ASTR 400/700: Stellar Astrophysics

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Stellar Atmospheres

Chapter 9.3, 9.4

Definition of Opacity

- Consider a beam of parallel light rays traveling through a gas.
- Any process that removes photons from this beam of light is called absorption
- Absorption includes Scattering!!
- True absorption is by electronic transitions in atoms (and sometimes molecules)
- Change in Intensity is

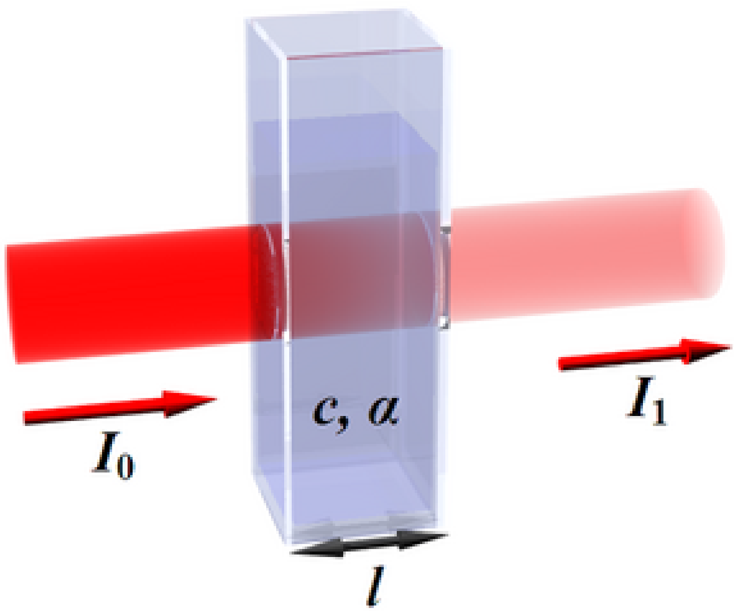
$$dI_\lambda = -\kappa_\lambda \rho I_\lambda \, ds.$$

Proportional to:

distance traveled

density of gas

absorption coefficient



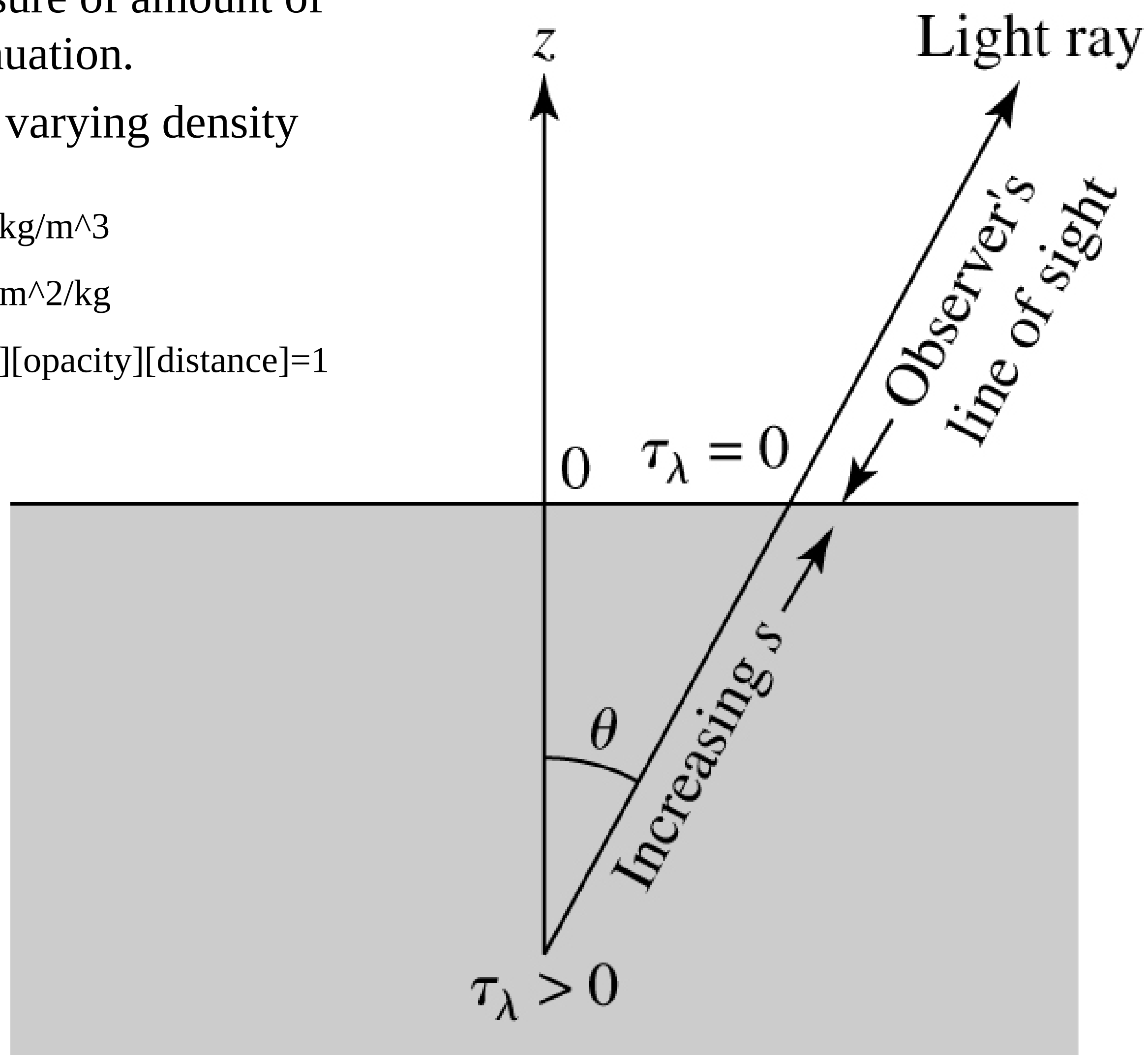
Optical Depth

- Unit-less Measure of amount of attenuation.
- Accounts for varying density

[density]=kg/m^3

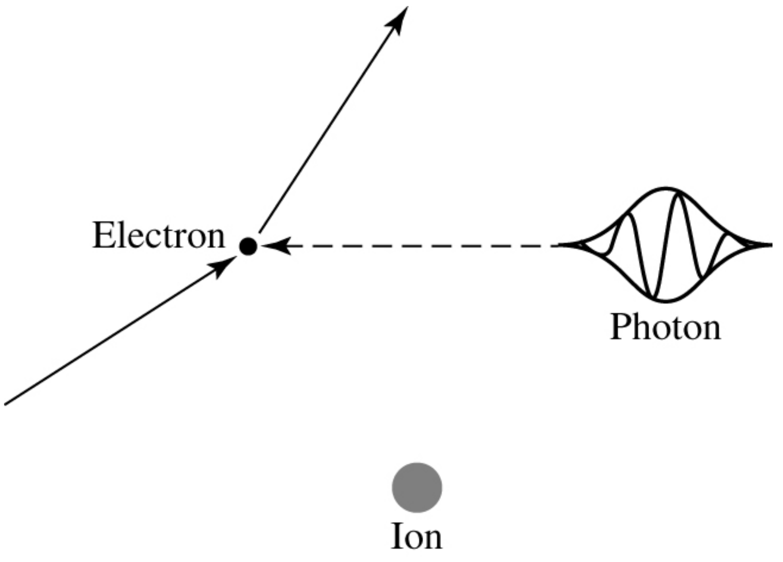
