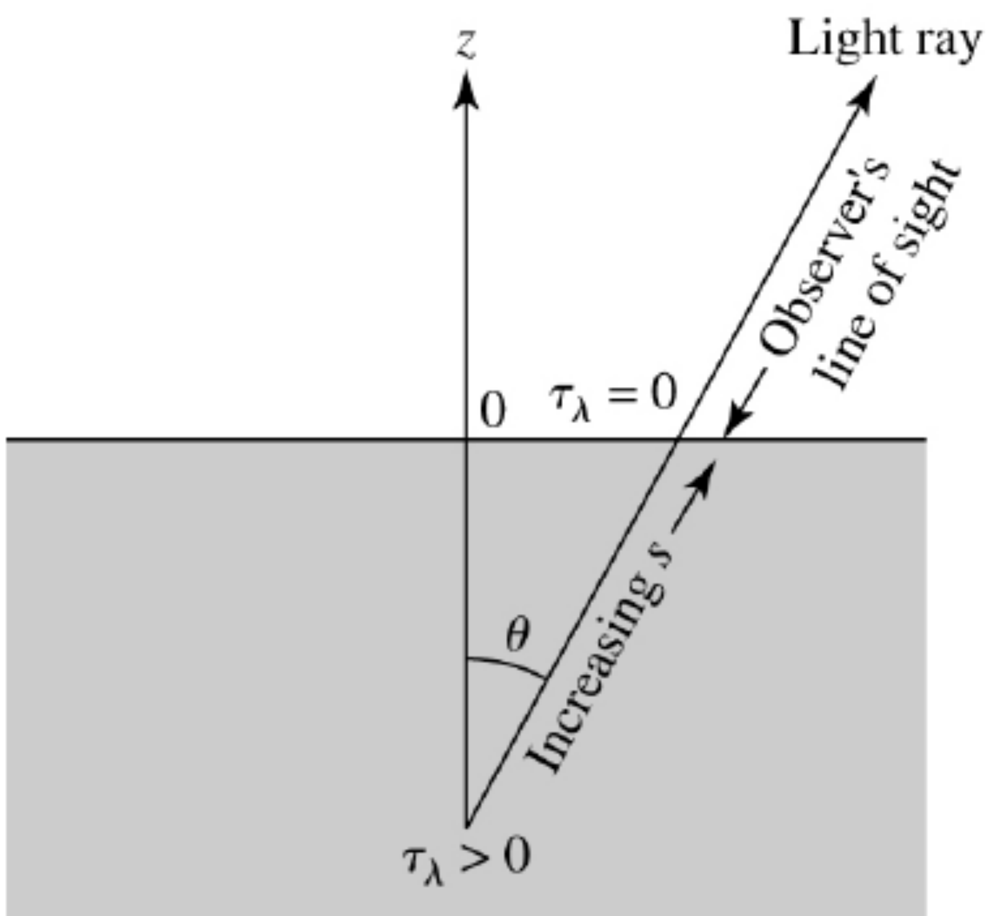

Optical Depth, τ_λ

For scattered photons the characteristic distance, ℓ, is the m.f.p. of the photons.

$$l = \frac{1}{\kappa_\lambda \rho} = \frac{1}{n\sigma_\lambda}$$

Both $\kappa_\lambda \rho$ and $n\sigma_\lambda$ can be thought of as the fraction of photons scattered per meter

$$\boxed{d\tau_\lambda = -\kappa_\lambda \rho \, ds}$$

Difference in optical depth along a path length, *ds*

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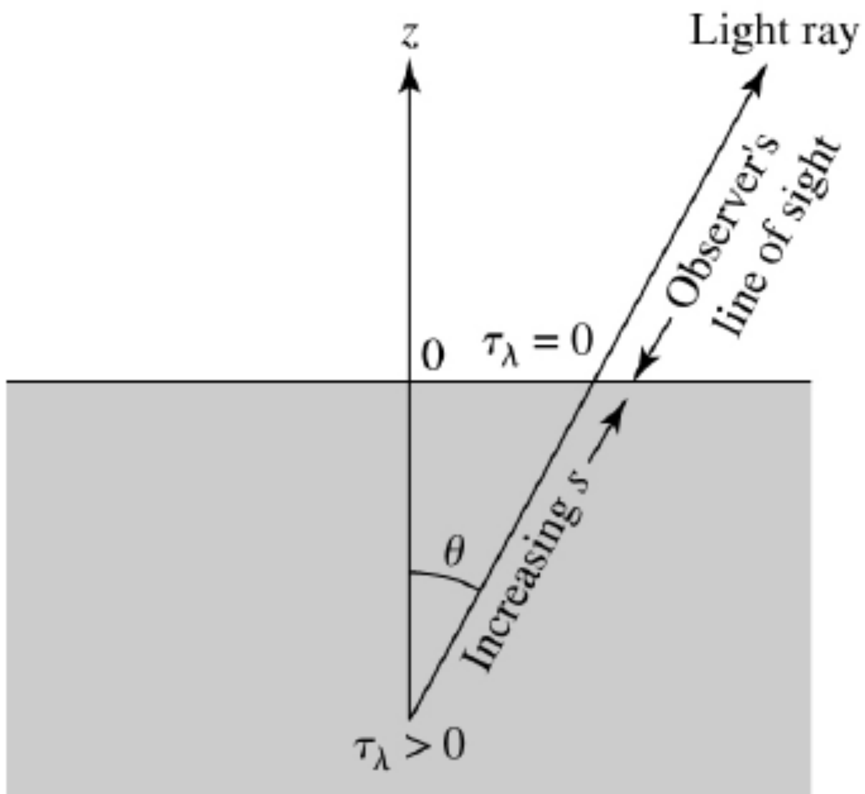

$$\Delta\tau_\lambda = \tau_{\lambda,final} - \tau_{\lambda,init} = -\int_0^s \kappa_\lambda \rho \, ds$$

Outermost layers of star have $\tau_\lambda = 0$

After emerging from the star, the light travels unimpeded toward the observer.

