Astronomy 210

Section 1– MWF 1500-1550
134 Astronomy Building

This Class (Lecture 11):

Spectroscopy

Next Class:

Matter and Light

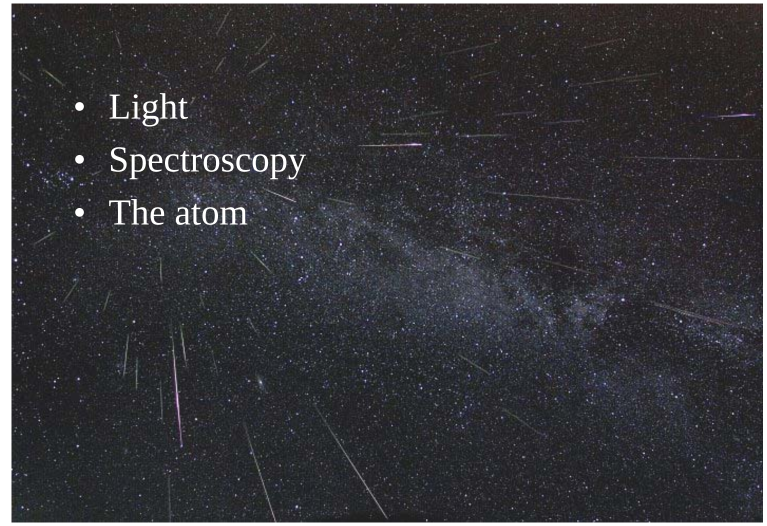
Planetarium Observing

Stardial Observing

Exam #1 next week

Music: *Space Dog* – Tori Amos

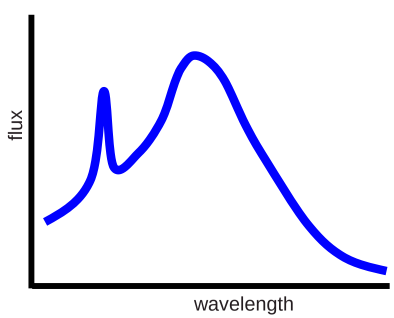
Outline



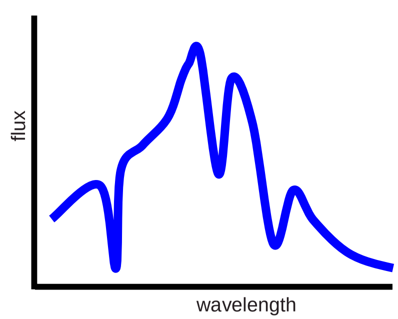
- Light
- Spectroscopy
- The atom

The Spectrum

The "spectrum" of a light source also refers to the fractional contribution of all of the different wavelengths to its total light output. It is the Flux distribution vs λ.



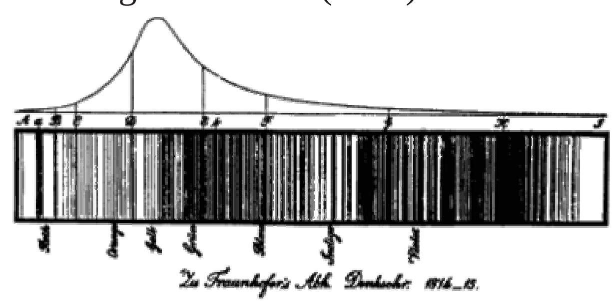
Emission



Absorption

Spectrum Lines

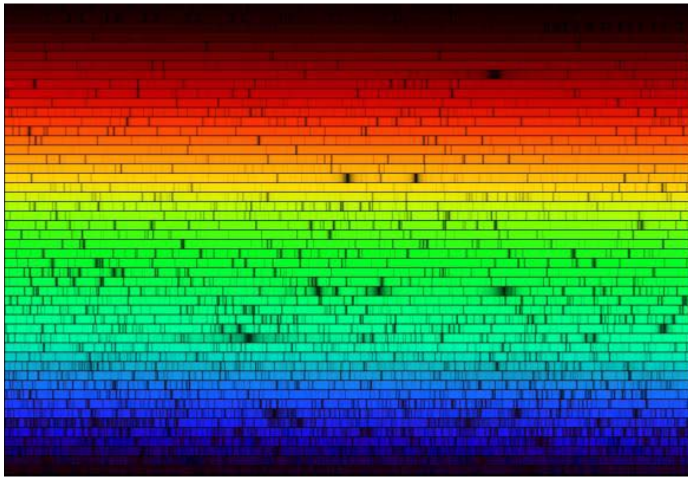
- Fraunhofer discovered that Sun's spectrum contained narrow gaps (absorption lines) when viewed at high resolution (1814)



