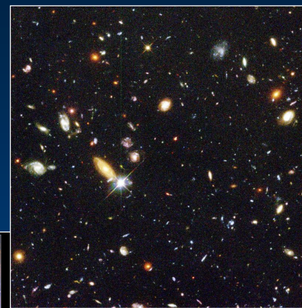
Properties of Electromagnetic Radiation Chapter 5

Concepts:

- Electromagnetic waves
- Types of spectra
- Temperature
- Blackbody radiation

- Dual nature of radiation
- Atomic structure
- Interaction of light and matter
- Emission and absorption lines
- Doppler shift



Radiation carries information

- How hot is the Sun?
- How does it compare to other stars?
- What is the chemical composition of stars?
- What is the nature of gas clouds between the stars?
- How do stars and gas clouds orbit in galaxies?
- How do we know that the Universe is expanding?

Radiation – light, radio waves, infrared, etc. – travels as electromagnetic waves

What is light?

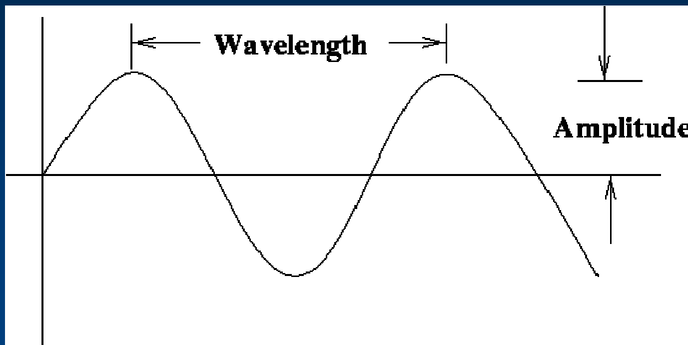
- Light is an example of *electromagnetic (EM) radiation*
- Electromagnetic radiation can be treated either as
  - waves
  - photons ("particles" of radiation)
- Both natures have to be considered to describe all essential properties of radiation

What is a wave?

- A wave is the transfer of energy from one point to another, without the transfer of material between the points
- A wave is manifested by a periodic change in the properties of a medium that it travels through

Properties of a wave

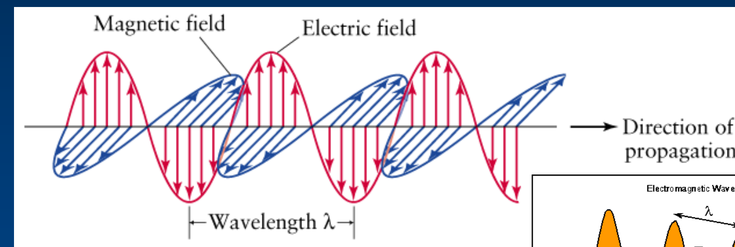
Amplitude: height of the wave (e.g. m for water waves)
<u>Wavelength (λ)</u>: distance between adjacent crests (m)
Period: the time it takes for one complete wave cycle to pass a given point (s)
<u>Frequency (ν)</u>: number of wave cycles that pass a point in 1s (Hz, or cycles/sec)
<u>Speed</u>: horizontal speed of a point on a wave as it propagates (m/s)



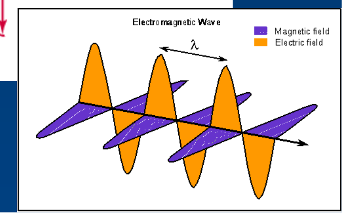
Period = 1/ν
Speed = λ/P = λν

Electromagnetic waves

- EM waves: self propagating, oscillating electric and magnetic fields.
- Speed of all EM waves (in vacuum) is speed of light c = 3.00 x 10^8 m/s.
- c = λ ν, where λ is the wavelength, and ν is the frequency [Hz].



EM waves are different from other waves, since they don't need a medium to propagate in!

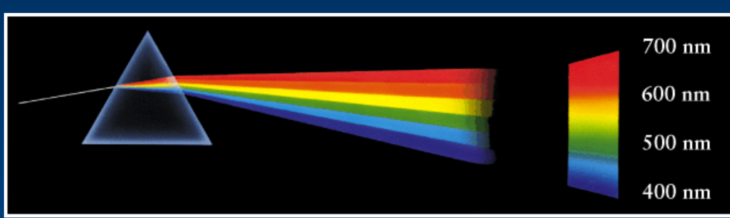


The human eye is sensitive to EM radiation with wavelength range:

400 nm < λ < 700 nm where 1 nm =10^{-9} m.
= 4,000 Å < λ < 7,000 Å where 1 Å is 10^{-10} m.