Therefore, τ_λ = 0 gives the initial optical depth of a ray of light that traveled a distance *s* to reach the top of the photosphere.

$$\boxed{0 - \tau_{\lambda,0} = -\int_0^s \kappa_\lambda \rho \, ds} \qquad \tau_\lambda = \int_0^s \kappa_\lambda \rho \, ds.$$

$$I_\lambda = I_{\lambda,init} e^{-\kappa_\lambda \rho s} = I_{\lambda,init} e^{-\tau_\lambda}$$

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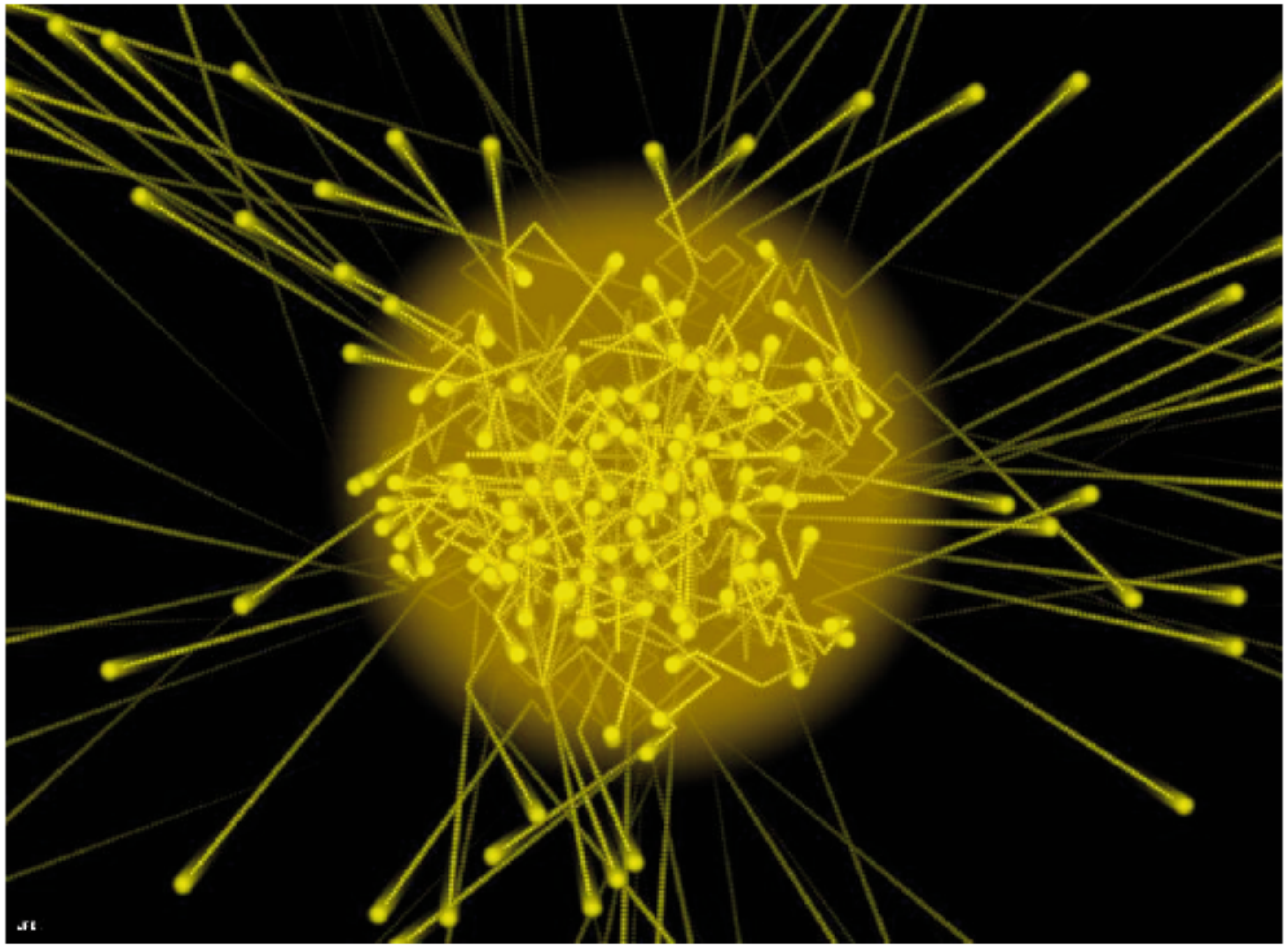

$$I_\lambda = I_{\lambda,init} e^{-\tau_\lambda}$$

If a packet of photons emerges from an optical depth, τ_λ =1, the intensity of the ray is diminished by a factor of e^{-1}.

The optical depth can be thought of as the number of mfp's from the original position to the surface.

Typically, see no deeper into the star at a given wavelength than τ_λ ~ 1.

The corresponding physical depth in the star is wavelength dependent. Imagine shining a red light in the fog - move it deeper into the fog until it just starts to disappears. Then the light is at τ_{red} ~ 1. Now, do the same for a blue light - you'll find that the physical distance will be slightly different for τ_{red} ~ 1 and τ_{blue} ~ 1 (Think about blue skies and red sunsets)