Joseph von Fraunhofer (1787-1826)

Prism spectrograph

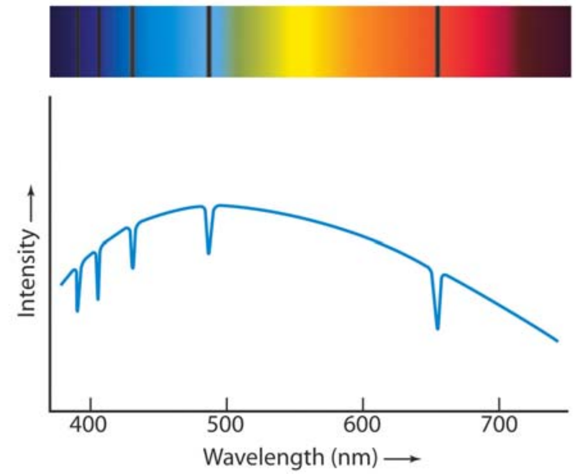
What Color is Sunlight?



 http://antwrp.gsfc.nasa.gov/apod/ap000815.html

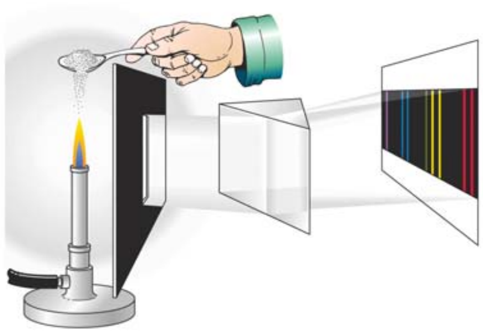
Spectrum Lines

- When astronomers looked at the spectra of the Sun and stars, they saw **gaps**
- Not a perfect smooth spectrum!
- Called *dark spectrum lines*



In the Laboratory

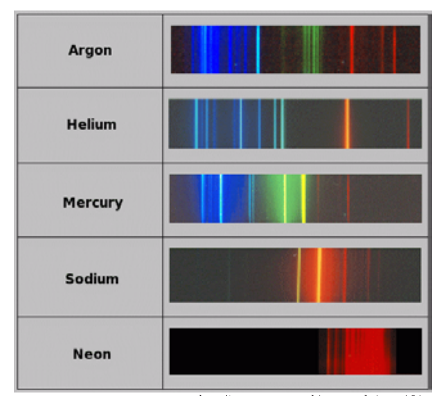
- Bright spectrum lines were produced and studied in the laboratory in the mid-1800s
- Discovered that burning different chemical elements produced different patterns of lines



Spectrum Lines = Fingerprints

The pattern of spectrum lines produced by a gas depends on its chemical composition

Or a barcode!