[nm = nanometer,
Å = Ångström]

This goes from violet to red.



This also demonstrates <u>refraction</u>: light bends when density of medium changes. Bending angle depends on <u>wavelength</u>. Also introduces a way to make a spectrum.

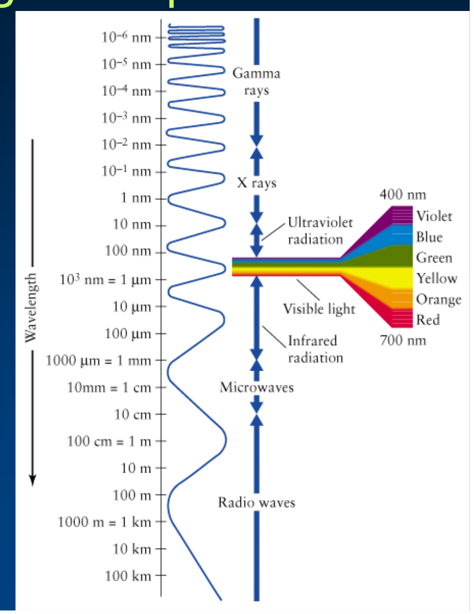
The electromagnetic spectrum

There's much more beyond the visible!

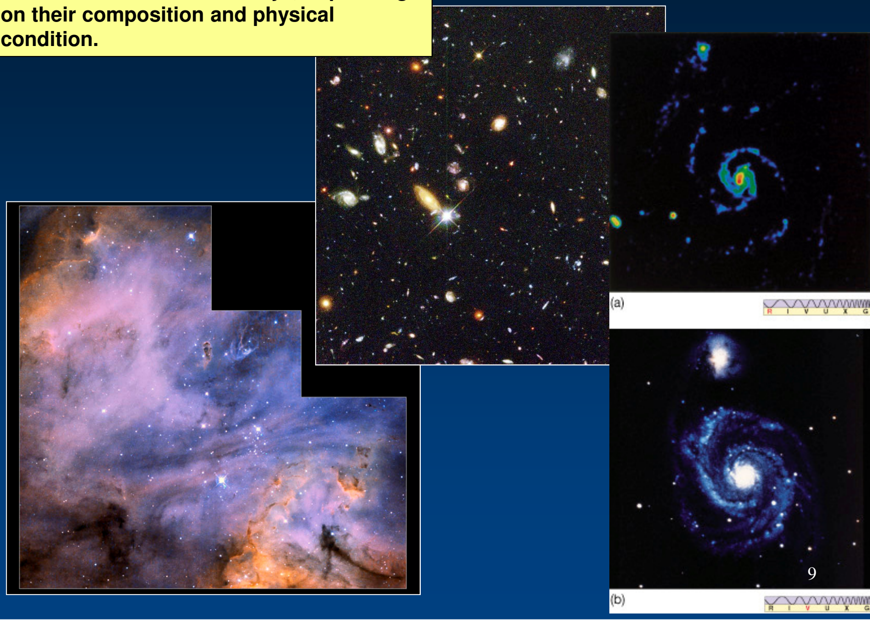
In order of increasing wavelength:

Gamma rays, X rays, Ultraviolet (UV), Visible, Infrared (IR), Microwaves, Radio.

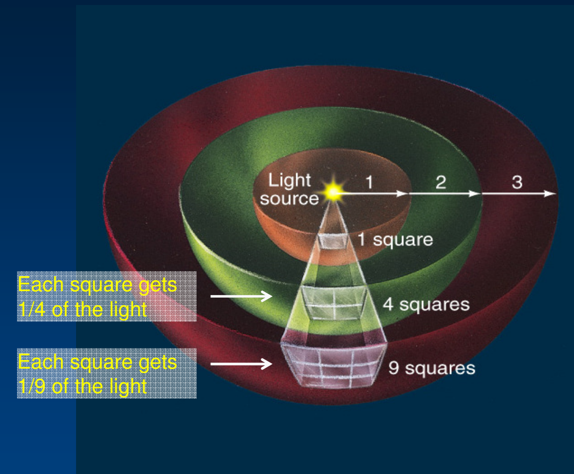
Note use of nm, µm, mm, cm, m, km



Different objects in the Universe give off EM radiation in different ways, depending on their composition and physical condition.



