Blackbody Radiation

Lecture 4

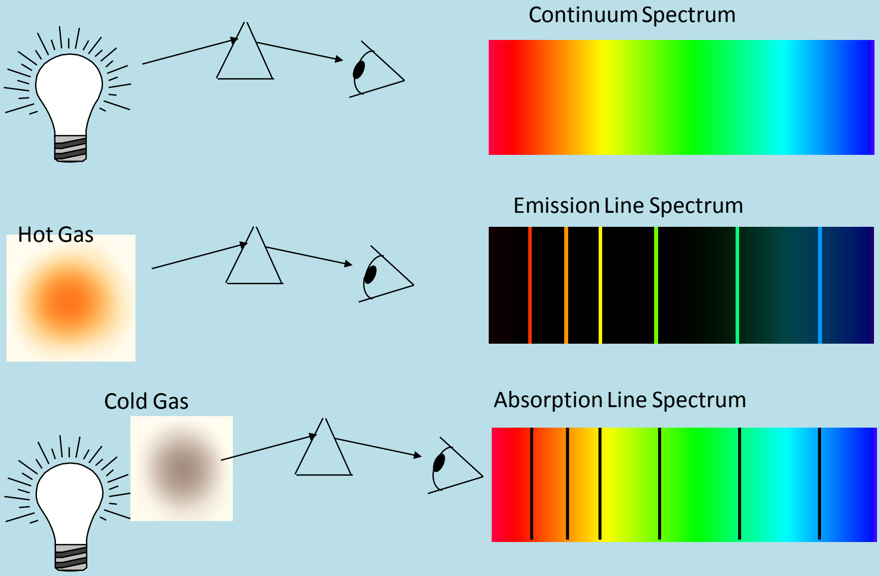
ASTRONOMY

IS PHYSICS

IN DISGUISE

Kirchhoff's Laws

- These are three laws that govern the spectrum we see from objects.
- They allow us to interpret the spectra we observe.