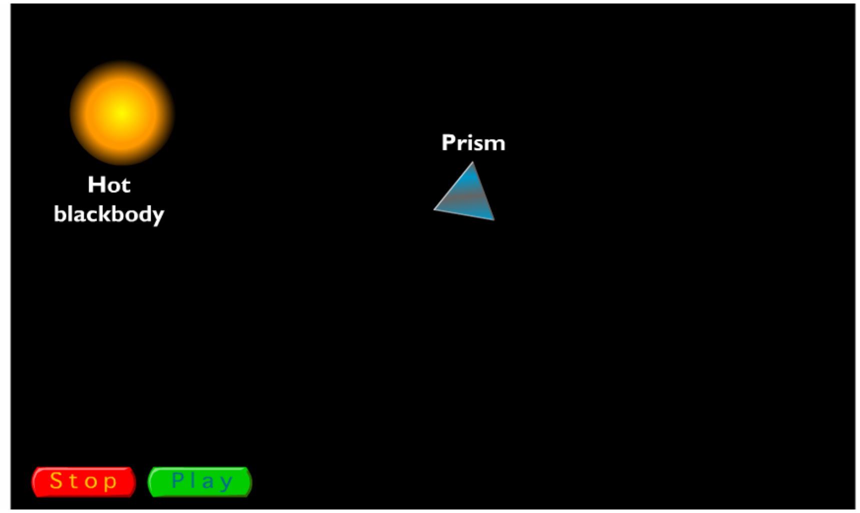


http://www.astro.washington.edu/astro101v

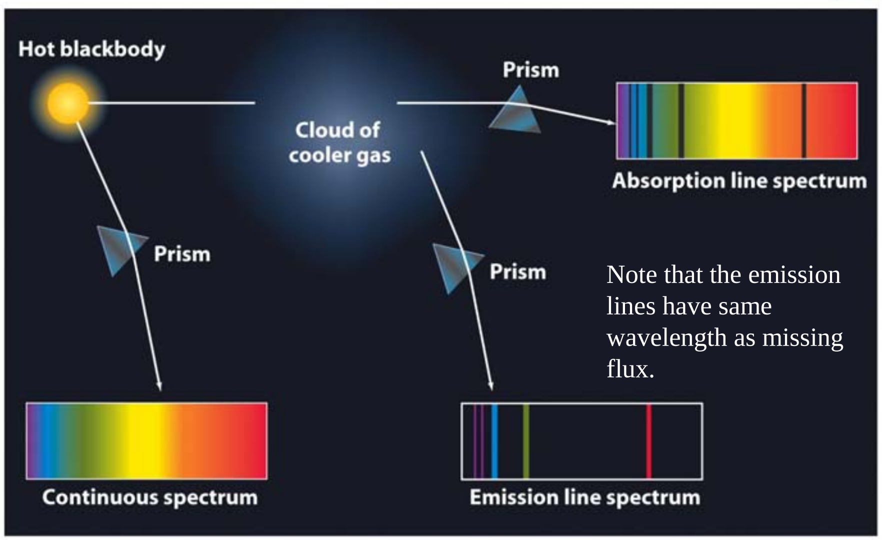
Kirchoff's Laws

- In 1859, Gustav Kirchhoff discovered the conditions under which three basic types of spectra are formed:
  – A hot, dense object produces a **continuous spectrum**
  – A hot low-density gas produces an **emission-line spectrum**
  – A continuous spectrum source viewed through a cooler gas produces an **absorption-line spectrum**

Kirchoff's Laws



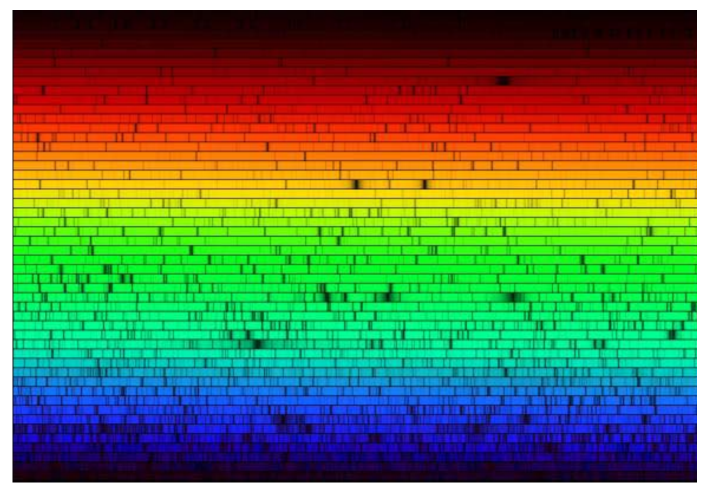
Kirchoff's Laws



What Color is Sunlight?

Sun is a hot, dense object

So, there must be a cooler, less dense solar atmosphere surrounding it.



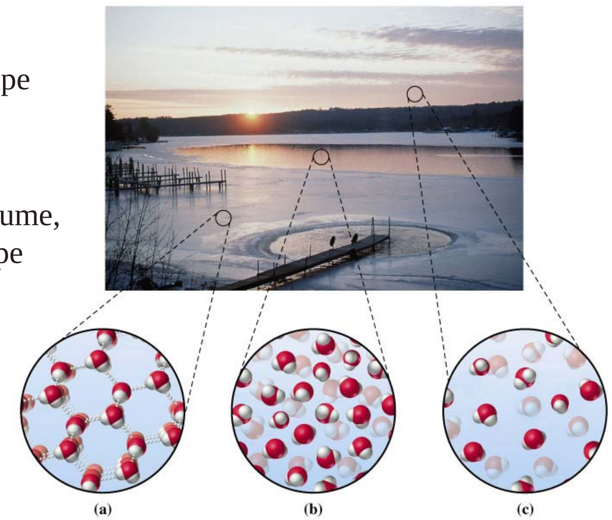
http://antwrp.gsfc.nasa.gov/apod/ap000815.html

How Do Spectrum Lines Form?