The "Inverse-Square" Law for Radiation



Apparent Brightness $\alpha \frac{1}{d^2}$ d is the distance between source and observer.

How do radiation and matter interact?

- Emission - light bulb, star
- Absorption - your skin can absorb light, in turn the absorbed energy heats your skin. Dust grains in space behave similarly. Atoms also absorb radiation.
- Transmission - glass and air lets light pass through (with refraction and diffraction possible)
- Reflection and scattering - light can bounce off matter leading to reflection (in one direction) or scattering (in many directions). Dust grains also scatter light.

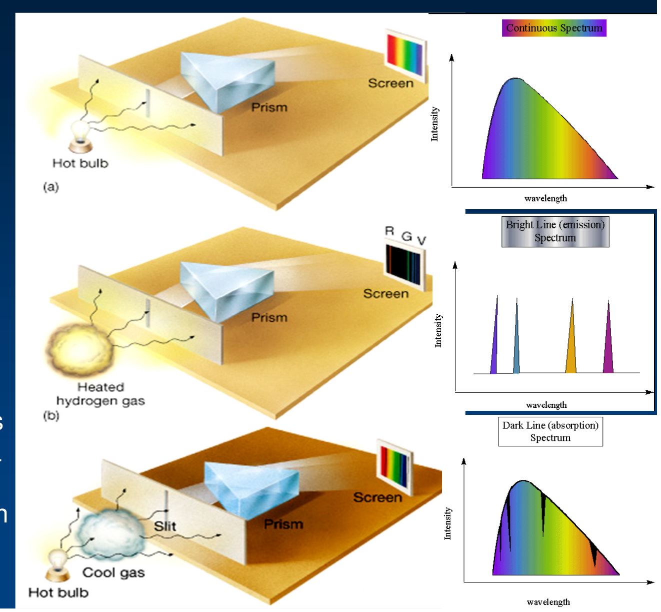
Three types of spectra and Kirchhoff's laws

Kirchhoff's laws of spectroscopy (1859):

A hot, opaque body, or a hot, dense gas produces a continuous spectrum.

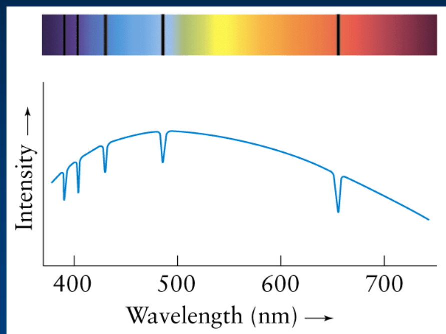
A hot, transparent gas produces an emission line spectrum.

A cool, transparent gas in front of a source of a continuous spectrum produces an absorption line spectrum.



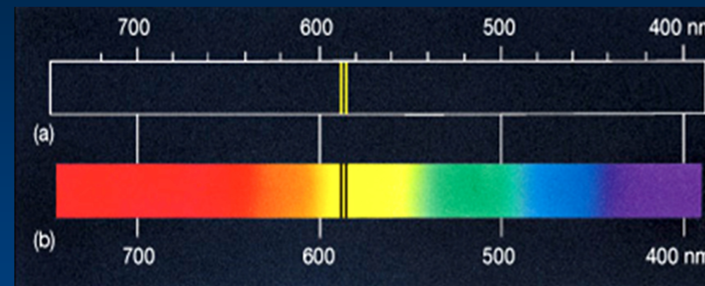
Note: two ways to show a spectrum:

1) as an image
2) (more usefully) as a plot of intensity vs wavelength (or frequency)



Each element has unique spectral lines. For a gas of a given element, absorption and emission lines occur at same wavelengths.

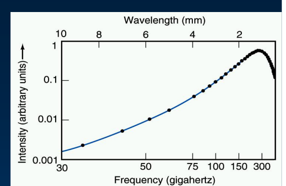
Sodium

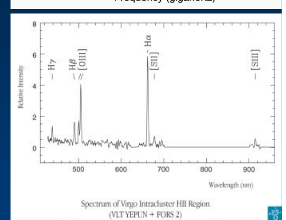


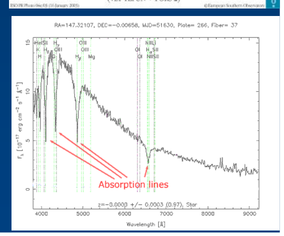
Understood after development of quantum mechanics in early 1900's.

