

Astronomía Avanzada I (Semester 1 2024)

## **Stellar Atmospheres (2)**

Introduction to Radiative Transfer

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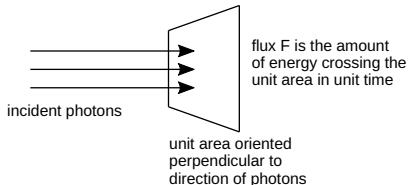
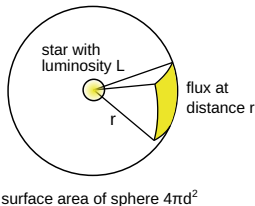
# Recap: Flux

Flux (or radiant flux),  $F$ , is the total amount of energy that crosses a unit area per unit time. Flux is usually given in watts per square meter ( $\text{W}/\text{m}^2$ ).

The flux of an astronomical source depends on the luminosity of the object and its distance from the Earth, according to the inverse square law:

$$F = \frac{L}{4\pi r^2}$$

where  $F$  = flux measured at distance  $r$ ,  
 $L$  = luminosity of the source,  
 $r$  = distance to the source.



# Recap: Flux

**example:** The luminosity of the Sun is  $L_{\odot} = 3.839 \times 10^{26} \text{ W}$ .  
At a distance of  $1 \text{ AU} = 1.496 \times 10^{11} \text{ m}$ , Earth receives a radiant flux above its absorbing atmosphere of

$$F = \frac{L}{4\pi r^2} = 1365 \text{ W m}^{-2}.$$

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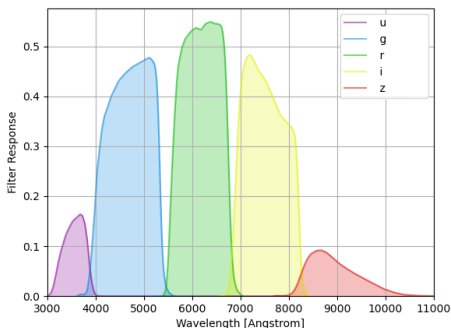
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# Recap: Magnitudes and Broad-Band Filters

We often measure the flux  $F$  from astronomical objects via a **logarithmic magnitude scale**.

Magnitudes almost universally involve a set of **broad-band filters**, e.g. Johnson *UBVRI* or Sloan *ugriz*:



# Recap: Magnitudes and Broad-Band Filters

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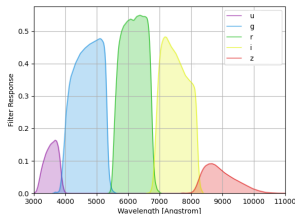
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We often measure the flux  $F$  from astronomical objects via a logarithmic magnitude scale.

Magnitudes almost universally involve a set of **broad-band filters**, e.g. Johnson *UBVRI* or Sloan *ugriz*:



We then calculate:

$$m = -2.5 \log \int_0^{\infty} F_{\nu} W(\nu) d\nu + \text{const}$$

with:

$F_{\nu}$  a star's spectral energy distribution (SED)

$W(\nu)$  a filter passband

# Recap: The Black Body

We have already seen:

**Black-body radiation** is the thermal electromagnetic radiation within, or surrounding, a body in thermodynamic equilibrium with its environment, emitted by an idealized black body (opaque, non-reflective).

For a black body, the **Stefan-Boltzmann law** states that the total energy radiated per unit area per unit time (also known as the flux) is directly proportional to the fourth power of the black body's temperature:

$$F = \sigma_{\text{SB}} T^4.$$

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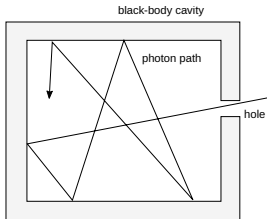
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# The Black Body

Imagine a box which is completely closed except for a small hole.

Any light entering the box will have a very small likelihood of escaping, and will eventually be absorbed by the gas or walls.

For constant temperature walls, this is in **thermodynamic equilibrium**.



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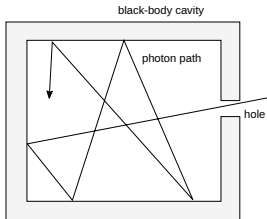
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Any light entering the box will have a very small likelihood of escaping, and will eventually be absorbed by the gas or walls.

For constant temperature walls, this is in **thermodynamic equilibrium**.



If this box is **heated**, the walls will emit photons, filling the inside with radiation. A small fraction of the radiation will leak out of the hole, but so little that the gas within it remains in equilibrium.

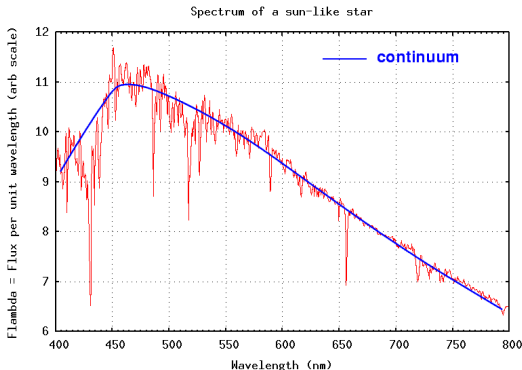
The emitted radiation is that of a **black body**.

Stars share properties of the black-body emitter, in the sense that a negligibly small fraction of the radiation escapes from each.



# Stars as Black Bodies

Comparison of black body spectrum vs. stellar spectrum:



This spectrum of a solar-like star shows just how far a typical star's spectrum (red) deviates from the ideal blackbody (blue).

credit: Michael Richmond,

<https://aasnova.org/2018/10/31/perfect-blackbodies-in-the-sky/>)

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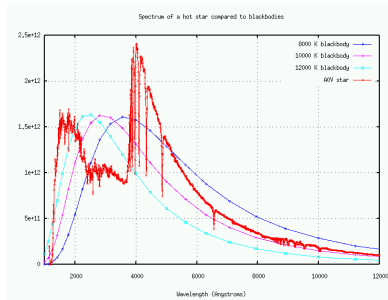
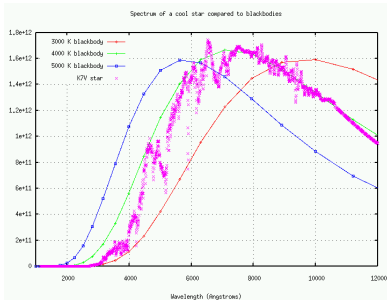
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# Stars as Black Bodies

How close to black bodies are real stars? It depends...

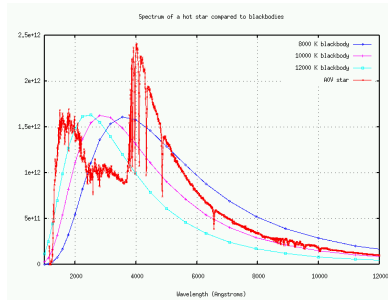
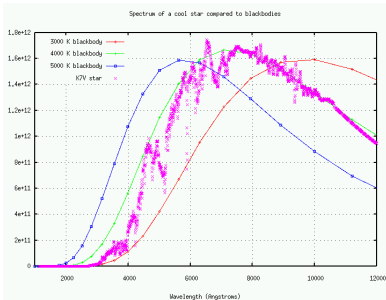
For relatively cool stars (e.g. a K7 dwarf), a black body is a pretty good model, whereas for hot stars, the spectrum differs very strongly from a black body in the near-UV:



# Stars as Black Bodies

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For relatively cool stars (e.g. a K7 dwarf), a black body is a pretty good model, whereas for hot stars, the spectrum differs very strongly from a black body in the near-UV:



The reason for this difference: sources of continuous and line opacity in the stellar photospheres.