[opacity]=m^2/kg

[Optical Depth]=[density][opacity][distance]=1

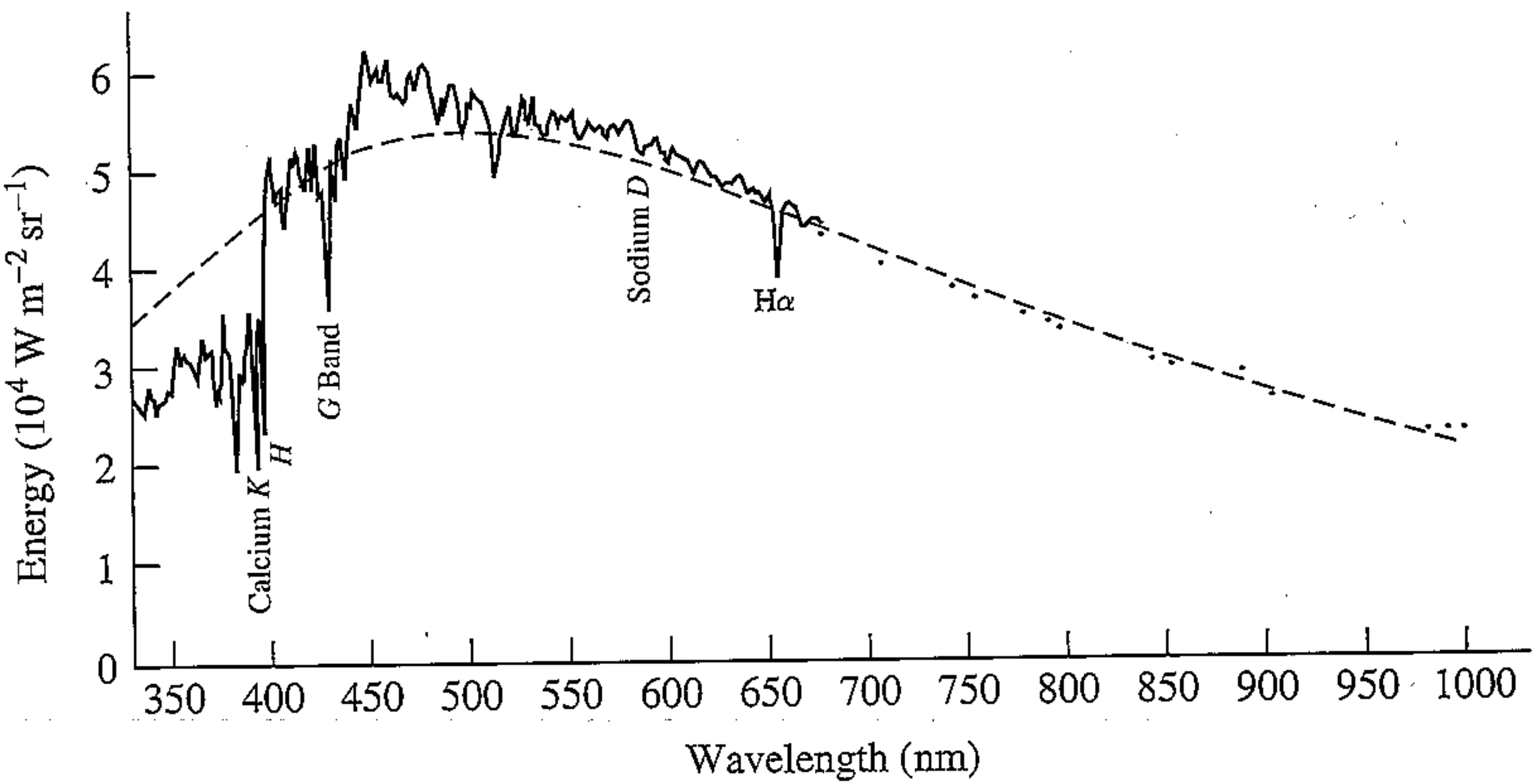


Sources of Opacity

- Bound-Bound Transitions
- Bound-Free Absorption (photo-ionization)
- Free-Free Absorption
- Electron-Electron Scattering