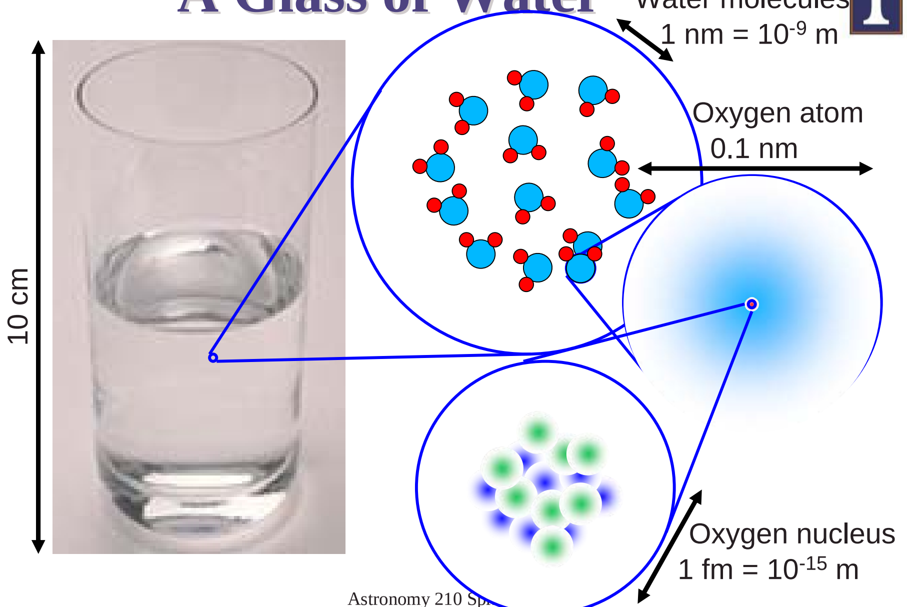
To answer this question, we need to delve into the structure of matter itself…

States of Matter

- Solid
  - Definite shape and volume
- Liquid
  - Definite volume, flexible shape
- Gas
  - Flexible shape *and* volume

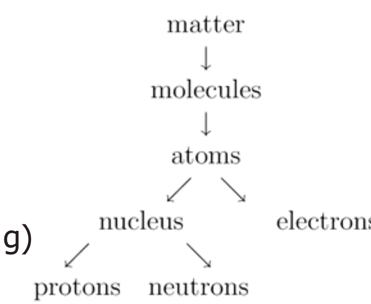


A Glass of Water



Parts of an Atom

Atoms are made of **electrons**, **protons**, and **neutrons**

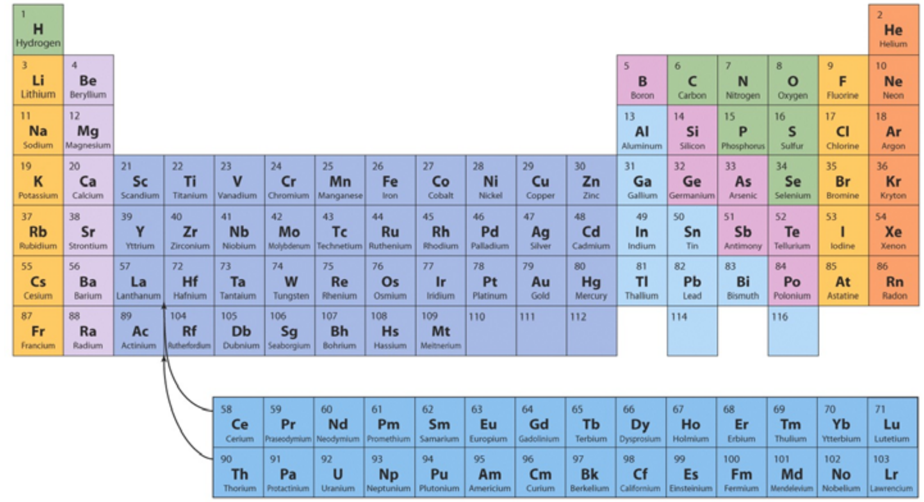


- **Electrons**
  Negatively charged (charge -1)
  Lightweight (mass 9.110 x 10^{-28} g)
- **Protons**
  Positively charged (charge +1)
  1832 times as massive as an electron (mass 1.673 x 10^{-24} g)
- **Neutrons**
  No electric charge
  A little more massive than a proton (mass 1.675 x 10^{-24} g)