# Stars as Black Bodies



What's the difference?

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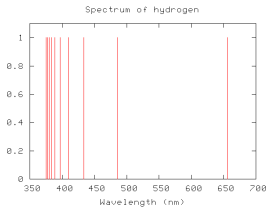
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The outer parts of stellar atmospheres are largely H. In the red of the optical, H is nearly transparent, allowing blackbody radiation to escape. However, in the blue and near-UV, strong H absorption lines lead to absorption below  $3650 \text{ \AA}$ . The energy is re-emitted as less-energetic photons at longer wavelengths.



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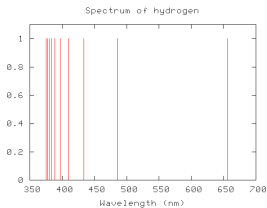
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This effect, called **line-blanketing**, redistributes much of the UV energy of the star into the visible and IR.

# Recap: The Stefan-Boltzmann Law

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Blackbody radiation is continuous and isotropic, with the intensity only varying with wavelength and temperature.

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Following empirical (Josef Stefan in 1879) and theoretical (Ludwig Boltzmann in 1884) studies of black bodies, there is a relation between flux and temperature, known as the Stefan-Boltzmann law:

$$F = \sigma T^4$$

with the Boltzmann constant  $\sigma_{\text{SB}} = 5.6705 \times 10^{-5} \text{ erg/cm}^2/\text{s/K}^4$

Despite stars not being black bodies, the **effective temperature** is calculated using the above equation:

$$L = 4\pi R^2 = \sigma_{\text{SB}} T^4$$

The effective temperature is the temperature which a black body would need to radiate the same amount of energy as the star.

# The Planck Formula

The **black body intensity** is defined (following discovery by Max Planck in 1900) as either

$$B_{\lambda}(T) = \frac{2hc^2}{\lambda^5} \frac{1}{\exp(hc/\lambda kT) - 1}$$

or

$$B_{\nu}(T) = \frac{2h\nu^3}{c^2} \frac{1}{\exp(h\nu/kT) - 1}$$

where  $c = 2.99 \times 10^{10}$  cm,  $h = 6.67 \times 10^{-27}$  erg s,  $k = 1.38 \times 10^{-16}$  erg/s.

We can use this to compute the bolometric flux:

$$\begin{aligned} F &= \pi \int_0^{\infty} B_{\nu}(T) d\nu = \pi \int_0^{\infty} \frac{2h\nu^3}{c^2} \frac{1}{\exp(h\nu/kT) - 1} d\nu \\ &= \pi \frac{2h}{c^2} \left( \frac{kT}{h} \right)^4 \int_0^{\infty} \frac{x^3}{e^x - 1} dx = \pi \frac{2h}{c^5} \left( \frac{kT}{h} \right)^4 \frac{\pi^4}{15} = \sigma_{\text{SB}} T^4 \end{aligned}$$



# Wien's Displacement Law

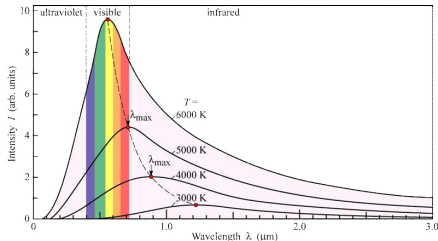
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For increasing temperatures, the black body intensity increases over all  $\lambda$ , and the maximum in the energy distribution shifts to shorter  $\lambda$ .

**Wien's displacement law** states that the spectral radiance of black-body radiation per unit wavelength peaks at the wavelength  $\lambda_{\max}$  given by:

$$\lambda_{\max} = \frac{b}{T}$$

where  $T$  is the absolute temperature and  $b$  is Wien's displacement constant,  $b = 2.897771955 \times 10^3 \text{ m K}$ .



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# Wien's Displacement Law

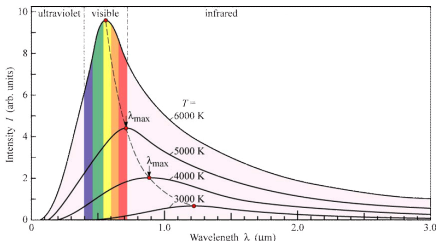
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example:  $\lambda_{\max} = 5175 \text{ \AA}$  for the Sun

# Rayleigh-Jeans and Wien approximations

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At **long wavelengths**  $\lambda \gg \lambda_{\text{max}}$  (small frequencies  $\nu \ll \nu_{\text{max}}$ ), the Planck equation can be approximated by the **Rayleigh-Jeans law**:

$$B_{\nu}(T) \sim 2 \frac{\nu^2}{c^2} kT, \quad B_{\lambda}(T) \sim 2ckT\lambda^{-4}$$

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# Rayleigh-Jeans and Wien approximations

At **long wavelengths**  $\lambda \gg \lambda_{\max}$  (small frequencies  $\nu \ll \nu_{\max}$ ), the Planck equation can be approximated by the **Rayleigh-Jeans law**:

$$B_{\nu}(T) \sim 2 \frac{\nu^2}{c^2} kT, \quad B_{\lambda}(T) \sim 2ckT\lambda^{-4}$$

At **short wavelengths**  $\lambda \leq \lambda_{\max}$  (large frequencies  $\nu \geq \nu_{\max}$ ) the **Wien law** is a good approximation:

$$B_{\nu}(T) \sim 2 \frac{h\nu^3}{c^2} \exp\left(-\frac{h\nu}{kT}\right), \quad B_{\lambda}(T) \sim 2 \frac{hc^2}{\lambda^5} \exp\left(-\frac{hc}{\lambda kT}\right)$$

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# Interaction Radiation - Matter

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When radiation interacts with matter, energy can be removed from, or delivered to, the radiation field.

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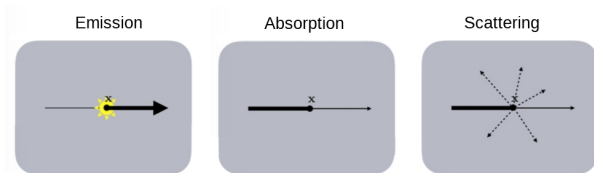
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We can distinguish different forms of interaction:

**True emission:** The photon is generated, it extracts kinetic energy from the gas.

**True absorption:** The photon is destroyed (thermalized), energy is transferred into kinetic energy of the gas.

**Scattering:** The photon interacts with a scatterer - the direction is changed, the energy slightly changed, there is no energy exchange with the gas.

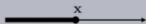


# Interaction Radiation - Matter

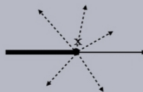
Among them, there are two physical processes that contribute to the opacity  $\kappa_\lambda$  (the subscript means the absorption is depending on the photon wavelength):

true absorption and scattering.

Absorption



Scattering



# True Absorption and True Emission

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The following are examples for **true absorption**:

**photoionization** (bound-free): Excess energy is transferred into kinetic energy of the released electron  $\Rightarrow$  effect on local temperature

The electron will interact with photons by means of electronic transitions (and spectral lines) only if it is bound to the atom. If the medium is able to deliver enough energy to separate it from the nucleus, "photo-ionization" will occur.