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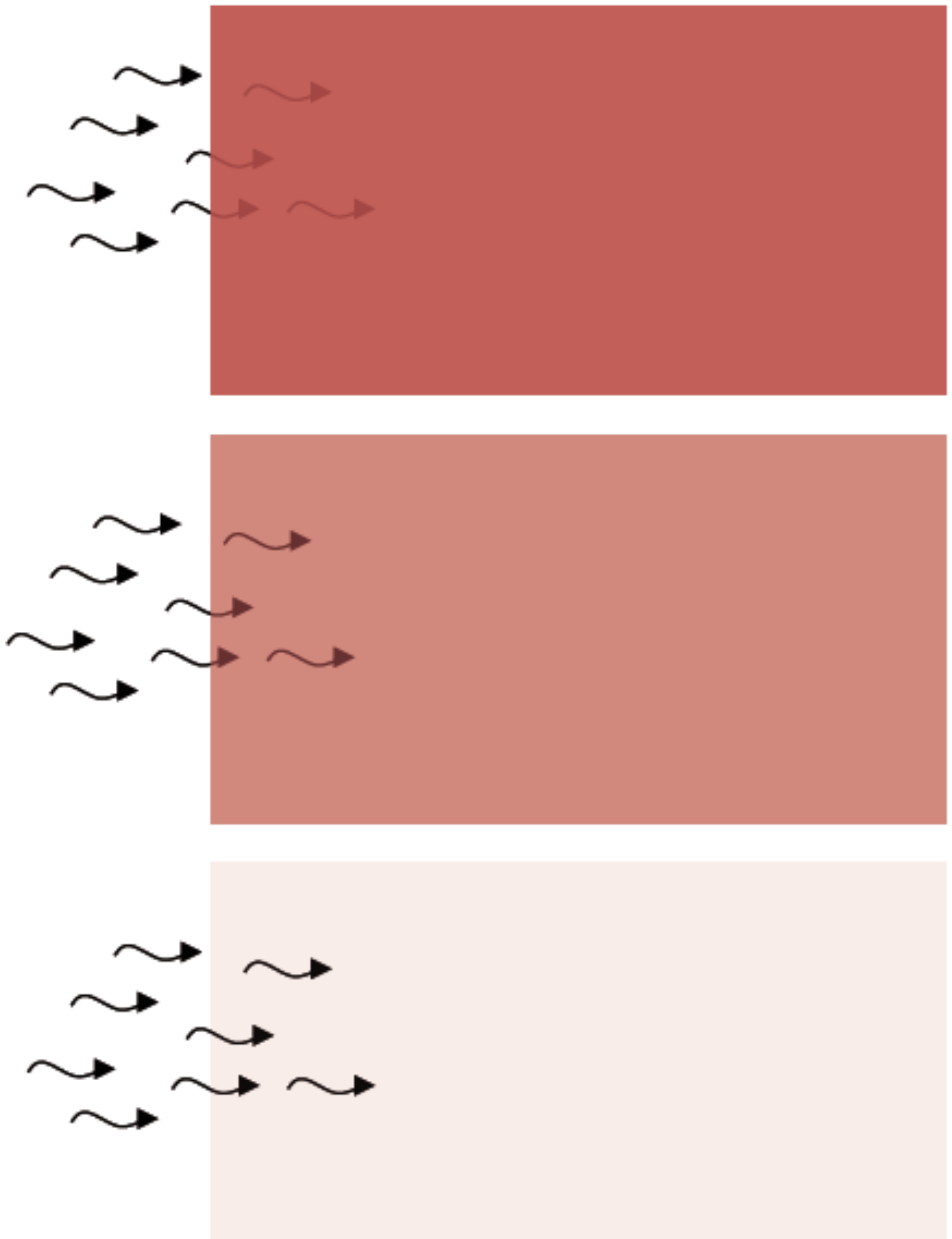

Optically thick: $\tau_\lambda >> 1$

A light ray passing through a volume of gas loses most of its initial intensity

Optically thin: $\tau_\lambda << 1$

A light ray passing through a volume of gas emerges with most of its initial intensity

A gas can be optically thick at one wavelength and optically thin at other wavelengths! Earth's atmosphere is optically thin at visible wavelengths, but optically thick at UV wavelengths.

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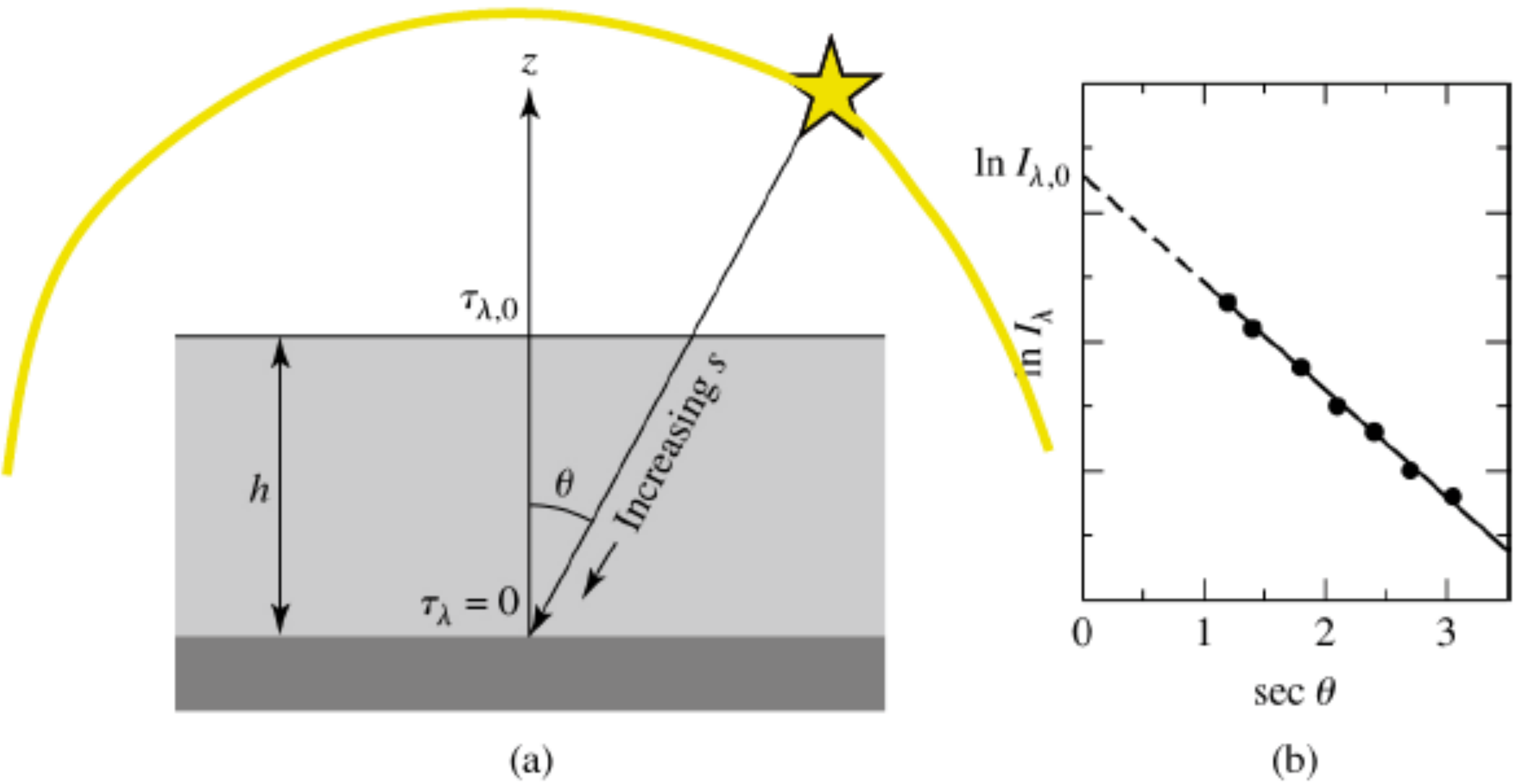

The atmosphere of the Earth also has an optical depth that diminishes starlight.

