Lecture Outline: Spectroscopy (Ch. 3.5 + 4)

[Lectures 2/6 and 2/9]

We will cover nearly all of the material in the textbook, but in a somewhat different order.

First, we consider a property of wave motion, the **Doppler effect**, that allows us to determine how fast something is moving. If you had to pick one phenomenon associated with light that has allowed us to learn about the universe, it is the Doppler effect. Late in the course we'll see how it reveals that the entire universe is in a state of expansion, and allows us to obtain the distance to a galaxy billions of light years away simply from the wavelength of a spectral line that has been affected by the Doppler effect.

The Doppler effect

The Doppler effect is one of most useful and important techniques used in all of astronomy. We will encounter it again and again.

It basically recognizes that :

The wavelength (or frequency) of a wave, as measured by an observer, depends on the relative radial speed of the source and observer.

Radial motion means: motion towards or away; along the line of sight. The Doppler effect involves *only* this component of motion.

Moving away: wavelengths increase ("**redshift**")
Moving toward: wavelengths decrease ("**blueshift**")

⇒ Shift in $\lambda \propto$ radial velocity
⇒ this is how we get speeds of cosmic objects, stars, galaxies, even expansion of universe.

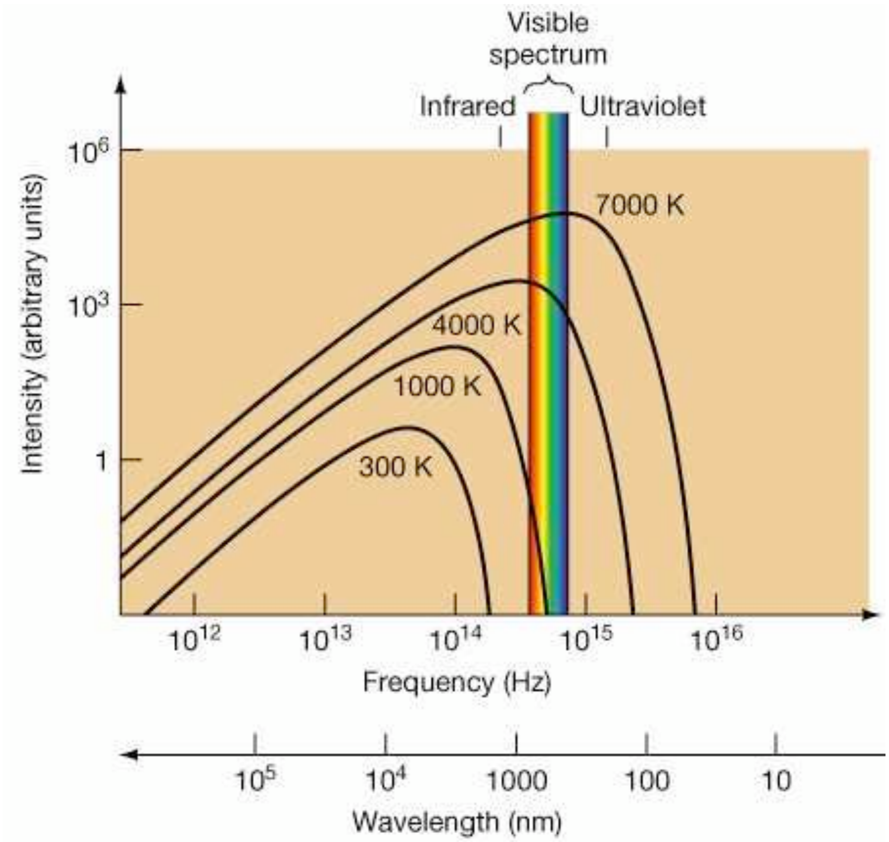
Actual formula is:
λ(apparent)/ λ(true) = 1 + (speed of object/speed of light)

For most objects in the universe, this relative shift is tiny (because the speed of light is so much larger than the speeds of most objects we deal with), so we can't detect it using the "shift" of the whole spectrum. But we *can* use places in the spectrum whose wavelengths are precisely known ⇒ *spectral lines* (the subject of Chapter 4)

Spectral lines—very narrow, well-defined (in wavelength) wavelength/frequency regions in the spectrum where excess photon energy appears (emission lines) or else where photons are missing (absorption lines).