**photoexcitation** (bound-bound): Followed by electron collisional de-excitation; excitation energy is transferred to the electron  $\Rightarrow$  effect on local temperature

**photoionization** (bound-bound): Followed by collisional ionization.

The **reverse** processes are examples for true emission.

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# Scattering

The following are examples for **scattering processes**:

A **2-level atom** absorbs photon with frequency  $\nu_1$ , re-emits photon with frequency  $\nu_2$ . The frequencies differ slightly because:

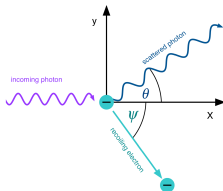
- levels  $a$  and  $b$  have non-vanishing energy width
- Doppler effect because atom moves



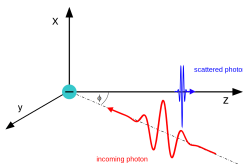
The scattering of photons **by free electrons**:

Compton- or Thomson scattering (inelastic vs. elastic), collision of a photon with free electron.

Compton Scattering



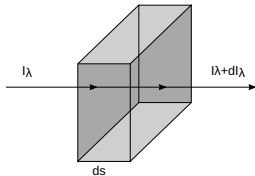
Thomson Scattering





# The Absorption Coefficient

**Absorption:** any process that removes photons from a beam of light.



The change in the intensity,  $dI_\lambda$ , of a ray of wavelength  $\lambda$  as it travels through a gas (i.e.: stellar atmosphere) can be expressed as

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

where  $\kappa_\lambda$  is the so-called **absorption coefficient (opacity)** [ $\text{cm}^2 \text{g}^{-1}$ ],  $\rho$  is the density (in mass per unit volume), and  $ds$  is a length. The distance  $s$  is measured along the path traveled by the ray and increases in the direction that the ray travels.

It can also be interpreted as  $\alpha_\lambda = \kappa_\lambda \rho$  where  $\alpha_\lambda$  is the absorption coefficient [ $\text{cm}^{-1}$ ].

# Optical Depth

The **mean free path** is the average distance a particle (such as an atom, a molecule, or a photon) travels before substantially changing its direction or energy, typically as a result of one or more collisions with other particles.

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The **mean free path** is the average distance a particle (such as an atom, a molecule, or a photon) travels before substantially changing its direction or energy, typically as a result of one or more collisions with other particles.

We can calculate the mean free path of the photons:

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

Define an optical depth,  $\tau_\lambda$ , back along a light ray by

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

where  $s$  is the distance measured along a photon's path in its direction of motion. Note that when observing the light from a star, we are looking back along the path traveled by the photon.

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where  $s$  is the distance measured along a photon's path in its direction of motion. Note that when observing the light from a star, we are looking back along the path traveled by the photon.

The difference in optical depth between a light ray's initial position ( $s = 0$ ) and its final position after traveling a distance  $s$  is

$$\Delta\tau_{\lambda} = \tau_{\lambda,f} - \tau_{\lambda,0} = -\int_0^s \rho\kappa_{\lambda} ds$$

# Optical Depth

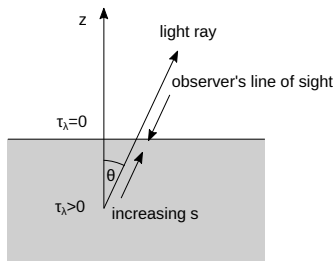
Let the outermost layers of a star to be at  $\tau_\lambda = 0$  for all wavelengths. We then have

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

$$\tau_\lambda = \int_0^s \rho \kappa_\lambda ds$$

with

$$\tau_\lambda \begin{cases} \ll 1, & \text{(optical thin)} \\ \gg 1, & \text{(optical thick).} \end{cases}$$



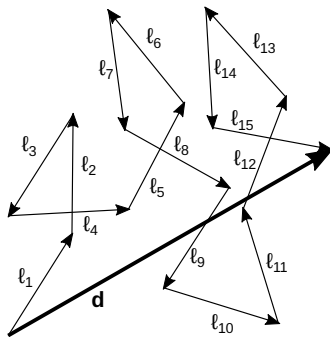
Note that  $\tau_\lambda$  is the optical depth of the ray's initial position, a distance  $s > 0$  from the top of the stellar atmosphere. Furthermore,

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

# Opacity and Random Walk

The photon diffusion process follows a path called **random walk**, which can be described by a net vector displacement **d** as the result of making a large number  $N$  of randomly directed steps, each of length  $\ell$  (the mean free path):

$$\mathbf{d} = \ell_1 + \ell_2 + \dots + \ell_N$$



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We find that

$$\begin{aligned}\mathbf{d} \odot \mathbf{d} &= \ell_1 \odot \ell_1 + \ell_2 \odot \ell_2 + \dots + \ell_1 \odot \ell_N + \\ &\quad \ell_2 \odot \ell_1 + \ell_2 \odot \ell_2 + \dots + \ell_2 \odot \ell_N + \\ &\quad \dots + \\ &\quad \ell_N \odot \ell_1 + \ell_N \odot \ell_2 + \dots + \ell_N \odot \ell_N \\ &= \sum_{i=1}^N \sum_{j=1}^N \ell_i \odot \ell_j\end{aligned}$$

or

$$d^2 = N\ell^2 + \ell^2 \sum_{i=1}^N \sum_{j=1}^N \cos \theta_{ij}$$

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or

$$d^2 = N\ell^2 + \ell^2 \sum_{i=1}^N \sum_{j=1}^N \cos \theta_{ij}$$

Since

$$d^2 = N\ell^2 + \ell^2 \sum_{i=1}^N \sum_{j=1}^N \cos \theta_{ij} \simeq N\ell^2$$

when  $N \ll 1$ , the displacement  $d$  for a random walk is related to the length of the mean free path  $l$  by  $d = \ell\sqrt{N}$ .



# Opacity and Random Walk

Because the optical depth  $\tau$  is roughly the number of photon mean free paths to the stellar surface, the distance to the surface can also be written as

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

with  $N = \tau_{\lambda}^2$ .

When  $\tau_{\lambda} \sim 1$ , a photon may escape from that level of the star.

More careful analysis shows that the average level from which photons of wavelength  $\lambda$  can escape is at a characteristic optical depth of  $\tau \simeq 2/3$ .

Looking into a star at any angle, we look back to an optical depth of about  $\tau_{\lambda} \simeq 2/3$ , as measured back along the line of sight.

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# Opacity and Optical Depth

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An optical depth of  $\tau = 0$  corresponds to no reduction in intensity, i.e. the top of a star's photosphere.

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An optical depth of  $\tau = 1$  corresponds to a reduction in intensity by a factor of  $e = 2.7$ .

If the optical depth is large ( $\tau \gg 1$ ), negligible intensity reaches the observer.

In stellar atmospheres, typical photons originate from  $\tau = 2/3$ .

# Radiation: Terms

For correctly describing how light interacts with the material in a stellar atmosphere, we need a carefully defined **terminology**.

What we will consider here is the **net flow of energy** in a given direction, instead of the specific path taken by individual photons.

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# Radiation: Terms

For correctly describing how light interacts with the material in a stellar atmosphere, we need a carefully defined **terminology**.

What we will consider here is the **net flow of energy** in a given direction, instead of the specific path taken by individual photons.

We start with defining **Specific and Mean Intensity**.