The brightness of a star has to be corrected for atmospheric extinction (absolute photometry).

$$\tau_\lambda = \int_0^s \kappa_\lambda \rho \, ds = -\int_h^0 \kappa_\lambda \rho \frac{dz}{\cos\theta}$$

$$= \sec\theta \int_0^h \kappa_\lambda \rho \, dz$$

$$= \tau_{\lambda,0} \sec\theta$$

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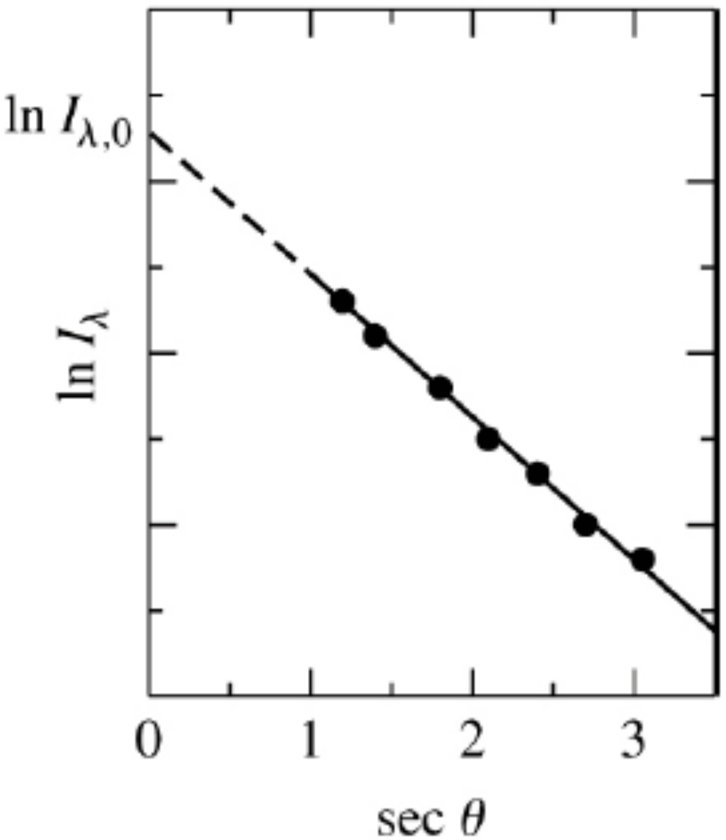

(b)

Intensity varies with position in the sky (hour angle) as a f(θ)

Atmospheric dispersion corrector used to bring light of different wavelengths to a single focus

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

Two unknowns: $I_{\lambda,0}$ and $\tau_{\lambda,0}$

function of $\sec\theta$ can be made. As shown in Fig. 8(b), the *slope* of the best-fitting straight line is $-\tau_{\lambda,0}$. Extrapolating the best-fitting line to $\sec\theta = 0$ provides the value of $I_{\lambda,0}$ at the point where the line intercepts the I_λ-axis.[12] In this way, measurements of the specific intensity or radiative flux can be corrected for absorption by Earth's atmosphere.

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Sources of opacity

Set by interactions of photons with particles (atoms, ions, free electrons). Both scattering and absorption remove photons from a beam of light.

If opacity changes slowly with wavelength, it determines the shape of the continuum.

Rapid changes in opacity occur from atomic absorption and create spectral lines.

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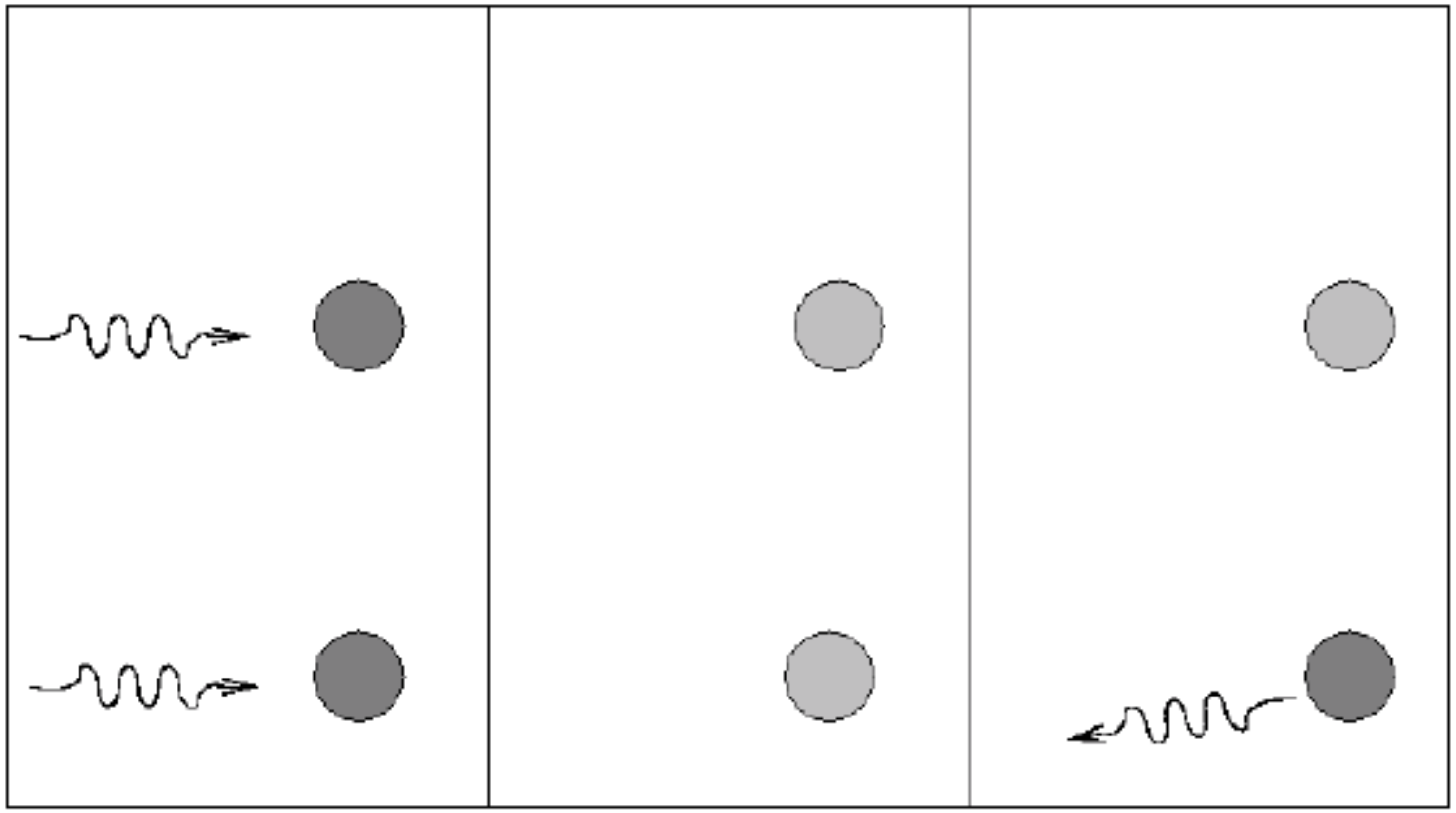

Bound-bound transitions: change in orbital level. Electron is initially bound and remains bound. Electron absorbs and re-emits in random direction, taking photon out of the solid angle light ray, or a cascade of photons is emitted (degraded) in random directions.

