Chapter 7
Atoms and Spectra

Guidepost

In the previous chapter you learned how telescopes gather light, cameras record images, and spectrographs spread light into spectra. Now you will learn why astronomers make such efforts. Here you will find the answers to three important questions:

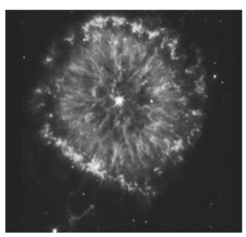
1. How do atoms interact with light?
2. What types of spectra can be observed?
3. What can you learn from the spectra of celestial objects?

The answers to these questions will give us the tools to understand the objects of the Solar System, and stars and galaxies well beyond our own.

The Amazing Power of Starlight

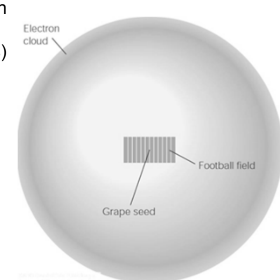
Just by analyzing the light received from a star, astronomers can retrieve information about a star's:

1. Total energy output
2. Surface Temperature
3. Radius
4. Chemical composition
5. Velocity relative to Earth
6. Rotation Period



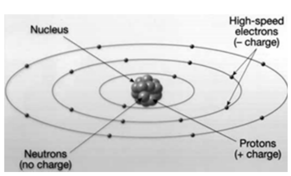
Atomic Structure

- An atom consists of an *atomic nucleus* (protons and neutrons) and a cloud of electrons surrounding it.
- Almost all of the mass is contained in the nucleus, while almost all of the space is occupied by the electron cloud.



Atomic Structure

Protons have a positive charge and electrons have a negative charge. Neutrons have no charge. Normal atoms have a neutral charge (positive and negative charges are balanced).



Most of the mass of the atom is in the nucleus, with protons and neutrons having nearly identical masses. Electrons have a mass ~1830 x LESS than a proton.

http://edtech2.boisestate.edu/millerc/edtech573/atom.html

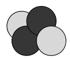
Atomic Density

As an illustration of how compact the nucleus of an atom is:

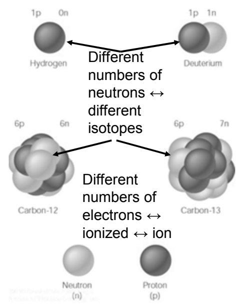
If you could fill a teaspoon just with material as dense as the matter in an atomic nucleus, it would weigh ~ 2 billion tons!!

Different Kinds of Atoms

- The kind of atom depends on the number of protons in the nucleus.
- Most abundant: Hydrogen (H), with one proton (+ 1 electron).
- Next: Helium (He), with 2 protons (and 2 neutrons + 2 el.).

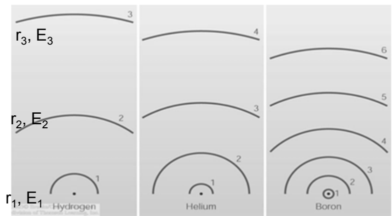


Helium 4



Electron Orbits

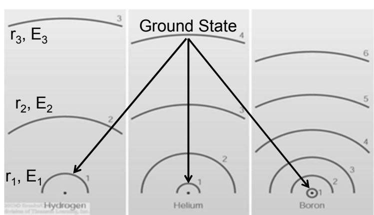
- *Electron orbits* in the electron cloud are restricted to very specific radii and energies.



- These characteristic electron energies are different for each individual element.

Electron Orbits (2)

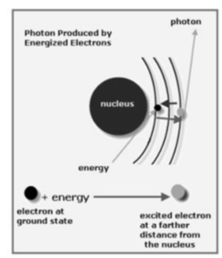
- The lowest energy level is called the *ground state*.



- The lowest energy level is also the one where the electrons are held most tightly.

The Excitation of Atoms

- An electron can be kicked into a higher orbit when two atoms collide. The atoms absorb energy, promoting electrons in one or both atoms to higher levels.
- When the electrons return to their ground state, the atom gives off a photon with energy equal to the difference in energy between the two levels.

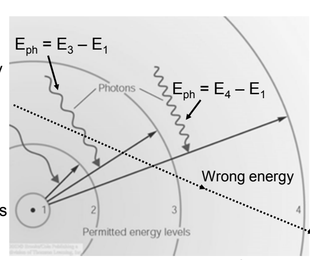


(Remember that $E_{ph} = hf$)

http://scienceprojectideasforkids.com/2010/flame-colors-photon/

The Excitation of Atoms (2)

- An electron can be kicked into a higher orbit when it absorbs a photon with exactly the right energy.
- The photon is absorbed, and the electron is in an excited state.
- All other photons pass by the atom unabsorbed.