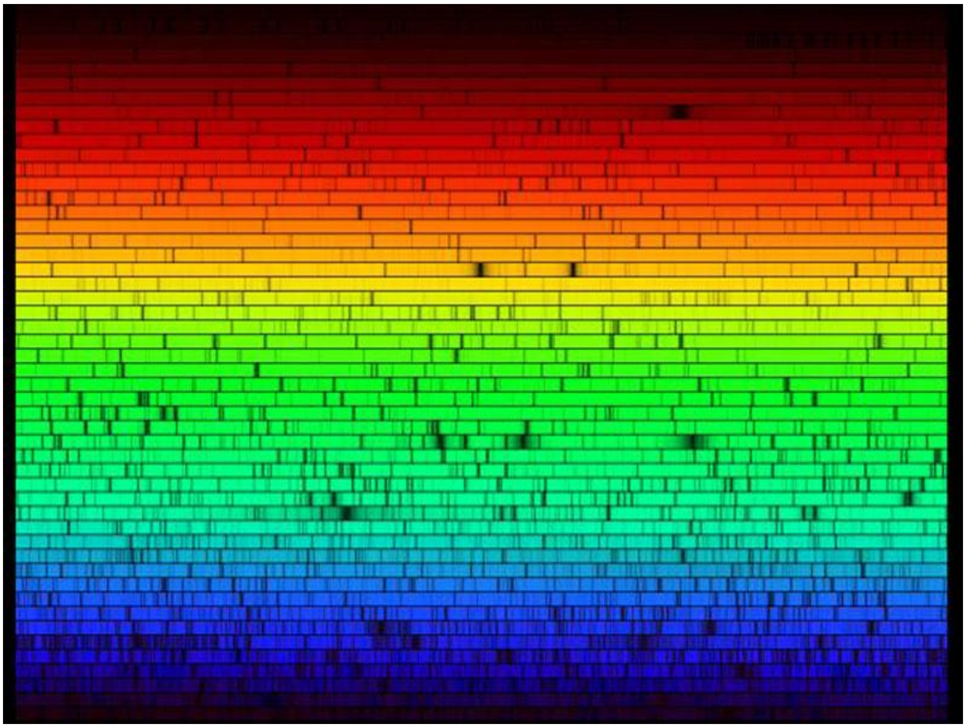
Continuum Spectrum

Hot Gas

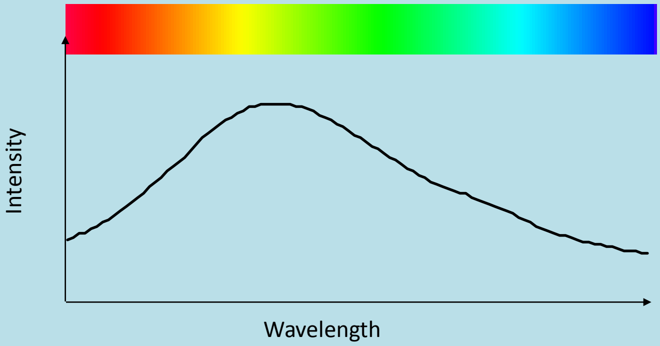
Emission Line Spectrum

Cold Gas

Absorption Line Spectrum

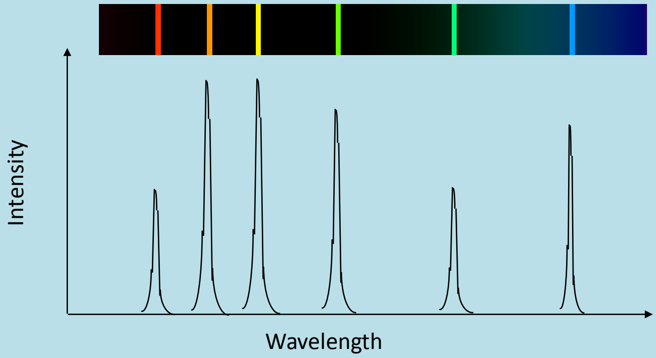


1 A hot solid, liquid or gas at high pressure has a continuous spectrum.



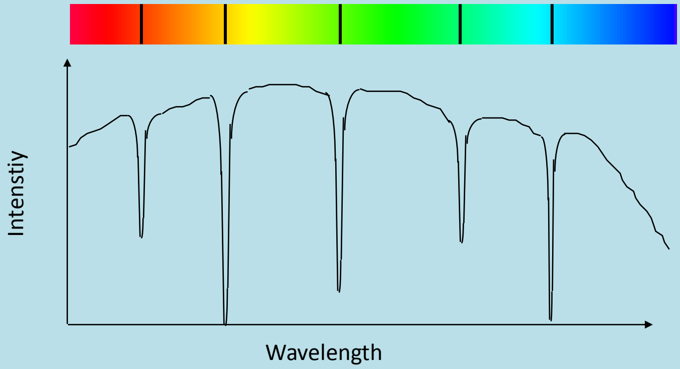
There is energy at all wavelengths.

2 A gas at low pressure and high temperature will produce emission lines.



Energy only at specific wavelengths.

3 A gas at low pressure in front of a hot continuum causes absorption lines.



Dark lines appear on the continuum.

Heat Transfer

- All objects give off and receive energy.
  - In everyday life, we call this heat.
- The hotter an object, the more energy it will give off.
- An object hotter than its surroundings will give off more energy than it receives
  - With no internal heat (energy) source, it will cool down.

Energy Transfer

- Ways to transport energy:

1. Conduction:
   - particles share energy with neighbors
2. Convection:
   - bulk mixing of particles, e.g. turbulence
3. Radiation:
   - photons carry the energy

Internal energy of objects

- All objects have internal energy which is manifested by the microscopic motions of particles.
- There is a continuum of energy levels associated with this motion.
- If the object is in thermal equilibrium then it can be characterized by a single quantity, it’s temperature.

Radiation from objects

- An object in thermal equilibrium emits energy at all wavelengths.
  - resulting in a continuous spectrum
- We call this thermal radiation.

Blackbody Radiation

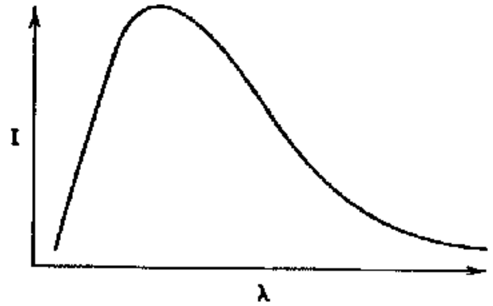
- A black object or blackbody absorbs all light which hits it.
- This blackbody also emits thermal radiation. e.g. photons!
  - Like a glowing poker just out of the fire.
- The amount of energy emitted (per unit area) depends only on the temperature of the blackbody.