$\kappa_{\lambda,\mathrm{bb}}$ forms absorption lines in stellar spectra

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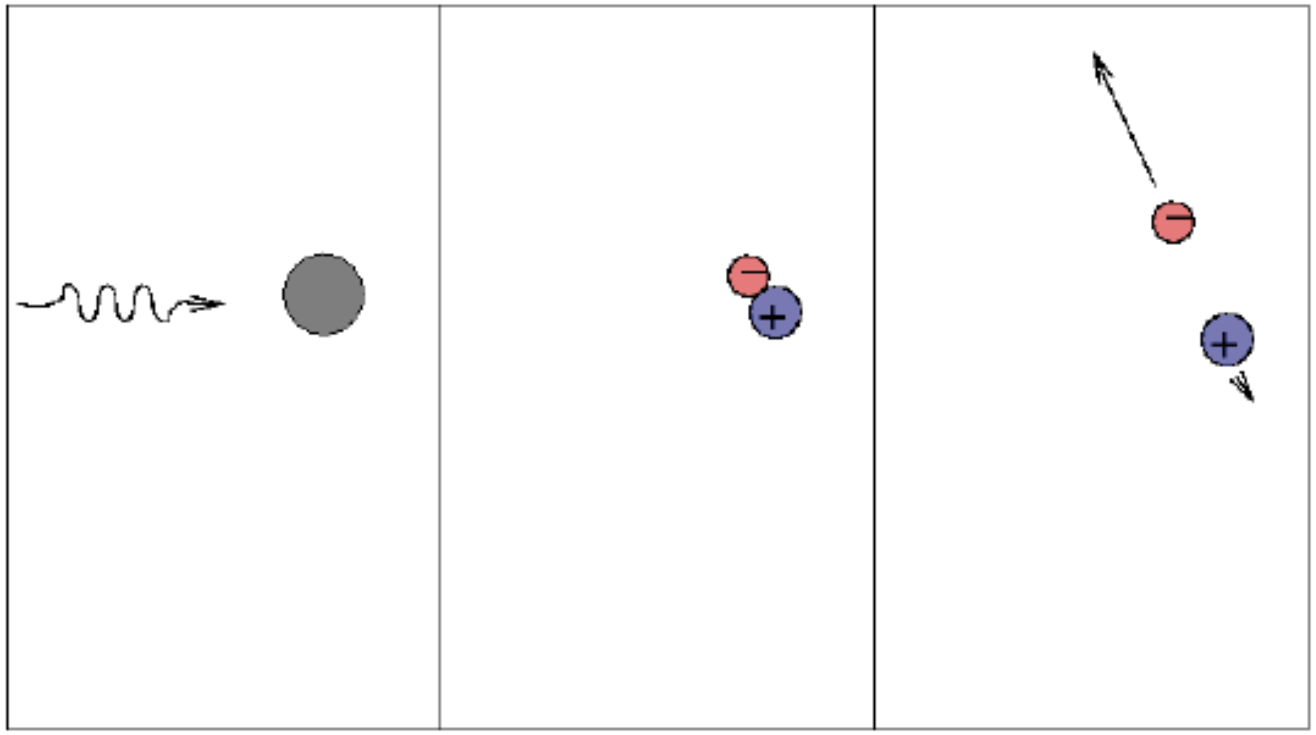

Bound-free transitions: photoionization

The cross section for photoionization is given by:

For H atom in state - n

$$\sigma_{bf} = 1.31\times10^{-19}\frac{1}{n^5}\left(\frac{\lambda}{500nm}\right)^3 m^2$$

$\kappa_{\lambda,\mathrm{bf}}$ is a source of continuum opacity

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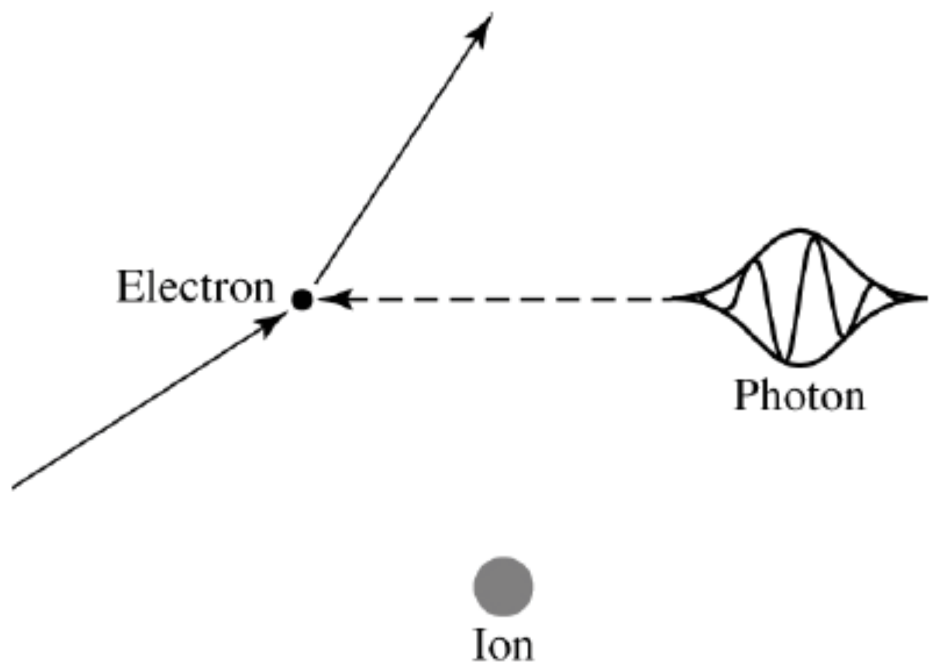

Loosely bound electron

Free-free absorption: scattering

When and only when an electron is near an ion, the photon sees the pair essentially as an excited atom and the electron can absorb the photon and increase it's kinetic energy.