Balmer Jump



Energy (10^4 W m^{-2} sr^{-1})
0
1
2
3
4
5
6
Calcium K
H
G Band
Sodium D
Hα
350
400
450
500
550
600
650
700
750
800
850
900
950
1000
Wavelength (nm)

Continuum Opacity and the H^- ion

- Hydrogen atoms can "catch" an additional electron
  - Binding energy is 0.754 eV
- Photons with wavelength of 1640nm or less can ionize this Hydrogen ion

An additional source of opacity for stars cooler than type F0

Total Opacity is sum of all contributions:

$$\kappa_\lambda = \kappa_{\lambda,\mathrm{bb}} + \kappa_{\lambda,\mathrm{bf}} + \kappa_{\lambda,\mathrm{ff}} + \kappa_{\mathrm{es}} + \kappa_{\mathrm{H}^-}$$

Rosseland Mean Opacity

- An attempt at estimating the average opacity over all wavelengths
- Weight by the rate at which Intensity distribution (blackbody radiation) varies with temperature.
  - Determine dependence of other parameters such as temperature

$$\frac{1}{\bar{\kappa}} \equiv \frac{\int_0^\infty \frac{1}{\kappa_\nu} \frac{\partial B_\nu(T)}{\partial T}\, d\nu}{\int_0^\infty \frac{\partial B_\nu(T)}{\partial T}\, d\nu}.$$

$$X \equiv \frac{\text{total mass of hydrogen}}{\text{total mass of gas}}$$

$$Y \equiv \frac{\text{total mass of helium}}{\text{total mass of gas}}$$

$$Z \equiv \frac{\text{total mass of metals}}{\text{total mass of gas}}.$$

$$\bar{\kappa}_{\text{bf}} = 4.34 \times 10^{21} \frac{g_{\text{bf}}}{t} Z(1+X) \frac{\rho}{T^{3.5}} \text{ m}^2 \text{ kg}^{-1}$$

$$\bar{\kappa}_{\text{ff}} = 3.68 \times 10^{18} g_{\text{ff}} (1-Z)(1+X) \frac{\rho}{T^{3.5}} \text{ m}^2 \text{ kg}^{-1},$$

$$\bar{\kappa}_{\text{es}} = 0.02(1+X) \text{ m}^2 \text{ kg}^{-1}.$$

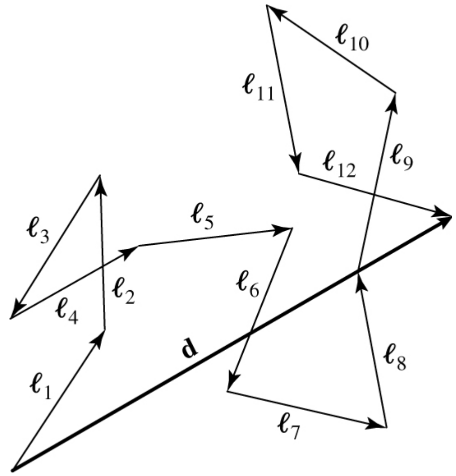
$$\bar{\kappa}_{\text{H}^-} \approx 7.9 \times 10^{-34} (Z/0.02) \rho^{1/2} T^9 \text{ m}^2 \text{ kg}^{-1}.$$

$$\bar{\kappa} = \overline{\kappa_{\text{bb}} + \kappa_{\text{bf}} + \kappa_{\text{ff}} + \kappa_{\text{es}} + \kappa_{\text{H}^-}}.$$

Radiative Transfer

- Energy Transfer in the form of Electromagnetic radiation
- In an equilibrium steady-state star there can be no change in the total energy contained within any layer of the stellar interior or atmosphere
- Implies absorption must be balanced by emission
  - Inverse emission processes
- Emission processes re-direct photons from initial path

Random Walk



$$d = l\sqrt{N}$$

Tortuous path:

100 steps --> d=10 l

10000 steps --> d=100 l

1000000 steps --> d=1000 l

Optical Depth is roughly the number of photon mean free paths from that point to the surface.