(Remember that $E_{ph} = hf$)

The Excitation of Atoms (3)

An example of the absorption and emission of photons by atoms is shown here. Neon and other gases absorb and emit light as its electrons jump up and down the energy levels of the atom.

https://wikis.nyu.edu/xdesign/mediawiki/index.php/Neon_Signs/

Black Body Radiation (1)

Any object above the temperature of 0 Kelvin (absolute zero) will emit radiation of a particular wavelength / frequency.

Temperature is a measure of the activity/agitation of the atoms and molecules making up a substance. The frequency is directly related to the temperature of the object. In the case of stars, they can take on a variety of colors.

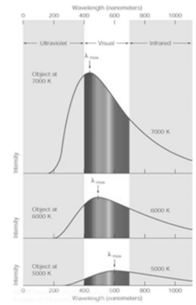
http://science.nationalgeographic.com/science/space/universe/stars-article/

Black Body Radiation (2)

The light from a star is usually concentrated in a rather narrow range of wavelengths.

The spectrum of a star's light is approximately a thermal spectrum called a **black body spectrum**.

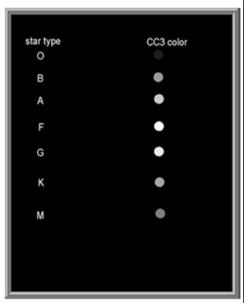
A perfect black body emitter would not reflect any radiation. Thus the name "black body".



Black Body Radiation (3)

The light from a star is usually concentrated in a rather narrow range of wavelengths.

Different stars have different spectra, and the sum of all the emitted light frequencies gives stars their color.



Two Laws of Black Body Radiation

1. The *hotter* an object is, the *more luminous* it is:

$$L = A\sigma T^4$$

where A = surface area;
σ = Stefan-Boltzmann constant
(5.67×10^{-8} W/(m^2K^4))

Called the Stefan-Boltzmann Law.

Two Laws of Black Body Radiation

2. The peak of the black body spectrum shifts toward shorter wavelengths when the temperature increases.

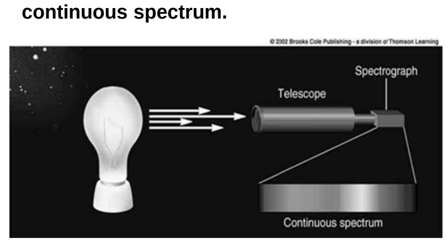
→ Wien's Displacement Law:

$$\lambda_{max} \approx 3{,}000{,}000 \text{ nm} / T_K$$

(where T_K is the temperature in Kelvin).

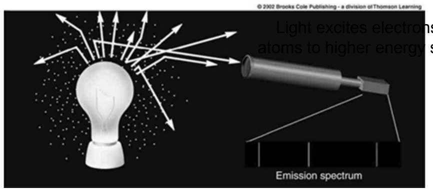
Kirchhoff's Laws of Radiation (1)

1. A solid, liquid, or dense gas excited to emit light will radiate at all wavelengths and thus produce a **continuous spectrum.**



Kirchhoff's Laws of Radiation (2)

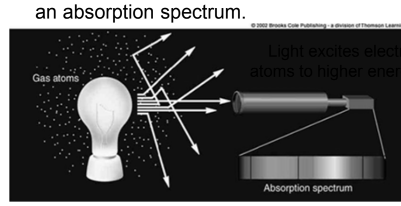
2. A low-density gas excited to emit light will do so at specific wavelengths and thus produce an **emission spectrum.**



Transition back to lower states emits light at specific frequencies

Kirchhoff's Laws of Radiation (3)

3. If light comprising a continuous spectrum passes through a cool, low-density gas, the result will be an absorption spectrum.



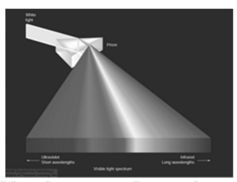
Frequencies corresponding to the transition energies are absorbed from the continuous spectrum.

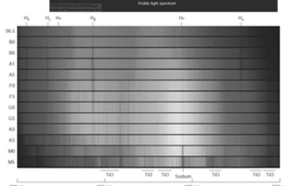
Light and Matter

Spectra of stars are more complicated than pure black body spectra.

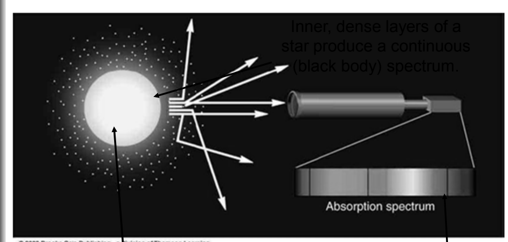
→ characteristic lines, called absorption lines.

To understand those lines, we need to understand atomic structure and the interactions between light and atoms.