Do you think this would contribute to line opacity (absorption line) or continuum opacity?

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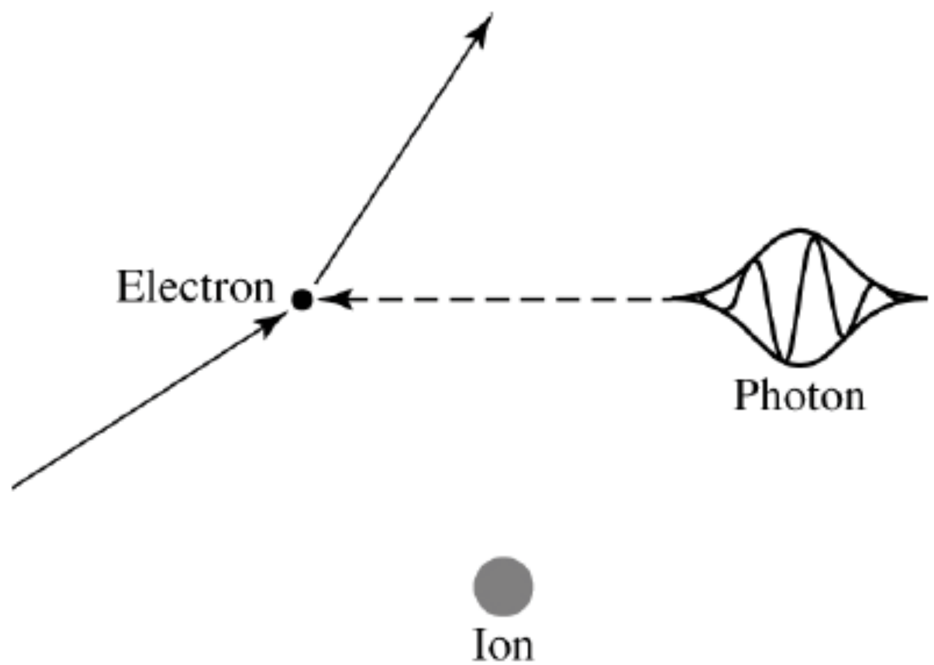

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Right - this event can occur for a wide range of photon energies and contributes to continuum opacity

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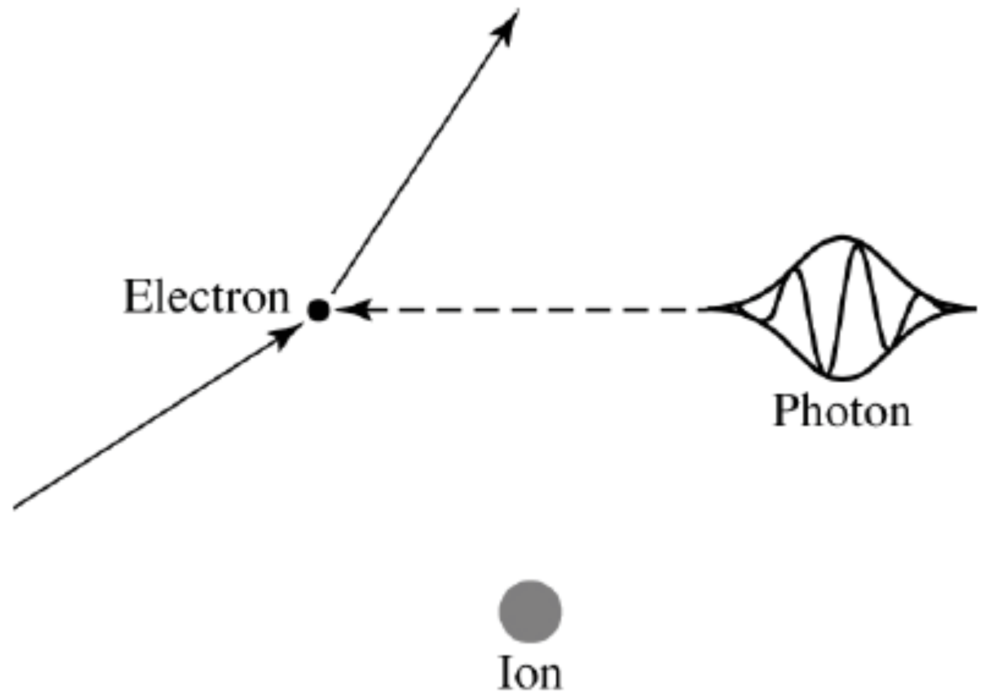

Loosely bound electron

Free-free emission: Bremsstrahlung "braking radiation"

This is the inverse of ff absorption. When and only when an electron passes near an ion, it can loose kinetic energy and emit photons - again, this will contribute to the continuum

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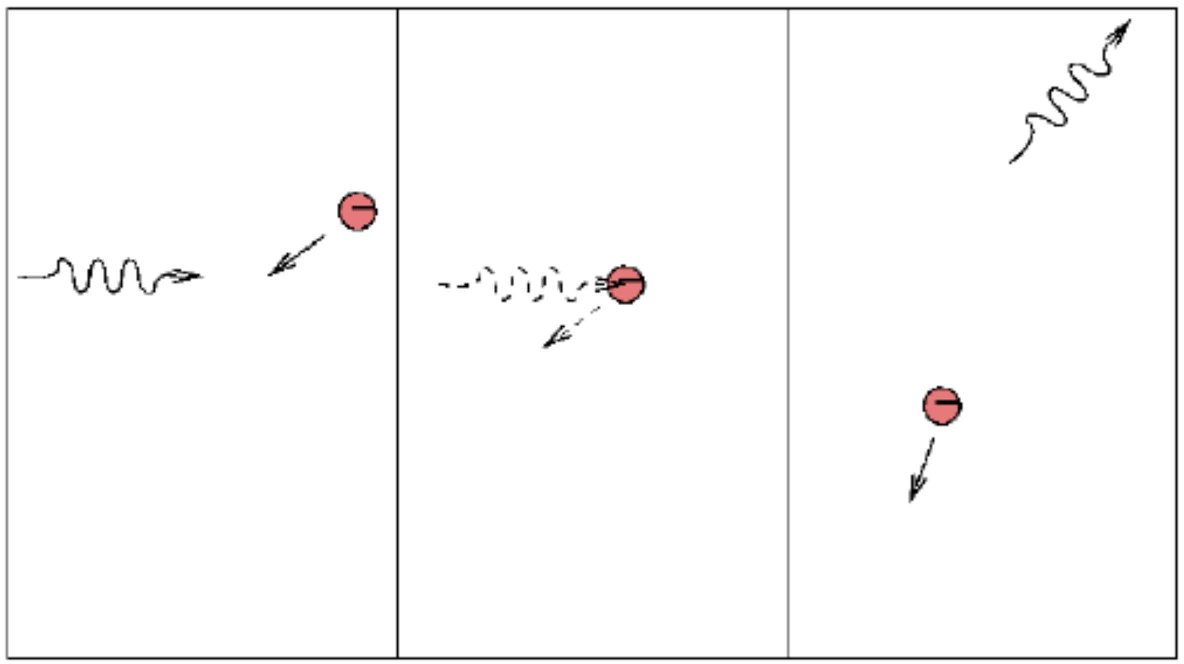