Atoms and Elements

- All matter is made of **elements**
  - 92 natural and 23+ artificial
  - Hydrogen, Carbon, Oxygen, Iron, Uranium, etc.
  - Each element is composed of a different kind of **atom**
- The number of protons (or Z) in an atom determines the type of element
  - Hydrogen has 1 proton (Z=1), oxygen has 8 protons (Z=8), etc.
- Neutrons are “packing material”.
- Atoms interact via electrons
  - Shared among atoms to make **molecules**
  - Atoms missing or with extra electrons are called **ions**

Periodic Table



Isotopes

- Same element (same # p) can have different # neutrons.

  $\Rightarrow$ isotopes
- For example, most H is ^{1}H = 1p, 0n
- but ~10^{-4} of H is deuterium ^{2}H = 1p, 1n
- About 10 kg of your body is ^{1}H, and 1g is deuterium
- Or most U is 238U = 92p, 146n

http://www.steelbrigade.com/SBpromotions.html

Balmer

- Empirically found wavelengths of H emission lines

$$\lambda = 3.65\times10^{-7}\frac{n^2}{n^2-4} \quad \text{for } n \text{ integer} \geq 3$$

for n = 3

$$\lambda = 3.65\times10^{-7}\frac{9}{9-4} = 656\,nm$$

- What does this tell us?

Prince Louis-Victor de Broglie

- Not only does light behaves like particle & wave, but so does matter!

  $\Rightarrow$ matter waves exist!
- Then what is the wavelength?

For photons :

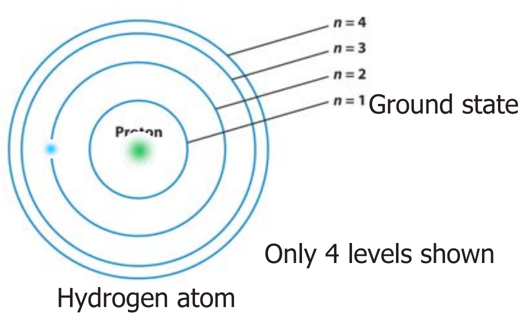
For matter must be the same :

Bohr's Atom

- Bohr model of the atom
- Quantum structure: e^- orbits are matter waves
- Semiclassical: mixes Newtonian & quantum ideas
- de Broglie waves $\Rightarrow$ standing waves in atom
- e^- orbits are circular
- Only certain radii, speeds allowed— quantized states $\Rightarrow$ only certain allowed energies
- During e^- transitions between states, photon emitted
- So, photon energies quantized $\Rightarrow$ spectral lines

Atomic Structure

- Electrons orbit the *nucleus* of each atom
- The nucleus consists of protons and neutrons
- Number of protons = number of electrons (total charge=0)
- The electrons can only have special orbits called *energy levels*
- The lowest energy level is the *ground state*



Explaining

Electron becomes a standing wave. Since the orbit is defined, only certain values allowed, such that

$$2\pi r = n\lambda = n\frac{h}{m_e v}$$

Orbit

- So, if the electron is in an orbit, what is the force?
- Coulomb force provides centripetal acceleration. Like gravity, but different.

Orbit

- So, if the electron is in an orbit, what is the force?
- Coulomb force provides centripetal acceleration. Like gravity, but different.

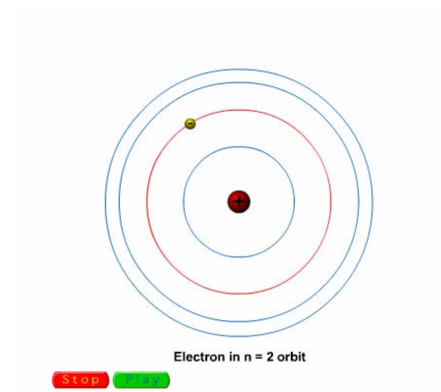
(cgs charge units : $e_{cgs}^2 = ke_{SI}^2 = e_{SI}^2 \big/ 4\pi\varepsilon_0$)

Orbit

- So, if the electron is in an orbit, what is the force?
- Coulomb force provides centripetal acceleration. Like gravity, but different.