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# Solid Angle in Spherical Coordinates

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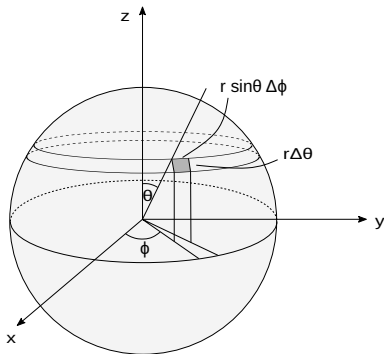
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Put the center at a given point of a stellar atmosphere, with the polar axis along the star's radius.

Area of a patch on a unit radius sphere limited by  $(\theta, \theta + \Delta\theta)$  and  $(\phi, \phi + \Delta\phi)$  is  $\Delta\Omega = \sin\theta \Delta\theta \Delta\phi$ .

# Specific Intensity

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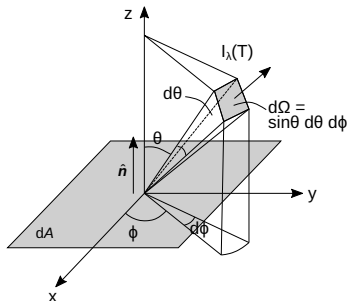
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Define  $dE_\lambda$  as the amount of energy carried by a ray of light with a wavelength between  $\lambda$  and  $\lambda + d\lambda$  (frequency between  $\nu$  and  $\nu + d\nu$ ) passing through a surface of area  $dA$  at an angle  $\theta$  into a cone of solid angle  $d\Omega$  in a time interval  $dt$ .

The **specific intensity** of the ray is defined as

$$I_\lambda \equiv \frac{dE_\lambda}{d\lambda dt dA \hat{n} \cdot d\Omega}, \quad I_\nu \equiv \frac{dE_\nu}{d\nu dt dA \hat{n} \cdot d\Omega}$$



# Specific Intensity

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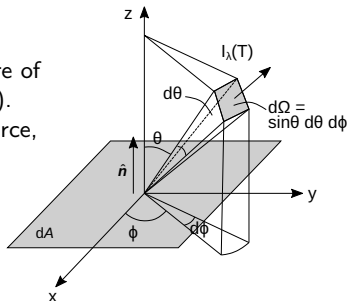
Summary

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The **specific intensity**  $I_\lambda$  is then a measure of brightness with units of  $\text{erg}/(\text{s cm}^2 \text{ rad}^2 \text{ \AA})$ .  $I_\lambda$  is independent of distance from the source, and can only be measured directly if we resolve the radiating surface (e.g. Sun, nebulae, planets).

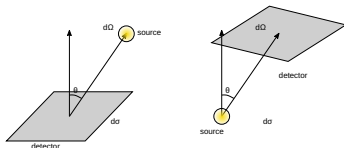


# Specific Intensity

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**Theorem:** Specific intensity is conserved (is constant) along any ray in empty space.

This follows directly from geometry. Let  $d\sigma_1$  and  $d\sigma_2$  be two infinitesimal surfaces along a ray of length  $r$ :



Let  $d\Omega_1 \ll 1$  rad be the solid angle subtended by  $d\sigma_2$  as seen from the center of the surface  $d\sigma_1$  and  $d\Omega_2 \ll 1$  rad be the solid angle subtended by  $d\sigma_1$  as seen from the center of the surface  $d\sigma_2$ . Then

$$d\Omega_1 = \frac{\cos \theta_2 d\sigma_2}{r^2}, \quad d\Omega_2 = \frac{\cos \theta_1 d\sigma_1}{r^2}$$

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# Specific Intensity

The power  $dP_1$  in the frequency range  $\nu$  to  $\nu + d\nu$  flowing through the area  $d\sigma_1$  in solid angle  $d\Omega_1$  is

$$\begin{aligned}dP_1 &= \frac{dE_1}{dt} \\&= (I_\nu)_1 \cos \theta_1 d\Omega_1 d\sigma_1 d\nu \\&= (I_\nu)_1 \cos \theta_1 \left( \frac{\cos \theta_2 d\sigma_2}{r^2} \right) d\sigma_1 d\nu \\&= (I_\nu)_1 \left( \frac{\cos \theta_1 \cos \theta_2 d\sigma_1 d\sigma_2}{r^2} \right) d\nu\end{aligned}$$

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Likewise

$$\begin{aligned}dP_2 &= \frac{dE_2}{dt} = (I_\nu)_2 \cos \left( \frac{\cos \theta_1 d\sigma_1}{r^2} \right) d\sigma_2 d\nu \\&= (I_\nu)_2 \left( \frac{\cos \theta_1 \cos \theta_2 d\sigma_1 d\sigma_2}{r^2} \right) d\nu\end{aligned}$$

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# Specific Intensity

The power  $dP_1$  in the frequency range  $\nu$  to  $\nu + d\nu$  flowing through the area  $d\sigma_1$  in solid angle  $d\Omega_1$  is

$$\begin{aligned}dP_1 &= \frac{dE_1}{dt} \\&= (I_\nu)_1 \cos \theta_1 d\Omega_1 d\sigma_1 d\nu \\&= (I_\nu)_1 \cos \theta_1 \left( \frac{\cos \theta_2 d\sigma_2}{r^2} \right) d\sigma_1 d\nu \\&= (I_\nu)_1 \left( \frac{\cos \theta_1 \cos \theta_2 d\sigma_1 d\sigma_2}{r^2} \right) d\nu\end{aligned}$$

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Radiation energy is conserved in free space (where there is no absorption or emission), so  $dE_1 = dE_2$  and  $(I_\nu)_1 = (I_\nu)_2$ . Q.E.D.

# Specific Intensity

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The conservation of specific intensity has two important consequences:

1. Brightness is independent of distance. Thus the camera setting for a good exposure of the Sun would be the same, regardless of being close to the Sun (e.g. near Venus) or far away from the Sun (e.g. near Mars).

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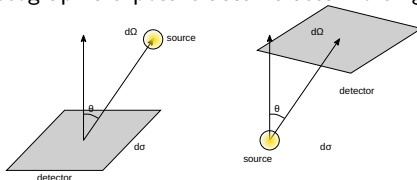
# Specific Intensity

The conservation of specific intensity has two important consequences:

1. Brightness is independent of distance. Thus the camera setting for a good exposure of the Sun would be the same, regardless of being close to the Sun (e.g. near Venus) or far away from the Sun (e.g. near Mars).

2. Brightness is the same at the source and at the detector. Thus you can think of brightness in terms of energy flowing out of the source or as energy flowing into the detector.

No passive optical system (e.g., a telescope) can increase the specific intensity of an extended source. Astronomical objects appear much brighter on photographs than to the eye (with or without a telescope) only as a long photographic exposure accumulates more light.