The cross-section for Thompson scattering is 2 billion times smaller than the hydrogen (bf) ionization cross-section, so large density of electrons required

Wavelength independent!

Electron scattering: Thompson scattering

When a photon passes near an electron, the electron can absorb energy by oscillating in the E-M field of the photon.

$$\sigma_T = \frac{1}{6\pi\varepsilon_o}\left(\frac{e^2}{m_e c^2}\right)^2 = 6.65\times10^{-29}\,m^2$$

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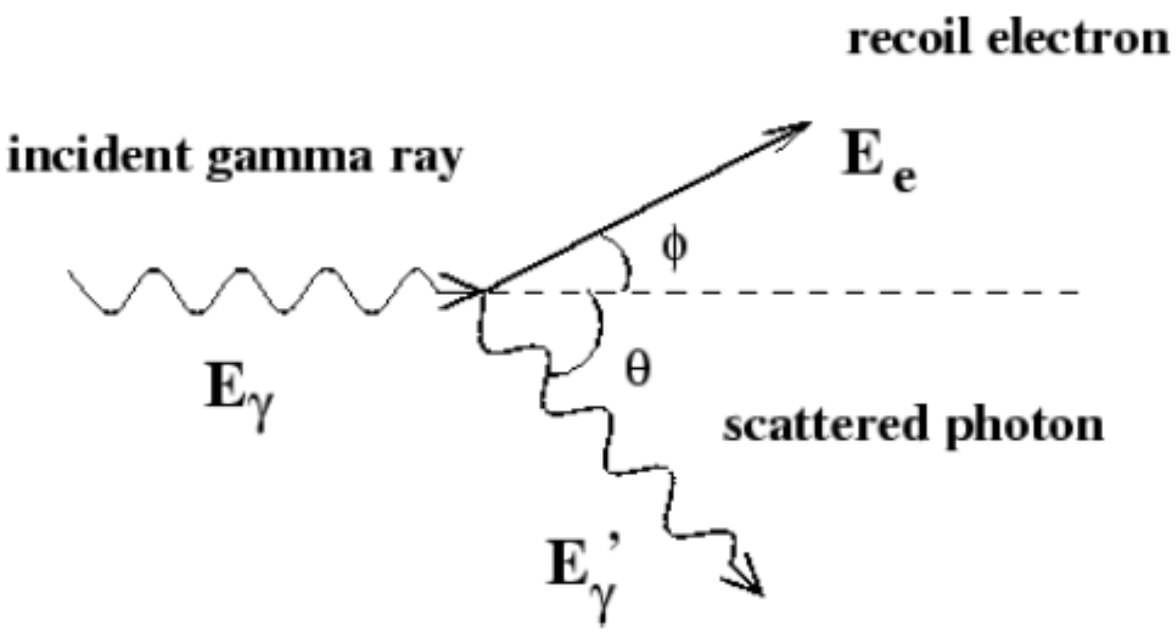

Loosely bound electron

Compton scattering:

A photon can be scattered when passing near an electron that is loosely bound to an atom. This occurs with high energy radiation where the wavelength of the photon is much smaller than the size of the atom.

The change in the energy of the photon is very small, but the direction is changed, reducing the number of photons in a beam.

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Loosely bound electron

Rayleigh scattering:

When the photon wavelength is much larger than the size of the atom, the photons undergo Rayleigh scattering. The cross-section for Rayleigh scattering is much smaller than Thompson scattering and proportional to $1/\lambda^4$, *so decreases with increasing photon wavelength!*

Blue light scatters more efficiently than red light. See blue sky when the Sun is overhead, but a greater optical depth is required to see scattered red light.

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The Balmer Jump!