How Do Spectrum Lines Form?

- Spectrum lines correspond to electron transitions between energy levels in an atom
- **Absorption:** light energy absorbed by atom, electron jumps to a higher energy level
- **Emission:** electron drops down to lower energy level; releases energy as light



Changes in Levels

- For a transition, the photon emitted or absorbed is from the difference in level
- If electron goes from $n_a \Rightarrow n_b$ with $n_a > n_b$ then photon energy will be

$$E_\gamma = E_{n_a} - E_{n_b}$$
$$= \frac{e^4 m_e}{2\hbar^2}\left(\frac{1}{n_a^2} - \frac{1}{n_b^2}\right)$$
$$= \frac{e^4 m_e}{2\hbar^2}\frac{n_a^2 - n_b^2}{n_a^2 n_b^2}$$

Lambda, Lambda, Lambda

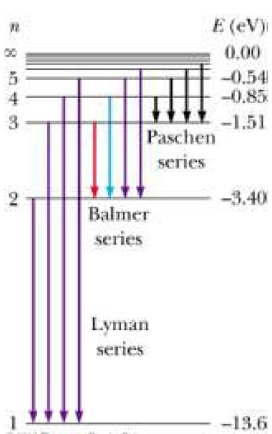
$$\lambda_\gamma = \frac{hc}{E_\gamma} \quad \text{can define } R = \frac{4\pi c\hbar^3}{e^4 m_e} = 1.1\times 10^7\, m^{-1}$$

Rydberg constant

$$\lambda_\gamma = \frac{1}{R}\frac{n_a^2 n_b^2}{n_a^2 - n_b^2}$$

With n_b=2, we obtain the Balmer result!

Series



new unit: 1 eV = 1.602 x 10^{-19} J

Or the amount of energy gained by an electron after going through a potential of 1 Volt.

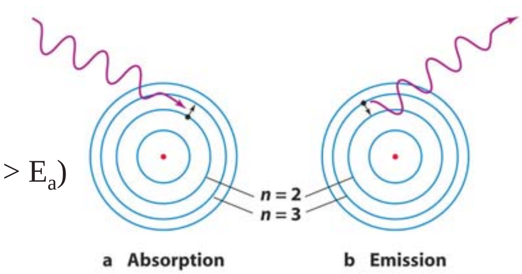
n_b=1 $\Rightarrow$ Lyman series

nb=2 $\Rightarrow$ Balmer series

nb=3 $\Rightarrow$ Paschen series

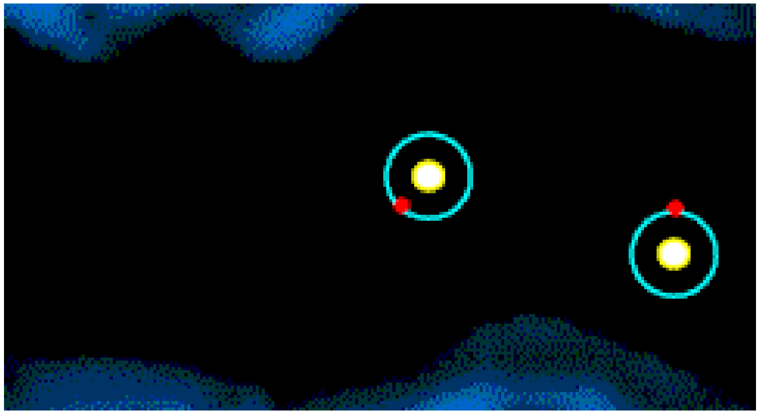
How Do Spectrum Lines Form?