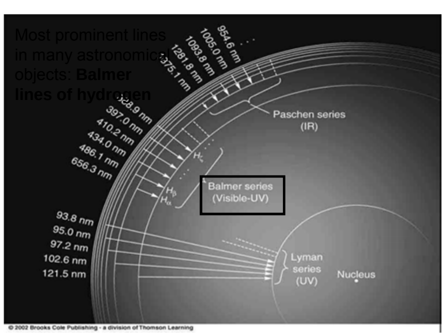
The Spectra of Stars



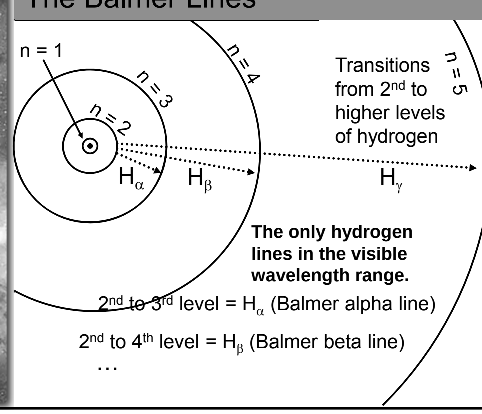
Cooler surface layers absorb light at specific frequencies.

=> Spectra of stars are *absorption spectra*.

Lines of Hydrogen



The Balmer Lines



Transitions from 2nd to higher levels of hydrogen

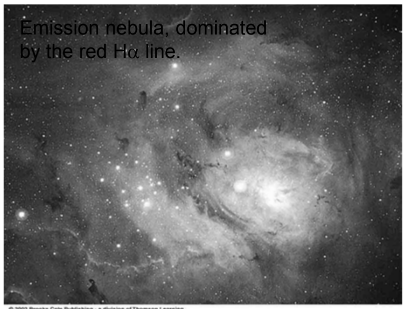
The only hydrogen lines in the visible wavelength range.

2nd to 3rd level = H_α (Balmer alpha line)

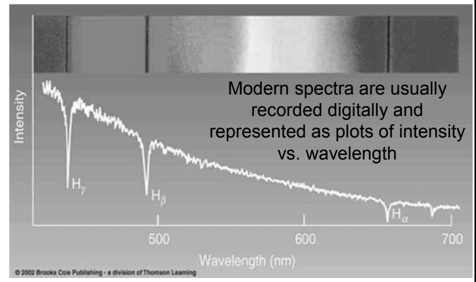
2nd to 4th level = H_β (Balmer beta line)

…

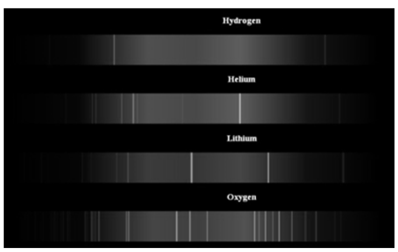
Observations of the H-Alpha Line



Absorption Spectrum Dominated by Balmer Lines



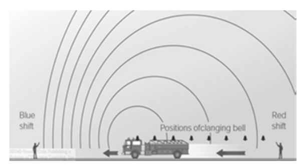
Spectra of Other Elements

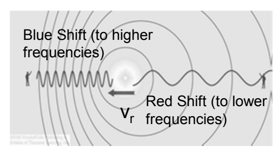


Each element has its own characteristic spectra because each element has unique energy levels for its electrons – spectra are like fingerprints.

http://mail.colonial.net/~hkaiter/electromagspectrum.html

The Doppler Effect





The light of a *moving source* is blue/red shifted by

$$\Delta\lambda/\lambda_0 = v_r/c$$

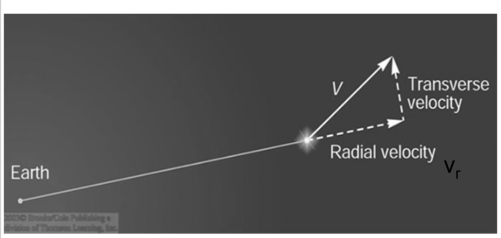
λ_0 = actual wavelength emitted by the source

$\Delta\lambda$ = Wavelength change due to Doppler effect

v_r = radial velocity

The Doppler Effect (2)

The Doppler effect allows us to measure the source's **radial velocity.**



The Doppler Effect (3)

Take λ_0 of the H_α (Balmer alpha) line:

λ_0 = 656 nm

Assume we observe a star's spectrum with the H_α line at λ = 658 nm. Then,

$\Delta\lambda$ = 2 nm.

We find $\Delta\lambda/\lambda_0 = 0.003 = 3 \times 10^{-3}$

Thus,

$v_r/c = 0.003$,

or

$v_r = 0.003 \times 300{,}000$ km/s = 900 km/s.

The line is red shifted, so the star is receding from us with a radial velocity of 900 km/s.