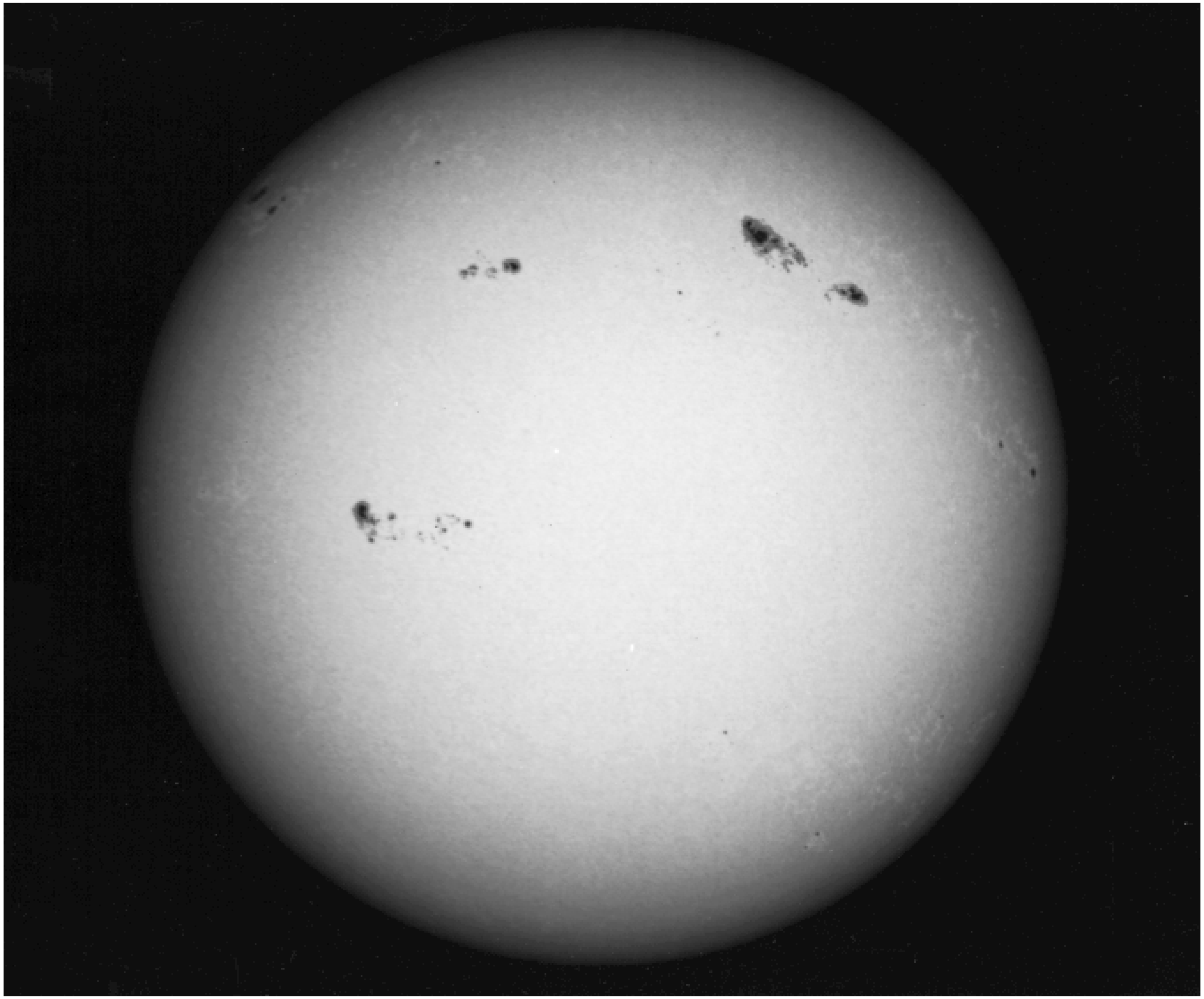
$$d = \tau_\lambda l = l\sqrt{N}$$

$$N = \tau_\lambda^2$$

How far do we look into a star?