# Flux

We can express  $d\Omega$  by means of  $\theta$  and  $\phi$ :

$$F_\lambda = \oint I_\lambda \cos \theta \, d\omega = \int_0^{2\pi} d\phi \int_0^\pi I_\lambda \cos \theta \sin \theta \, d\theta$$

If no flux enters the surface, and if there is no azimuthal dependence for  $I_\lambda$ , then

$$F_\lambda = \oint I_\lambda \cos \theta \, d\omega = 2\pi \int_0^\pi I_\lambda \cos \theta \sin \theta \, d\theta = -2\pi \int_0^\pi I_\lambda \cos \theta \, d(\cos \theta)$$

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# Intensity vs. Flux

The **mean intensity**  $J_\lambda$  (sometimes also written  $\langle I_\lambda \rangle$ ) is the directional average of the specific intensity (over  $4\pi$  steradians):

$$\begin{aligned} J_\lambda &\equiv \frac{1}{4\pi} \oint I_\lambda \, d\omega \\ &= \frac{1}{4\pi} \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi} I_\lambda \sin \theta \, d\theta \, d\phi \end{aligned}$$

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integrated over the whole unit sphere centered on the point of interest

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integrated over the whole unit sphere centered on the point of interest

The **flux**  $F_\lambda$  is the projection of the specific intensity in the radial direction (integrated over all solid angles):

$$J_\lambda = \oint \underbrace{I_\lambda \cos \theta}_{\text{projection}} d\Omega$$

The amount of energy going through  $1 \text{ cm}^2$  per second per  $1 \text{ \AA}$  into the solid angle  $d\Omega$  in the direction inclined by the angle  $\theta$  to the normal of the area.

# Specific Radiation Flux

**Specific radiation flux** or **flux density**  $F_\lambda d\lambda$  is the net energy having a wavelength between  $\lambda$  and  $\lambda + d\lambda$  that passes each second through a unit area in the direction of the  $z$  axis:

$$\begin{aligned} F_\lambda d\lambda &= \int I_\lambda d\lambda \hat{\mathbf{n}} \cdot d\Omega \\ &= \int I_\lambda d\lambda \cos \theta d\Omega \\ &= \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi} I_\lambda d\lambda \cos \theta \sin \theta d\theta d\phi \end{aligned}$$

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**Note:** The factor  $\cos \theta$  allows the **cancellation** of oppositely directed rays.

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**Note:** The factor  $\cos \theta$  allows the **cancellation** of oppositely directed rays.

For an isotropic radiation field, there is no net transport of energy and  $F_\lambda = 0$ .

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# Specific Radiation Flux

**Radiation flux** is the netto energy going through the area perpendicular to the z-axis.

It can be decomposed into two half-spaces:

$$\begin{aligned} F &= -2\pi \int_0^\pi I_\lambda \cos \theta \, d(\cos \theta) = 2\pi \int_{-1}^1 I(\mu) \mu \, d\mu \\ &= 2\pi \int_0^1 I(\mu) \mu \, d\mu + 2\pi \int_{-1}^0 I(\mu) \mu \, d\mu \\ &= 2\pi \int_0^1 I(\mu) \mu \, d\mu - 2\pi \int_0^1 I(-\mu) \mu \, d\mu \\ &= F^+ - F^- \end{aligned}$$

with  $\mu = \cos \theta$

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Netto = Outwards - Inwards

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with  $\mu = \cos \theta$

Netto = Outwards - Inwards **Special case:** isotropic radiation field:  $F = 0$   
(An isotropic radiator is a theoretical point source of waves which radiates the same intensity of radiation in all directions.)

# Specific Energy Density

How much energy is contained within the radiation field?

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# Specific Energy Density

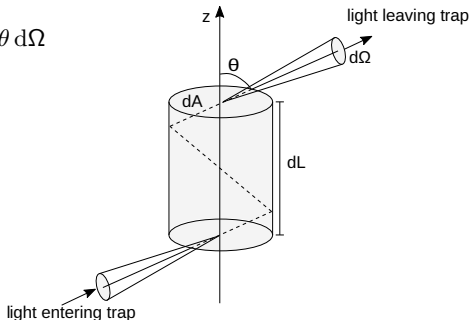
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How much energy is contained within the radiation field?

Use a "trap" consisting of a small cylinder of length  $dL$ , open at both ends, with perfect reflecting inside walls. The energy inside the trap is the same as what would be present at that location if the trap were removed.

The radiation travels through the trap in a time  $dt = dL/(c \cos \theta)$ .

$$\begin{aligned} E_{\lambda} d\lambda &= I_{\lambda} d\lambda dt dA \cos \theta d\Omega \\ &= I_{\lambda} d\lambda dA d\Omega \frac{dL}{c} \end{aligned}$$



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# Specific Energy Density

The **specific energy density**  $u_\lambda$  is the energy per unit volume with a wavelength between  $\lambda$  and  $\lambda + d\lambda$

$$\begin{aligned} u_\lambda d\lambda &= \frac{E_\lambda d\lambda}{dA dL} = \frac{I_\lambda d\lambda dA d\Omega dL}{c dA dL} = \frac{1}{c} \int I_\lambda \lambda d\Omega \\ &= \frac{1}{c} \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi} I_\lambda d\lambda \sin \theta d\theta d\phi = \frac{4\pi}{c} \langle I_\lambda \rangle d\lambda \end{aligned}$$

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For an isotropic radiation field,

$$u_\lambda d\lambda = \frac{4\pi}{c} I_\lambda d\lambda$$

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For an isotropic radiation field,

$$u_\lambda d\lambda = \frac{4\pi}{c} I_\lambda d\lambda$$

and for blackbody radiation

$$u_\lambda d\lambda = \frac{4\pi}{c} B_\lambda d\lambda = \frac{8\pi hc}{\lambda^5} \frac{1}{e^{hc/\lambda kT} - 1} d\lambda$$

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# Total Energy Density

The **total energy density** of a radiation field is found by integrating over all wavelengths or frequencies:

$$\begin{aligned} u &= \int_0^{\infty} u_{\lambda} d\lambda \\ &= \int_0^{\infty} u_{\nu} d\nu. \end{aligned}$$

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# Radiative Transfer

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We define the (mass) emission coefficient as the amount of radiation emitted per second, per unit wavelength interval, per unit mass, per unit solid angle, in certain direction.

So in the case of **pure emission**, one finds the change in specific intensity

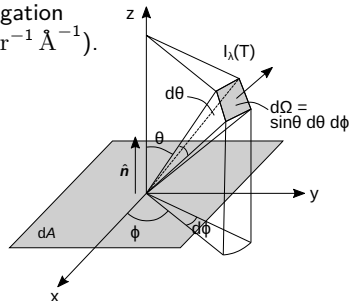
$$dI_{\lambda} = \rho j_{\lambda} ds$$

with

$I_{\lambda}$  specific intensity

$s$  is distance traveled in direction of propagation

$j_{\lambda}$  the emission coefficient ( $\text{erg cm}^{-3} \text{s}^{-1} \text{sr}^{-1} \text{\AA}^{-1}$ ).



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# Radiative Transfer

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Define the (mass) emission coefficient as the amount of radiation emitted per second, per unit wavelength interval, per unit mass, per unit solid angle, in certain direction.

So in the case of **pure emission**, one finds the change in specific intensity

$$dI_{\lambda} = \rho j_{\lambda} ds$$

with

$I_{\lambda}$  specific intensity

$s$  is distance traveled in direction of propagation

$j_{\lambda}$  the emission coefficient ( $\text{erg cm}^{-3} \text{s}^{-1} \text{sr}^{-1} \text{\AA}^{-1}$ ).

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This is the equation of radiative transfer for a purely emitting medium.

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This is the equation of radiative transfer for a purely emitting medium.

**on units:**

An erg is equal to one gram centimeter-squared per second-squared ( $\text{g cm}^2 \text{s}^{-2}$ ). This is equal to  $10^{-7}$  joules or 100 nanojoules (nJ) in SI units.

Steradian (ster) is the unit of solid angle in the International System of Units (SI). The entire sphere has a solid angle of  $4\pi$  sr.