Planck's Radiation Law

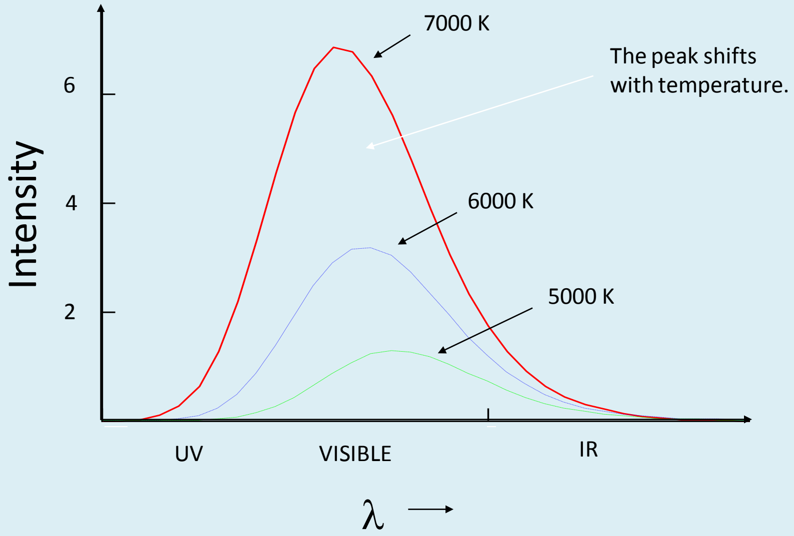
- In 1900 Max Planck characterized the light coming from a blackbody.
- The equation that predicts the radiation of a blackbody at different temperatures is known as Planck's Law.

Planck's Radiation Law

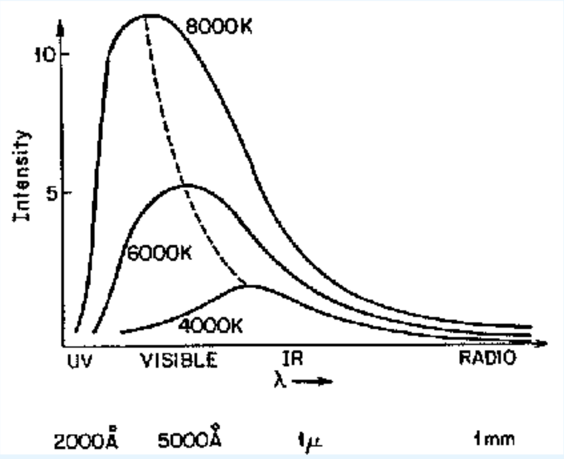
$$I_\lambda \Delta\lambda = \frac{2hc^2}{\lambda^5 \left[e^{(hc/\lambda kT} - 1\right]} \Delta\lambda$$



Blackbody Spectra



The peak shifts with temperature.



Properties of Blackbodies

- The peak emission from the blackbody moves to shorter wavelengths as the temperature increases (Wien’s law).
- The hotter the blackbody the more energy emitted per unit area at all wavelengths.
  - bigger objects emit more radiation

Wien’s law

- The wavelength of the maximum emission of a blackbody is given by:

$$\lambda_{peak} = \frac{2900}{T}$$

λ_{peak} in μm

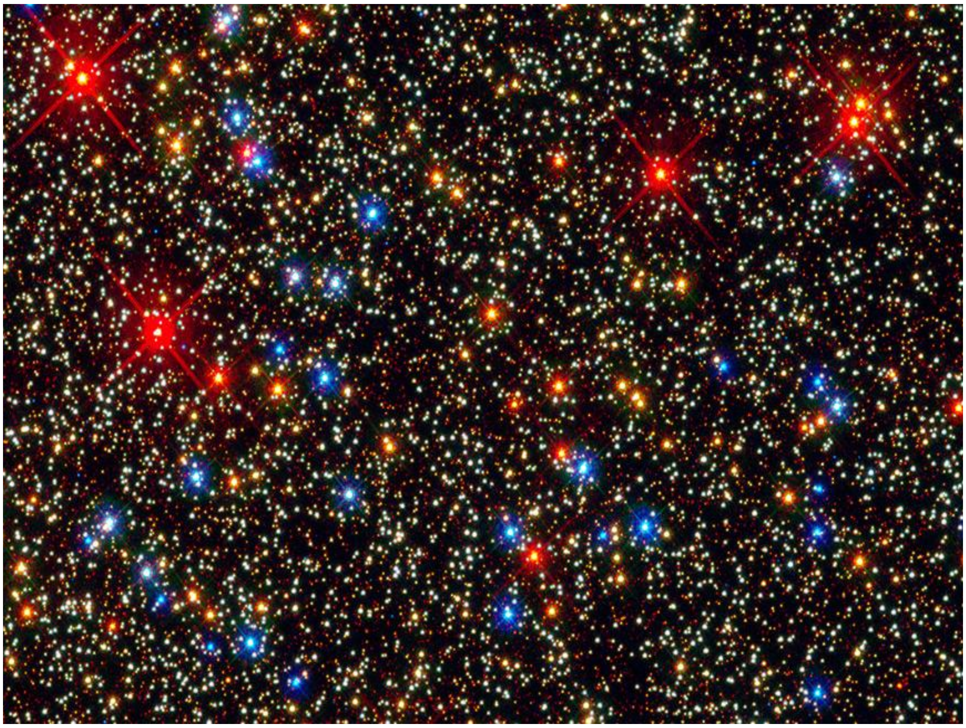
T in K

Object	T(K)	λ_{peak}
Sun	5800	0.5 μm = 5000 Å
People	310	9 μm
Neutron Star	10^8	2.9×10^{-5} μm = 0.3 Å

Consequences of Wien’s Law

- Hot objects look blue.
- Cold objects look red.

- Except for their surfaces, stars behave as blackbodies
  - blue stars are hotter, than red ones



Stefan-Boltzmann Law

- The radiated energy increases very rapidly with increasing temperature.

$$Power / area = \sigma T^4 \quad \text{W/m}^2 \ \text{(over all } \lambda\text{)}$$

where $\sigma = 5.7 \times 10^{-8}\ \text{W m}^{-2}\ \text{K}^{-4}$

- When T doubles the power increases 16 times: $2^4 = 2 \text{x} 2 \text{x} 2 \text{x} 2 = 16$

Energy Flux

- The Energy Flux, F, is the power per unit area radiated from an object.

$$F = \sigma T^4 \qquad \text{W/m}^2 \text{ (at all } \lambda\text{)}$$

- The units are energy, area and time.

Luminosity

- Total power radiated from an object.
- For a sphere (like a star) of radius R, the area is given by: $\text{Area} = 4\pi R^2 \quad (\text{m}^2)$
- So the luminosity, L, is:

$$L = 4\pi R^2 \sigma T^4 \qquad \text{Watts}$$

Luminosity - star example

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

- Doubling the radius increases the luminosity by a factor of 4
- Doubling the temperature increases the luminosity by a factor of 16.

Luminosity and Radius

- With my telescope I see two red stars that are part of a binary system.
- Star A is 9 times brighter than star B.
- What can I say about their relative sizes and temperatures?

$$\lambda_{peak} = \frac{2900}{T}$$

λ_{peak} in μm

T in K

Both Red ⇒ T the same.

Luminosity and Radius

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

- Star A is 9 times brighter:

$$\frac{L_A}{L_B} = \frac{4\pi R_A^2 \sigma T_A^4}{4\pi R_B^2 \sigma T_B^4} \Rightarrow 9 = \frac{R_A^2}{R_B^2}$$

$$\Rightarrow R_A = 3R_B$$

- So Star A is 3 times bigger than star B.

Temperature of Stars

- Suppose I observe the spectra of two stars, C, and D that form a binary pair.
- The peaks of the spectra are at
  - C: 3500 Å (0.35 μm, deep violet)
  - D: 7000 Å (0.70 μm, deep red)
- What is the temperature of the stars?

Temperature (cont'd)

- Use Wien's law to find the temperature.

$$\lambda_{peak} = \frac{2900}{T}$$

λ_{peak} in μm

T in K

$$\Rightarrow T_C = \frac{2900}{\lambda_{peak}} = \frac{2900}{0.35} = 8300K$$

$$T_D = \frac{2900}{\lambda_{peak}} = \frac{2900}{0.70} = 4150K$$

Luminosity and Radius

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

Watts

- If both stars are equally bright

$$\frac{L_C}{L_D} = \frac{4\pi R_C^2 \sigma T_C^4}{4\pi R_D^2 \sigma T_D^4} \qquad \Rightarrow 1 = \frac{R_C^2}{R_D^2}\,\frac{8300^4}{4150^4}$$

$$\Rightarrow R_D^2 = 16 R_C^2 \qquad \Rightarrow R_D = 4R_C$$

- So Star C is 4 times smaller than star D.