Astronomical and other examples:

- Continuous: incandescent lights, "the universe"
- Emission line: neon lights, hot interstellar gas -- "HII regions", "supernova remnants".
- Absorption line: stars (relatively cool atmospheres overlying hot interiors).







Two important concepts for understanding spectra: temperature and "blackbody radiation"…

Temperature

- A measurement of the internal energy content of an object.
- Solids: higher temperature means higher average vibrational energy per atom or molecule.
- Gases: higher temperature means more average kinetic energy (faster speeds) per atom or molecule.
- If it gets cold enough, all motion will stop. How cold is that?
- Corresponds to a temperature of -273° C (-459° F) - *absolute zero.*

Kelvin temperature scale

- An absolute temperature scale in which the temperature is directly proportional to the internal energy of the object.
  - Related to Celsius scale, but a different zero point
  - T(K) = T(°C) + 273 °C
  - 0 K: absolute zero – all motion stops
  - 273 K: freezing point of water
  - 373 K: boiling point of water

See box 5.1

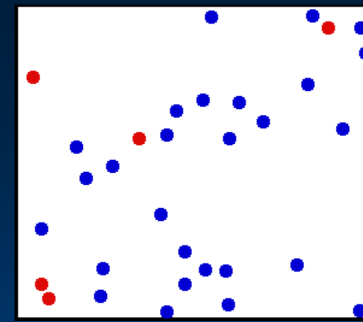
How do temperature and energy relate?

Consider an atom or a molecule in a gas:

$$\mathrm{KE} = \frac{1}{2} m V^2$$

For gas at temperature T (in K), average KE is:

$$\overline{\mathrm{KE}} = \frac{3}{2} kT$$



k is Boltzmann's constant, and has value 1.38 x 10^{-23} kg m^2 s^{-2} K^{-1}, (or Joules K^{-1}). For particles of mass m, equate:

$$\overline{\frac{1}{2} m V^2} = \frac{3}{2} kT \quad \Rightarrow V = \sqrt{\frac{3kT}{m}}$$

Average (strictly "root-mean-square") speed of particles of mass *m* in a gas of temperature *T*

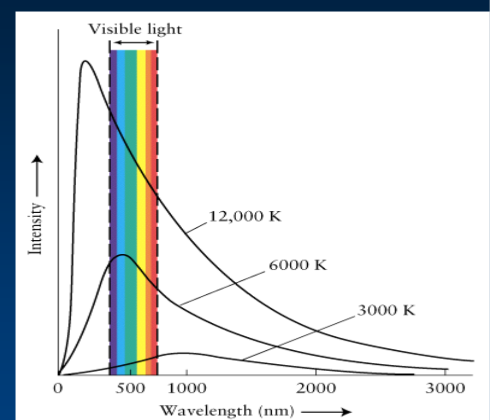
At a given T, there is an average KE for all the atoms or molecules in a gas, but their average speed will depend on their mass. Even for each mass, this *V* is only an average. Particles have a spread of speeds around the average.

Blackbody (thermal) radiation

- A blackbody is an ideal object that absorbs all radiation at all wavelengths: perfect absorber. Charcoal is a decent example.
  - No reflected light, no transparency
- But it re-emits radiation with a continuous spectrum of characteristic shape
- The more radiation an object absorbs and re-emits, the higher the temperature.
- The spectrum of its radiation has no contribution from reflected light. It's all re-emitted radiation, and spectrum depends on its temperature only (not on , e.g., composition).
- Hot, dense objects, like light bulb filaments or <u>stars</u>, shine with a spectrum that is approximately that of a blackbody, despite their temperature being due to <u>internally</u> generated energy.

Intensity, or brightness, as a function of frequency (or wavelength) is given by the "Planck formula":

$$I_\nu = \frac{2h\nu^3}{c^2}\left[\frac{1}{e^{h\nu/kT} - 1}\right]$$



where h is Planck's constant (h=6.6 x 10^{-34} J s), k is Boltzmann's constant, and c is the speed of light.

Units of I_ν: J s^{-1} m^{-2} $ster^{-1}$ Hz^{-1}

This is explanation of Kirchhoff's first law

Example: 3 blackbody (Planck curves) for 3 different temperatures typical of star atmospheres.