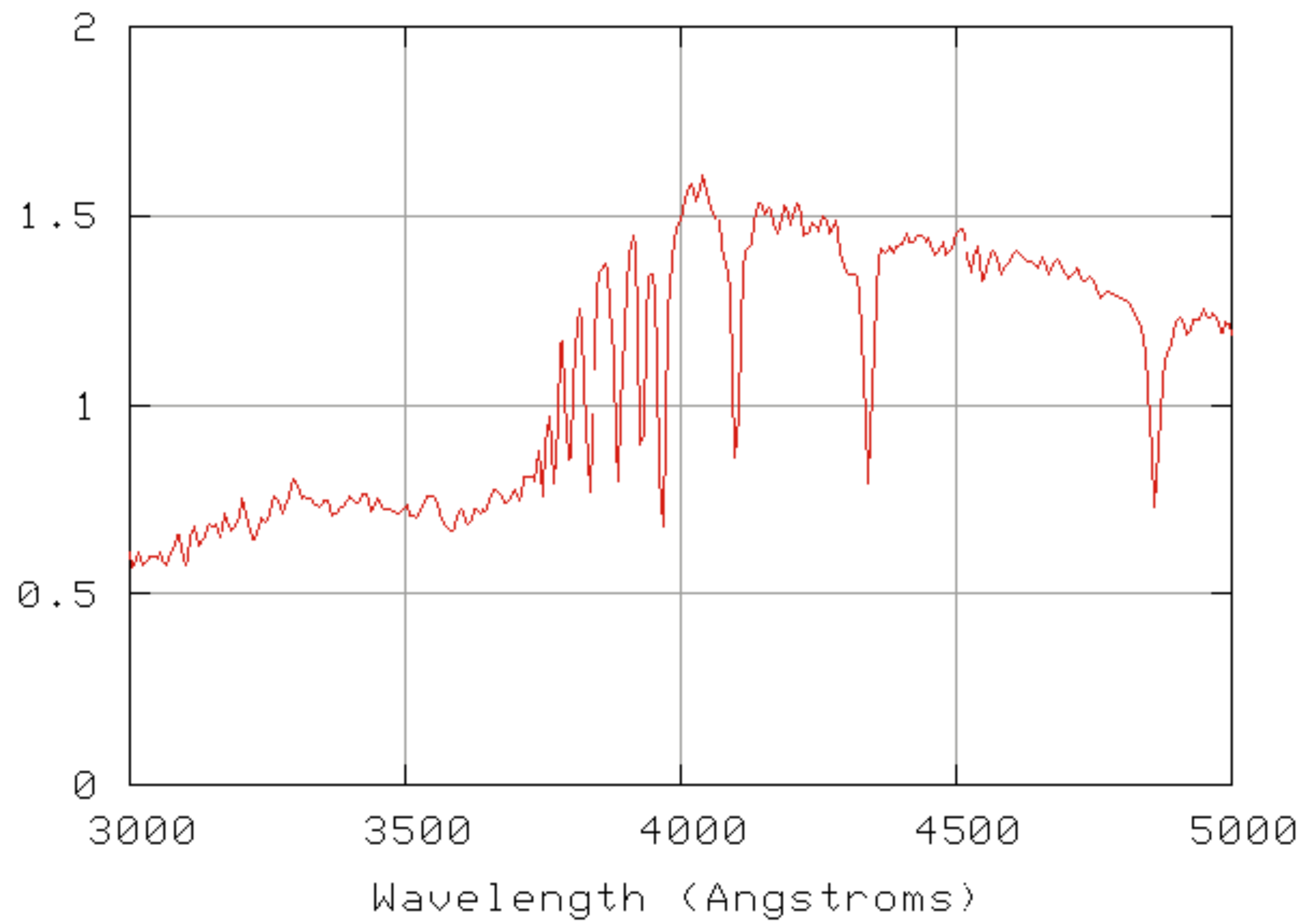
Dramatic increase in opacity

$$\boxed{E_2 = -\frac{13.6}{2^2}\ \text{eV} = -3.40\ \text{eV}.}$$

$$\lambda \leq \frac{hc}{3.4eV} = 3647A$$

So, photons with energy greater than this - i.e., with wavelengths shorter than 3647 Angstroms - will undergo bf absorption.

Spectrum of a G0V star



What will the strength of the Balmer jump depend on?

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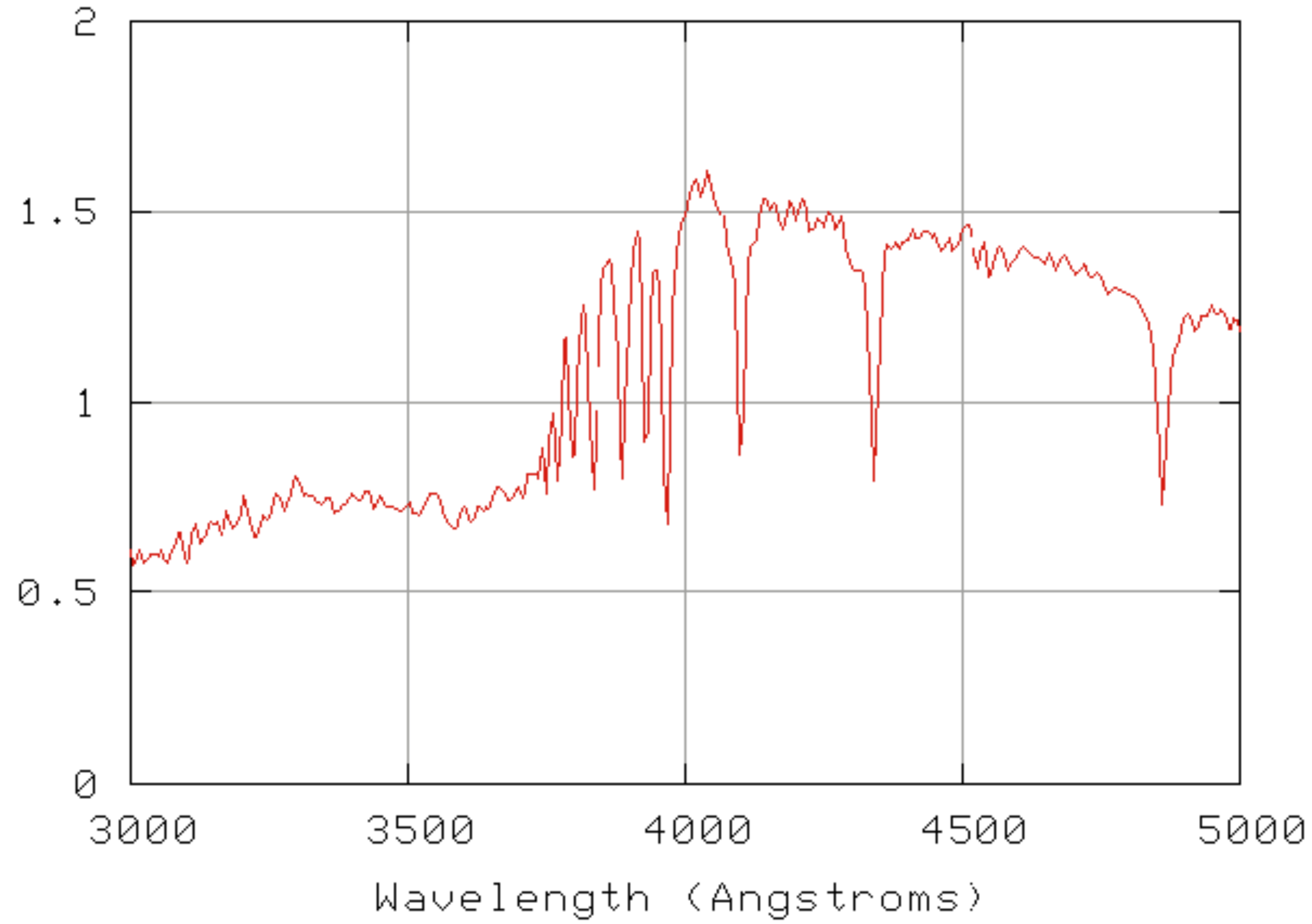

What will the strength of the Balmer jump depend on?

Fraction of atoms in the n=2 level (Boltzmann-Saha eqns). So strongest for A0 stars with temperatures of about 9500K.