# Radiative Transfer

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In the case of **pure absorption**, we find for the number of photons in a beam  $N_p$  to obey the following differential equation:

$$\frac{dN_p}{ds} = -N_p n \sigma = -N_p \kappa \rho$$

where  $s$  is the distance traveled in the direction of propagation.

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In the case of **pure absorption**, we find for the number of photons in a beam  $N_p$  to obey the following differential equation:

$$\frac{dN_p}{ds} = -N_p n \sigma = -N_p \kappa \rho$$

where  $s$  is the distance traveled in the direction of propagation.

The same applies to specific intensity:

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

with the **wavelength-dependent** monochromatic opacity  $\kappa_\lambda$ .

This is the equation of radiative transfer in a purely absorbing medium.

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The primary mode of energy transport through the surface layers of a star is by radiation.

The **radiative transfer equation** describes how the physical properties of the material are coupled to the spectrum we ultimately measure.

As a beam of light moves through the gas in the stellar atmosphere, photons are not only added by emission from the surrounding material (the case we saw so far), but are also removed from the beam by absorption or scattering.

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Summary

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As a beam of light moves through the gas in the stellar atmosphere, photons are not only added by emission from the surrounding material (the case we saw so far), but are also removed from the beam by absorption or scattering.

Incorporating both **absorption and emission**, one obtains

$$dI_{\lambda} = -\rho\kappa_{\lambda}I_{\lambda} ds + \rho j_{\lambda} ds$$

The **opacity**  $\kappa_{\lambda}$  has units of  $\text{cm}^2 \text{g}^{-1}$ . The change in the intensity of the beam is determined by the rates at which the competing process of emission and absorption occur.

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The **competition** between the rates at which photons are removed from the beam by absorption, and added to the beam by emission describes how rapidly the intensity of the light beam changes. To introduce the **ratio of emission to absorption**, we rewrite the previous equation

$$-\frac{1}{\rho\kappa_{\lambda}} \frac{dI_{\lambda}}{ds} = I_{\lambda} - \frac{j_{\lambda}}{\kappa_{\lambda}}.$$

Now, define the ratio of the emission coefficient to the absorption coefficient as the **source function**,  $S_{\lambda} \equiv j_{\lambda}/\kappa_{\lambda}$ , which has the same units as the intensity,  $\text{ergs s}^{-1} \text{cm}^{-3} \text{ster}^{-1}$ .

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We obtain the **radiative transfer equation (RTE)**:

$$-\frac{1}{\rho\kappa_{\lambda}} \frac{dI_{\lambda}}{ds} = I_{\lambda} - S_{\lambda}$$

The intensity of the light tends to become equal to the local value of the source function.

# Physical Interpretation of Source Function $S_\lambda$

In the Thermodynamic Equilibrium (TE), nothing changes with time.

A beam of light passing through such a gas volume will not change either:

$$dI_\lambda/d\tau_\lambda = 0 \Rightarrow S_\lambda = I_\lambda = B_\lambda$$

In TE, the source function equals the Planck function.

In the theory of stellar atmospheres, we make the assumption of **local thermodynamic equilibrium (LTE)** where  $S_\lambda = B_\lambda$ . This does not necessarily mean that  $S_\lambda = I_\lambda$ .

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# Optical Depth

Often, when describing radiative transfer, we use the **optical depth**.

The optical depth is a dimensionless quantity related to the absorption coefficient or opacity.

We find it by answering the **question**: What is the ratio of the final intensity to the original intensity?

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# Optical Depth

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We find it by answering the **question**: What is the ratio of the final intensity to the original intensity?

There are several factors which must affect the intensity in obvious ways:

- the greater the distance the beam travels, the more light will be removed from it
- the greater the density of material  $\rho$ , the more light will be scattered or absorbed
- the composition of the material; some atoms are much more efficient at absorbing light than others

# Optical Depth

We can put all this together in a mathematical equation:

$$dI = -\rho\kappa I ds$$

with

$I$  the incoming intensity of the light

$dI$  the amount of light added to the beam (hence the negative sign)

$ds$  the distance the light travels

$\rho$  the density of the material

$\kappa$  the opacity or absorption coefficient.

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$dI$  the amount of light added to the beam (hence the negative sign)

$ds$  the distance the light travels

$\rho$  the density of the material

$\kappa$  the opacity or absorption coefficient.

$\kappa$  serves two purposes: first, it is a constant of proportionality which serves to make the units match on both sides of the equation; second, it expresses the efficiency with which this particular sort of material (hydrogen, or helium, or electrons, or ...) absorbs and scatters light.

The wavelength-depending **spectral optical depth**  $\tau_\lambda$  is given similarly by

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

$$dI = -\rho\kappa_\lambda I ds$$

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# Radiative Transfer Equation

Let's **solve** the equation of radiative transfer.

Consider radiation passing through material in which opacity and emissivity are known functions of  $s$ . We attempt to solve the RTE through use of an integrating factor:

Rewrite the transfer equation with the optical depth,  $\tau_\lambda$ ,

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

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

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Integrate from front of slab ( $s = 0$ ) to  $s$ :

$$I_{\lambda} e^{-\tau_{\lambda}} = I_{\lambda,0} e^{-\tau_{\lambda,0}} + \int_{\tau_{\lambda}}^{\tau_{\lambda,0}} S_{\lambda} e^{-t} dt$$

where  $I_{\lambda,0}$  and  $\tau_{\lambda,0}$  are intensity and optical depth at front of slab (optical depth decreases as we travel through slab), and  $t$  is a dummy variable.

In terms of  $I_{\lambda}$  and  $S_{\lambda}$ , the solution can be written as

$$I_{\lambda} = I_{\lambda,0} e^{\tau_{\lambda} - \tau_{\lambda,0}} + \int_{\tau_{\lambda}}^{\tau_{\lambda,0}} S_{\lambda} e^{\tau_{\lambda} - t} dt$$

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This allows us to calculate the radiation field once we know source function  $S_{\lambda}$  as a function of optical depth  $\tau_{\lambda}$ .

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This allows us to calculate the radiation field once we know source function  $S_{\lambda}$  as a function of optical depth  $\tau_{\lambda}$ .

**The problem:** Despite it looks simple - in many situations  $S_{\lambda}$  (and  $\kappa_{\lambda}$ ) depend on  $I_{\lambda}$ !



# Radiative Transfer Equation

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There are some **simple** RTE cases:

**Emission, no absorption:**  $\kappa_\lambda \rightarrow 0$

$$I_\lambda = I_{\lambda,0} + \int_0^s j_\lambda \rho \, ds$$

*interpretation:* The intensity at  $s$  is the incoming intensity plus the sum of contributions from emitting material in the interval  $(0, s)$ .

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# Radiative Transfer Equation

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*interpretation:* The intensity at  $s$  is the incoming intensity plus the sum of contributions from emitting material in the interval  $(0, s)$ .

**Constant source function:**

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

*interpretation:* The intensity at  $s$  is the incoming intensity attenuated by factor  $e^{-\Delta\tau}$ , plus contributions from emitting material, also attenuated.

# Radiative Transfer Equation

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There are some **simple** RTE cases:

**Homogeneous radiation field:**

$$I_{\lambda} = I_{\lambda,0} = S_{\lambda}$$

In the special case of a **black body**:

Since  $I_{\lambda} = B_{\lambda}$  (Planck function),  $S_{\lambda} = B_{\lambda}$ , and  $j_{\lambda} = \kappa B_{\lambda}$ .