- Looking into a star at any angle, we always look back to an optical depth of about $\tau_\lambda = 2/3$ as measured straight back along the line of sight
- Photon's at a distance of less than 1 mean free path from the surface are likely to escape
- Star's photosphere is defined to be the layer from which visible light originates
  - Formation of spectral lines (absorption) occur because temperature of the material in the star decreases outwards from the center of the star

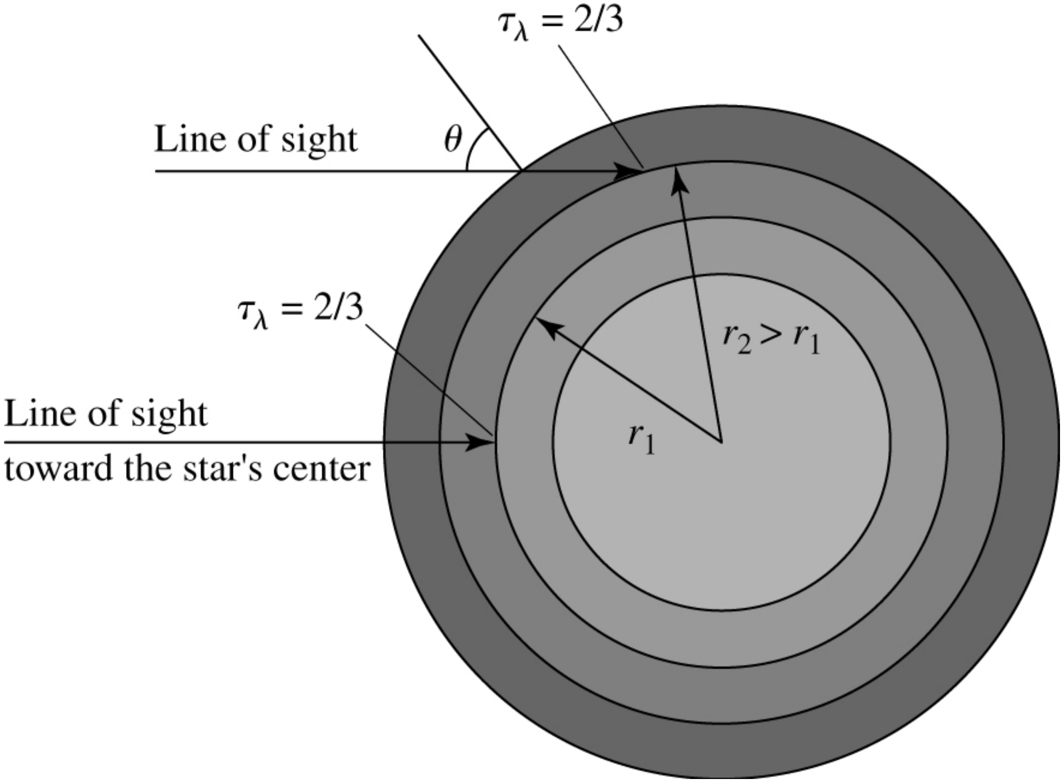
Limb Darkening



Limb Darkening

- When looking at the center of the sun one can see "deeper" than when looking at the edge of the sun
  - Deeper is hotter
  - Hotter is brighter…

LIMB DARKENING



Radiation Pressure Gradient

- Mean free path of photons in the interior of the star is typically a few cm.
- Center of star is few hundreds of millions of meters from its surface
- How do the photons ever get out?
- Temperature of star decreases outward from center. This causes the radiation pressure to decrease outwards as well

↓

Pressure Gradient

↓

Photon "Breeze" from star

Pressure Gradient produces a slight net movement of photons upward that carries the radiative flux

$$\frac{dP_{\text{rad}}}{dr} = -\frac{\bar{\kappa}\rho}{c} F_{\text{rad}}.$$

This causes a slow upward diffusion of randomly walking photons