Wien's law for a blackbody

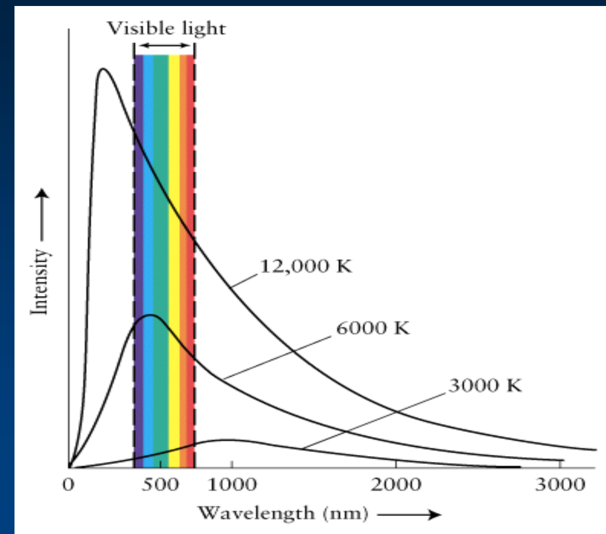
$$\lambda_{max} = 0.0029 \text{ (m K) / T}$$

where λ_{max} is the wavelength of maximum emission of the object in m and T is the temperature in K. The constant has units of m K.

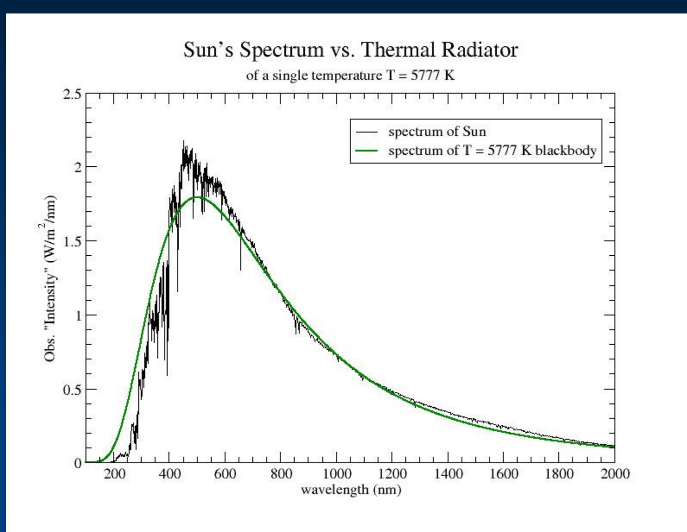
=> The hotter the blackbody, the shorter the wavelength of maximum emission

Hotter objects are bluer, cooler objects are redder.

Wavelengths of peaks of the curve illustrate Wien's Law.



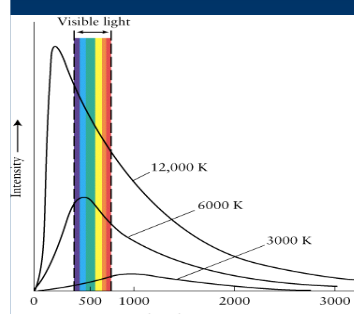
The spectrum of the Sun is *almost* a blackbody curve.



<u>Example 1:</u> How hot is the Sun at the "surface"?

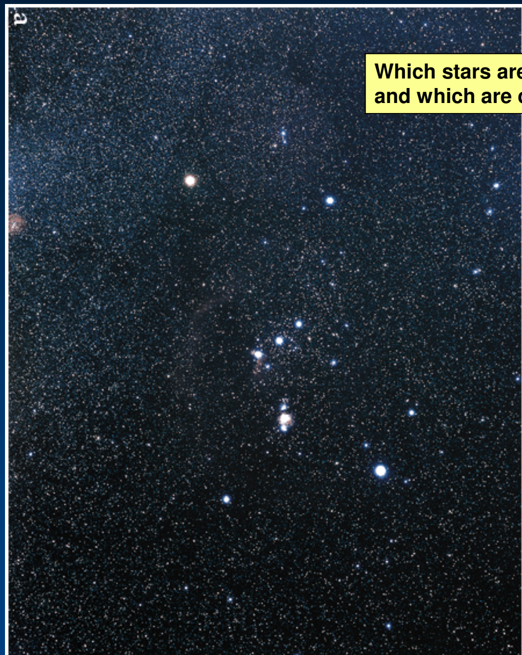
Measure λ_{max} to be about 500 nm, so $T_{sun} = (0.0029 \text{ m K}) / \lambda_{max} =$ $(0.0029 \text{ m K}) / 5.0\text{x}10^{-7} \text{ m} = 5800 \text{ K}$

<u>Example 2:</u> At what wavelength would the spectrum peak for a star which is 5800 K / 2 = 2900 K?