*interpretation:* most emission at wavelengths where opacity is high; good absorber is also good emitter

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The Stefan-Boltzmann law ( $F = \sigma_{\text{SB}} T^4$ ) defines a star's effective temperature, i.e. the temperature which a black body would need in order to radiate the same amount of energy as the star.

The specific intensity ( $I_\lambda$  or  $I_\nu$ ) is distance independent.

The flux ( $F_\lambda$  or  $F_\nu$ ) is the angular integral over the projection of the specific intensity in the radial direction and obeys the inverse square law.

The Planck function is monotonic in temperature.

# Recap: Flux and Brightness

The **(specific) intensity**  $I_\lambda$  is a measure of brightness:

$$I_\lambda = \frac{E_\lambda}{\cos \theta \, d\lambda \, d\sigma \, d\omega \, dt}$$

The **flux**  $F_\lambda$  is the projection of the specific intensity in the radial direction, integrated over all solid angles:

$$F_\lambda = \oint I_\lambda \cos \theta \, d\omega$$

$I_\lambda$  is independent of the distance from the source.  $F_\lambda$  obeys the inverse square law.

# Recap: Flux and Brightness

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Flux is related to the **intensity**:

The flux  $F_\lambda$  is a measure of the net energy flow across an area  $d\sigma$ , over a time  $dt$ , in a  $d\lambda$ . The only directional significance is whether the energy crosses  $d\sigma$  from the top or from the bottom.

Then we can write:

$$\begin{aligned} F_\lambda &= \frac{\oint dE_\lambda}{d\lambda d\sigma dt} \\ &= \oint I_\lambda \cos \theta d\omega \end{aligned}$$

The solid angle  $d\omega$  appears for  $I_\lambda$  but not for  $F_\lambda$ .

# Mean Intensity and Energy Density

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## The mean intensity

$$J_\lambda = \frac{1}{4\pi} \oint I_\lambda d\Omega$$

is related to the energy density  $u_\lambda$ :

Energy radiated through area element  $d\sigma$  during time  $dt$ :

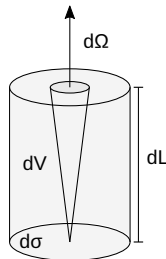
$$dE_\lambda = I_\lambda d\lambda d\sigma d\Omega dt$$

with  $l = c dt$ :  $dV = l d\sigma = c dt d\sigma$

Hence, the energy contained in the volume element  $dV$  per wavelength interval, the **energy density**, is

$$u_\lambda dV d\lambda = \oint I_\lambda d\Omega d\lambda d\sigma dt = 4\pi J_\lambda \frac{dV}{c} d\lambda$$

$$u_\lambda = \frac{4\pi}{c} J_\lambda \left[ \frac{\text{erg}}{\text{cm}^3 \text{ \AA}} \right]$$



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# Radiation Pressure

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Because a photon possesses an energy  $E$ , it also carries a **momentum**  $p_\lambda = E_\lambda/c$  and can exert a **radiation pressure**:

Consider photons transferring momentum to a solid wall. We get the force:

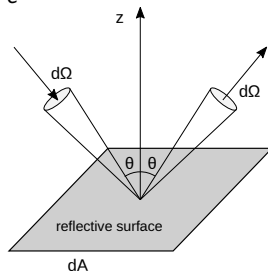
$$F = \frac{dp_{\lambda,\perp}}{dt} = \frac{1}{c} \frac{dE_\lambda}{dt} \cos \theta$$

The pressure is:

$$dP_\lambda = \frac{F}{d\sigma} = \frac{1}{c} \frac{dE_\lambda}{dt} \frac{\cos \theta}{d\sigma} = \frac{1}{c} I_\lambda \cos^2 \theta d\Omega d\lambda$$

with

$$I_\lambda = \frac{dE_\lambda}{\cos \theta d\lambda d\sigma d\Omega dt}$$



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# Radiation Pressure

The change in the  $z$  component of the momentum of photons with wavelengths between  $\lambda$  and  $\lambda + d\lambda$  that are reflected from the area  $dA$  in a time interval  $dt$  is

$$\begin{aligned}\Delta p_{\lambda} d\lambda &= [p_{\lambda,z}^{\text{final}} - p_{\lambda,z}^{\text{initial}}] d\lambda \\ &= \left[ \frac{E_{\lambda} \cos \theta}{c} - \left( -\frac{E_{\lambda} \cos \theta}{c} \right) \right] d\lambda \\ &= \frac{2E_{\lambda} \cos \theta}{c} d\lambda \\ &= \frac{2}{c} I_{\lambda} d\lambda dt dA \cos^2 \theta d\Omega\end{aligned}$$

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# Radiation Pressure

From Newton's 2nd and 3rd laws, the radiation pressure exerted by these photons with wavelengths between  $\lambda$  and  $\lambda + d\lambda$  in the case of reflection:

$$P_{\lambda}^{\text{rad}} = \frac{2}{c} \int_{\text{hemisphere}} I_{\lambda} d\lambda \cos^2 \theta d\Omega = \frac{2}{c} \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi/2} I_{\lambda} d\lambda \cos^2 \theta \sin \theta d\theta d\phi$$

Imagine removing the reflecting surface  $dA$  and replacing it with a mathematical surface. Instead of being reflected, photons will be streaming through  $dA$  from the other side. We have:

$$\begin{aligned} P_{\lambda}^{\text{rad}} d\lambda &= \frac{1}{c} \int I_{\lambda} d\lambda \cos^2 \theta d\Omega \quad (\text{transmission}) \\ &= \frac{1}{c} \int_{\pi=0}^{2\pi} \int_{\theta=0}^{\pi} I_{\lambda} d\lambda \cos^2 \theta \sin \theta d\theta d\phi \\ &= \frac{4\pi}{3c} I_{\lambda} d\lambda \quad (\text{isotropic radiation field}) \end{aligned}$$

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# Radiation Pressure

The total radiation pressure produced by photons with all wavelengths is

$$P_{\text{rad}} = \int_0^{\infty} P_{\lambda}^{\text{rad}} d\lambda.$$

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# Radiation Pressure

The total radiation pressure produced by photons with all wavelengths is

$$P_{\text{rad}} = \int_0^{\infty} P_{\lambda}^{\text{rad}} d\lambda.$$

For blackbody radiation, the total radiation pressure can be expressed as

$$\begin{aligned} P_{\text{rad}} &= \frac{4\pi}{3c} \int_0^{\infty} B_{\lambda}(T) d\lambda \\ &= \frac{4\sigma_{\text{SB}} T^4}{3c} = \frac{1}{3} u \end{aligned}$$

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# Radiation Pressure Gradient

Despite photon's *random walk* journey to the stellar surface, the energy from the deep interior of the star manages to escape into space.

The temperature in the stellar atmosphere decreases outward, the radiation pressure is smaller at larger radii. This gradient in the radiation pressure causes a **net flow of radiation energy moving outward** from the center of the star and eventually emerging at the stellar surface. This process can be described by

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

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

The transfer of radiation energy is a subtle process involving the slow outward diffusion of randomly walking photons, drifting towards the surface in response to small differences in the radiation pressure.