- Spectral lines correspond to electron transitions between energy levels in an atom
- **Excitation:** electron jumps to a higher energy level ($E_b < E_a$)
  - Collision
  - γ absorption
- **Emission:** electron drops down to lower energy level; releases energy ($E_b > E_a$)
  - Collision
  - Spontaneous

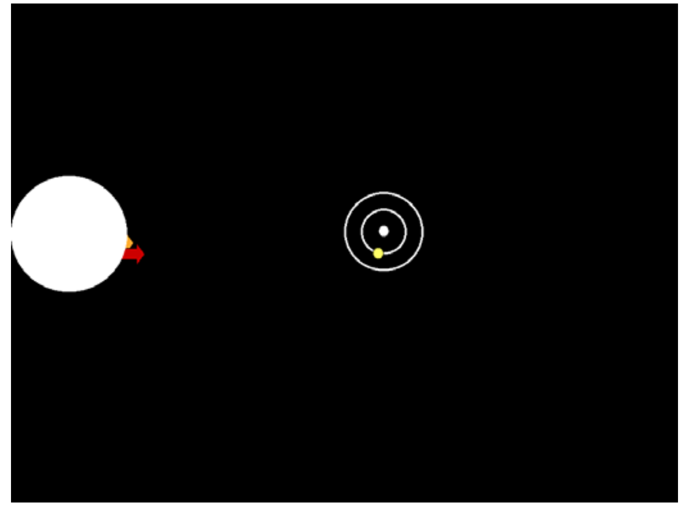


Atom Collisions

- Electrons get knocked-up to higher energy levels by collisions



Creation of Absorption and Emission Line Spectra



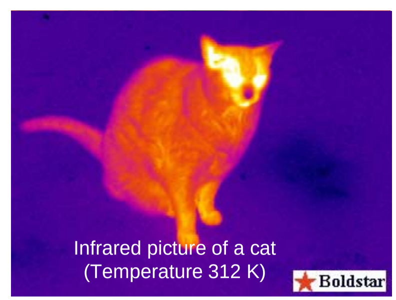
Ionize the Atom

- All E_n are bound states, $E < 0$ negative energies
- Also there are unbound states, $E > 0$, where the e^- is freed $\Rightarrow$ ionized!
- What is min E to ionize H from ground state (n = 1)?

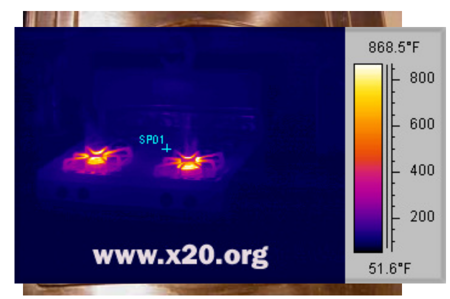
$$E_{ionize} = -E_1 = -\left(\frac{-Rch}{n^2}\right) = Rch = -13.6eV$$

Blackbody Radiation

- Light that objects emit because of their temperature is called **blackbody radiation**
- Blackbody radiation is composed of a continuous spectrum of wavelengths
- The **hotter** an object gets, the **more intense** and **shorter wavelength** (blue-er) its blackbody radiation becomes



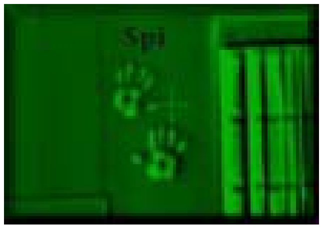
Infrared picture of a cat
(Temperature 312 K)



Visible-light picture of a stove element
(Temperature ~ 400 K)

Glowing Bodies

- So, everything we know is in fact giving off light– as long as it has a temperature, it is glowing.
- The higher the temperature the shorter the wavelength it glows in– compare the person on the right (in the near infrared) and a light bulb (in the visible).



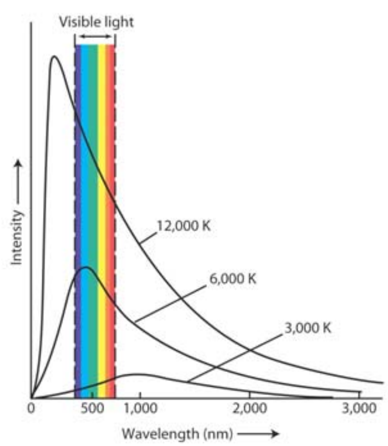
http://www.x20.org/thermal/thermal_weapon_sight_TIWS320.htm

Define Blackbody

- A perfect absorber of light
- It re-emits radiation according to its temperature
- Therefore, “blackbody radiation" = thermal radiation
- Usually, most familiar objects are well approximated as blackbody radiators
- A clear exception is a laser pointer.
  – Why?
- The spectrum of this ideal, only depends on its temperature!

The Spectrum of Blackbody Radiation

- Flux is > 0 for all λ
- The higher the temperature, the higher the flux for all λ
  (curves do not intersect!)
- For higher temperature the maximum occurs at shorter wavelengths.