Or a star with T= 5800 K x 2 = 11,600 K?

What colors would these stars be?



Which stars are hotter, and which are cooler?

Stefan-Boltzmann law for a blackbody

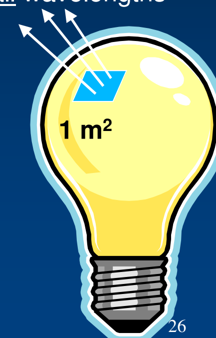
$$F_e = \sigma T^4$$

F_e is the emitted or emergent energy flux, in joules per second per square meter of surface (J s^{-1} m^{-2}, or W m^{-2}) over all wavelengths

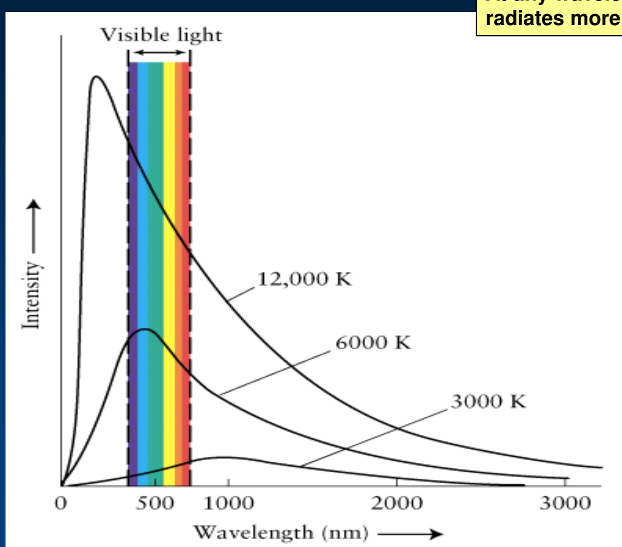
σ is a constant = 5.67 x 10^{-8} W m^{-2} K^{-4}

T is the object's temperature (in K).

The hotter the blackbody, the more radiation it gives off per unit area per second at all wavelengths.



At any wavelength, a hotter body radiates more intensely.

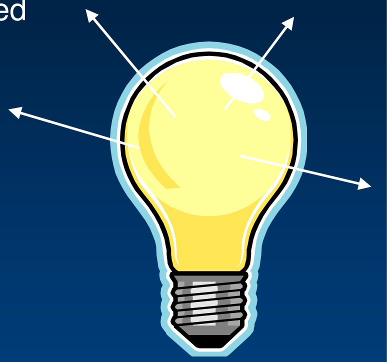


Example: If the temperature of the Sun were ten times what it is now, how much more energy would emerge from a unit area on the Sun every second?

See box 5-2 for more examples.

Luminosity and Blackbody Radiation

Luminosity is radiation energy emitted per second from entire surface:



$L = F_e$ x (surface area)

Units of L are J s^{-1} or W

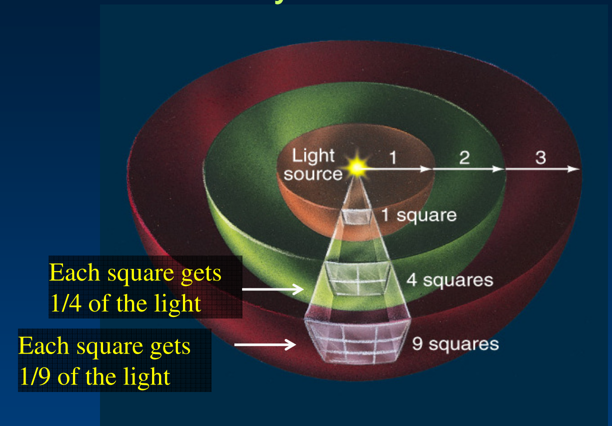
For sphere (stars),

$L = 4 \pi R^2 \times F_e$

For spherical blackbody (stars, approximately):

$L = 4 \pi R^2 \sigma T^4$

Luminosity and Incident Flux



For a source of luminosity L at a distance d from you, the incident flux you measure is:

$$F_i = \frac{L}{4\pi d^2} \quad \text{(in W m}^{-2}\text{)}$$

(True for any kind of radiation, not just blackbody).