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# Radiation Pressure Gradient

Assume a **grey atmosphere**, whose opacity is independent of wavelength and is described by the Rosseland mean opacity  $\bar{\kappa}$ , and ignore all the remaining wavelength dependencies by integrating over all wavelengths

$$I = \int_0^\infty I_\lambda \, d\lambda$$

and

$$S = \int_0^\infty S_\lambda \, d\lambda$$

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# Radiation Pressure Gradient

The transfer equation for a plane-parallel gray atmosphere is

$$\mu \frac{dI}{d\tau_{\perp}} = I - S$$

Integrating over all solid angles and recalling that  $S$  is isotropic, we have

$$\frac{d}{d\tau_{\perp}} \int I \mu d\Omega = \int I d\Omega - \int S d\Omega = \Omega$$

$$\frac{dF_{\text{rad}}}{d\tau_{\perp}} = 4\pi(\langle I \rangle - S)$$

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# Radiation Pressure Gradient

Furthermore, multiplying the transfer equation by  $\mu = \cos \theta$  and integrating over all solid angles, we find

$$\frac{d}{d\tau_{\perp}} \underbrace{\int I \mu^2 d\Omega}_{=cP_{\text{rad}}} = \underbrace{\int I \mu d\Omega}_{=F_{\text{rad}}} - S \underbrace{\int \mu d\Omega}_{=0}$$

Recall that

$$F_{\lambda} d\lambda = \int I_{\lambda} d\lambda \mu d\Omega$$

and

$$P_{\lambda, \text{rad}} d\lambda = \frac{1}{c} \int I_{\lambda} d\lambda \mu^2 d\Omega$$

Therefore, we have

$$\frac{dP_{\text{rad}}}{d\tau_{\perp}} = \frac{1}{c} F_{\text{rad}}.$$

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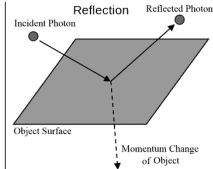
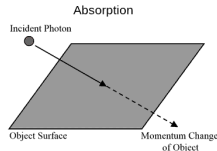
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A photon has **momentum**  $p_\lambda = E_\lambda/c$ .

We consider photons hitting a solid wall, transferring momentum. We have the **force**

$$F = \frac{dp_{\lambda\perp}}{dt} = \frac{1}{c} \frac{dE_\lambda}{dt} \cos \theta$$



This generates **radiation pressure**:

$$dP_\lambda = \frac{F}{d\sigma} = \frac{1}{c} \frac{dE_\lambda}{dt} \frac{\cos \theta}{d\sigma} = \frac{1}{c} I_\lambda \cos^2 \theta d\omega d\lambda$$

$$\Rightarrow P(\lambda) = \frac{1}{c} \oint_{4\pi} I_\lambda \cos^2 \theta d\omega = \frac{4\pi}{c} K_\lambda$$

Where  $K_\lambda$  is the **K-integral**

$$K_\lambda = \frac{1}{4\pi} \oint I_\lambda \cos^2 \theta d\omega.$$

# Understanding Spectra

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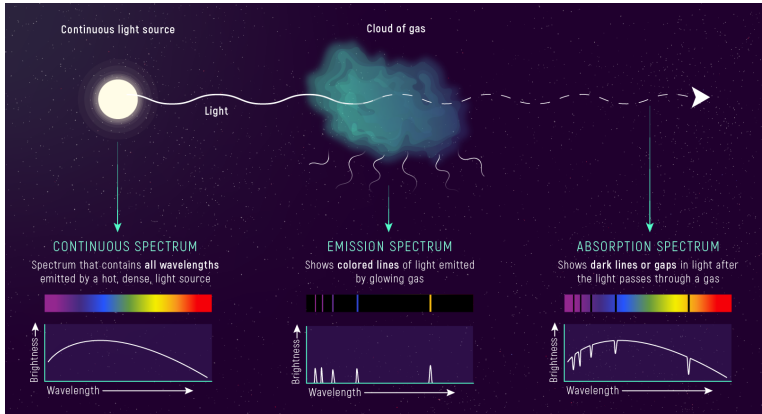
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credit: <https://webbtelescope.org/>

# Emission Nebula

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An emission nebula is a nebula formed of ionized gases that emit light of various wavelengths. The most common source of ionization is high-energy UV photons emitted from a nearby hot star.

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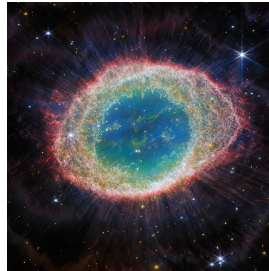
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Emission nebulae exist in three main forms: as diffuse nebulae, planetary nebulae, and supernova remnants.



left: IR image of emission nebula NGC 2174, Spitzer Space Telescope  
right: Ring Nebula as seen in IR and visible light by a multiple exposure of images from the James Webb Space Telescope's NIRCam, showing an outer layer of hydrogen that is very faint in visible light

# Spectrum of Emission Nebula

Nebular emission lines fall into two basic types: permitted recombination lines and forbidden (collisional) lines.

Analysis of line strength allows the determination of nebular temperature, density, and chemical composition.

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**Recombination lines** are caused when atoms in a nebula are ionized by absorbing energy from the UV radiated by a hot star. When free electrons are re-captured by various ions, they can land on any energy level, radiating emission lines as they skip downward. H and He produce only recombination lines, as do atoms and ions of oxygen, nitrogen, carbon, neon, and others.

# Spectrum of Emission Nebula

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**Forbidden lines** are not really forbidden, just difficult to produce from energy levels that do not readily interact with each other. They are caused when energetic free electrons collide with atoms or ions whose electrons are in the bottom level and excite these bound electrons to higher levels, from which they eventually drop downward to radiate emission lines. They are indicated by square brackets.

# Spectrum of Emission Nebula

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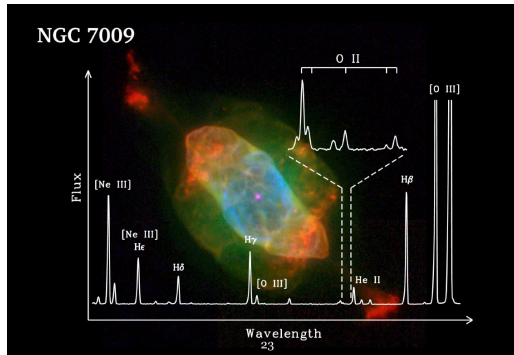
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The producing ion is indicated by Roman numeral, "I" for neutral, "II" for single ionization (one electron missing), "III" for double ionization (two missing), and so on. The full spectrum is at the bottom. The inset above it shows a vertically expanded view. Hydrogen and helium produce recombination lines. Square brackets indicate collisional (forbidden) lines, which include those of nitrogen, oxygen, neon, argon, and sulphur.



# Absorption vs. Emission

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## Emission line spectra:

- optically thin volume of gas with no background illumination (emission nebula)
- optically thick gas in which the source function increases outwards (UV solar spectrum)

## Absorption line spectra:

- optically thin gas in which the source function declines outward, generally  $T$  decreases outward (Stellar photospheres)
- optically thin gas penetrated by background radiation (ISM along the line of sight)

# Summary

Things we learned about:

- Radiation density and pressure are defined.
- The optical depth is a dimensionless quantity related to the absorption coefficient or opacity.
- The source function is defined as the ratio of emission to absorption coefficients.
- The source function equals the Planck function in LTE.
- Radiative transfer equation and its formal solution.
- Absorption and emission line spectra.

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