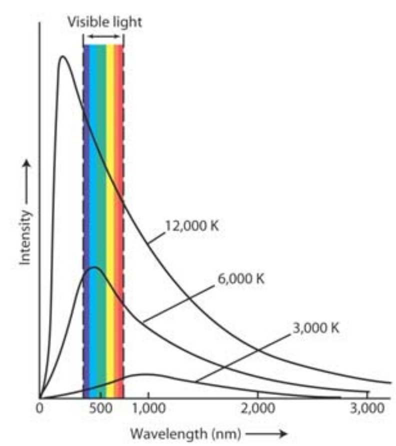


The Spectrum of Blackbody Radiation

- Flux is > 0 for all λ
- The higher the temperature, the higher the flux for all λ
  (curves do not intersect!)
- For higher temperature the maximum occurs at shorter wavelengths.

Wein's Law

$$\lambda_{\max} = \frac{2.9\times10^{-3}\ \text{mK}}{T}$$

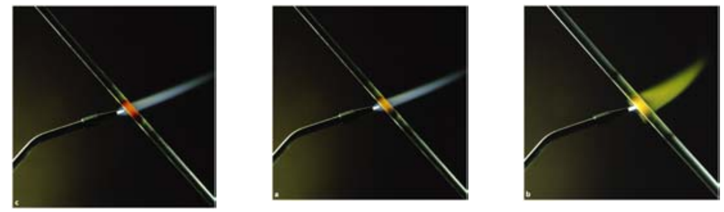


Think-Pair-Share

Which star is hotter?
- Vega (blue)
- Capella (yellow)
- Antares (red)

Red Hot?

- Actually Red hot is not too hot.
- Blue hot is hot.
- White hot is even hotter.



The Spectrum of Blackbody Radiation

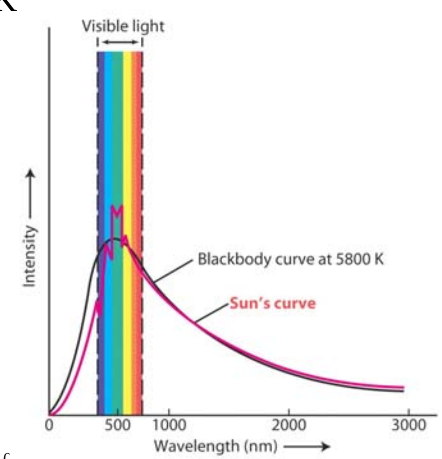
Sun's maximum is at $\cong 500$ nm

So, $T \approx \dfrac{2.9\times10^{-3}\text{ m K}}{500\times10^{-9}\text{ m}} = 5800\text{ K}$

The Sun's spectrum looks almost like a 5800 K blackbody.

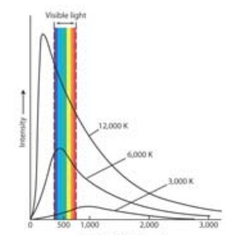
This is a very powerful tool! We can find the temperature by the spectrum.

Color ⇔ Temperature!



Blackbody Flux-ed

- The total flux from a blackbody is adding up the flux in the spectrum.
- Do you think it depends on temperature?



- Strongly dependent on temperature.
  - $F = \sigma T^4$ energy per per unit area per unit time

Blackbody Flux-ed

- The total flux from a blackbody is adding up the flux in the spectrum.
- Do you think it depends on temperature?
- Strongly dependent on temperature.
  - $F = \sigma T^4$ energy per per unit area per unit time

$$\sigma = 5.67\times10^{-8}\,\frac{\mathrm{W}}{\mathrm{m}^{-2}K^{-4}}\quad \text{Stefan - Boltzmann}$$

Stephan-Boltzmann Law

- Example 1: If a star was the same size as the Sun, but was twice as hot, it would be **<u>16 times</u>** as bright.
- Example 2: The total rate of energy emission from Sun = total solar power output = solar luminosity

$$L_\odot = 3.85\times10^{26}W$$

$$= \frac{3.85\times10^{26}W}{4\pi(7.0\times10^{8}m)^2} = 6.3\times10^{7}\,\frac{W}{m^2}$$

$$T = \left(\frac{F}{\sigma}\right)^{\frac{1}{4}} = 5800K$$