Luminosity and flux

- Luminosity, L, is the total energy radiated from an object per second.
    - – Measured in Watts
- Emitted Flux is the flow of energy out of a surface.
    - – Measured in Watts/m^2

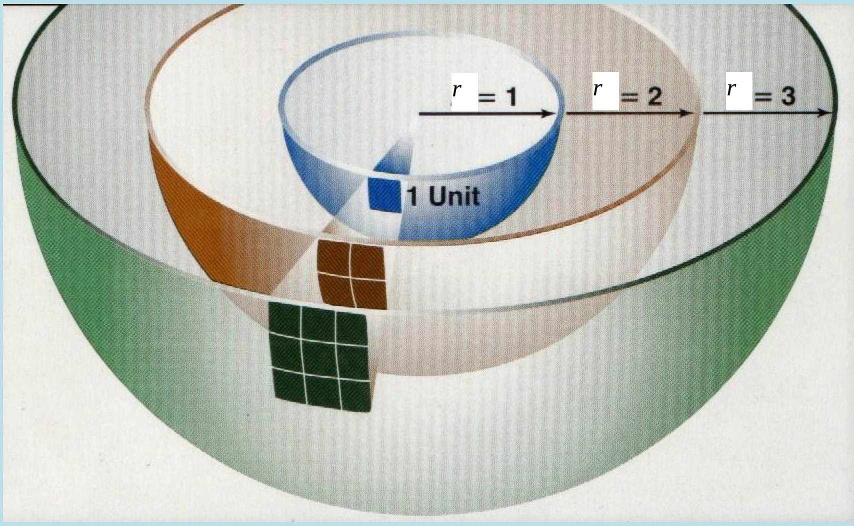
Flux (cont'd)

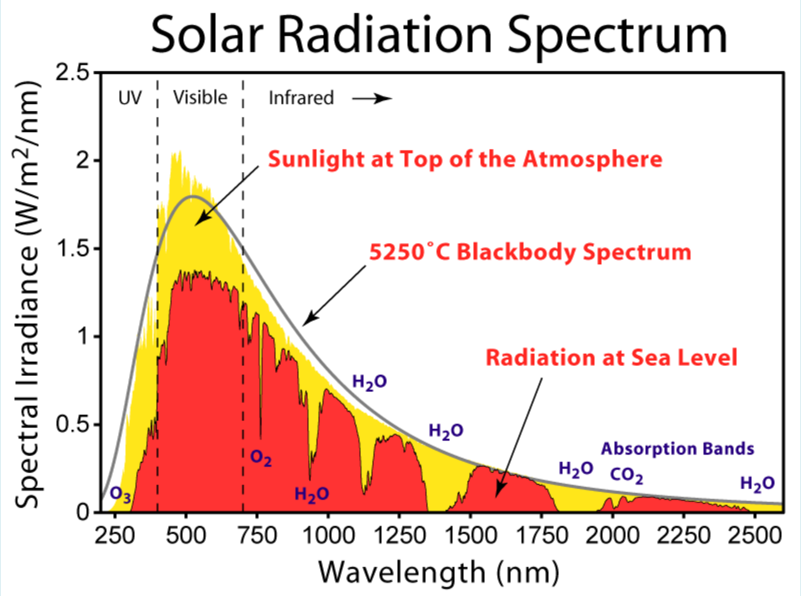
- The observed flux (apparent brightness) of an object is the power per unit area we receive from it.
    - – Depends on the distance to the object.
    - – Measured in W/m^2 e.g. f_{sun} = 1 kW/m^2

What does this mean?

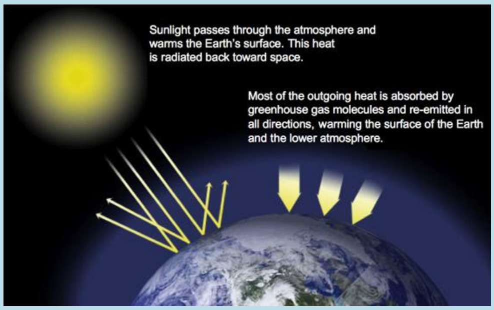
- Make a sphere of radius, r, around an object which is radiating power.
  - such as the sun or a light bulb
- All energy radiated from the object must pass through this sphere
  - -- The size of the sphere does not matter!

Brightness falls off with distance





Greenhouse Effect



Sunlight passes through the atmosphere and warms the Earth's surface. This heat is radiated back toward space.

Most of the outgoing heat is absorbed by greenhouse gas molecules and re-emitted in all directions, warming the surface of the Earth and the lower atmosphere.

- Sunlight gets in with a spectrum at T=5700K (transparent atmosphere windows)
- Energy is re-radiated (T~310K) at *longer* λ, where the atmosphere is opaque! (trapped energy)