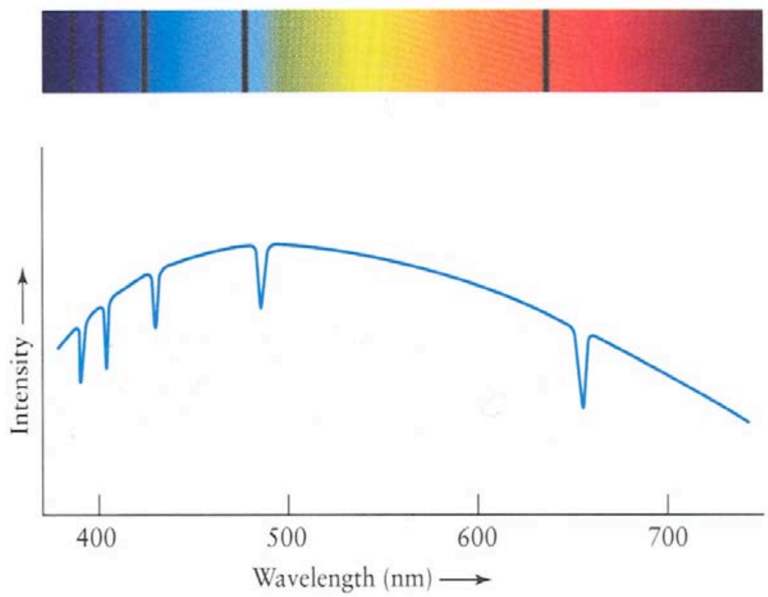
Often these lines are superimposed on a smooth, "continuous" spectrum, which is the near-blackbody emission of a heated object that we have been discussing so far (ch. 3, Wien, Stefan-Boltzmann).

The "continuous spectrum" of an object has properties that are controlled only by its temperature (recall Wien's, Stefan-Boltzmann laws). Look again at this plot of the use of the continuous spectrum as an "astronomical thermometer:"

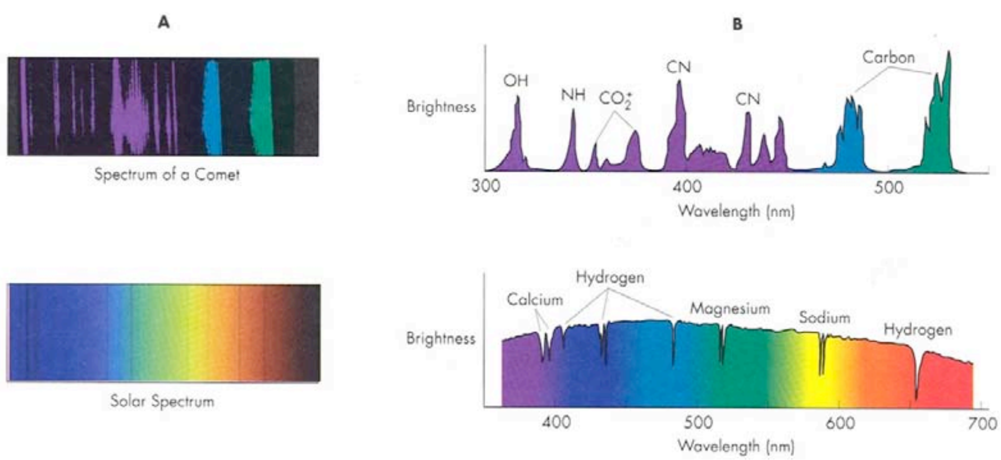


Now compare to the spectrum of an actual star, or planet, or comet, or just about anything. The first thing you notice are spectral absorption lines in stellar spectrum. These are wavelenths in the spectrum where light is "missing." It will turn out that the answer to the question "What could be causing the photons to be missing?" will lead us to ways to diagnose a star's properties, in particular the abundances of the elements.

Here is a cartoon view of absorption lines, both in the spectrum as a graph (below), and in the recorded spectrum (top), the band of colors--this is just how the spectra are gathered--pay no attention to the rectangular shape! I'll explain in class.



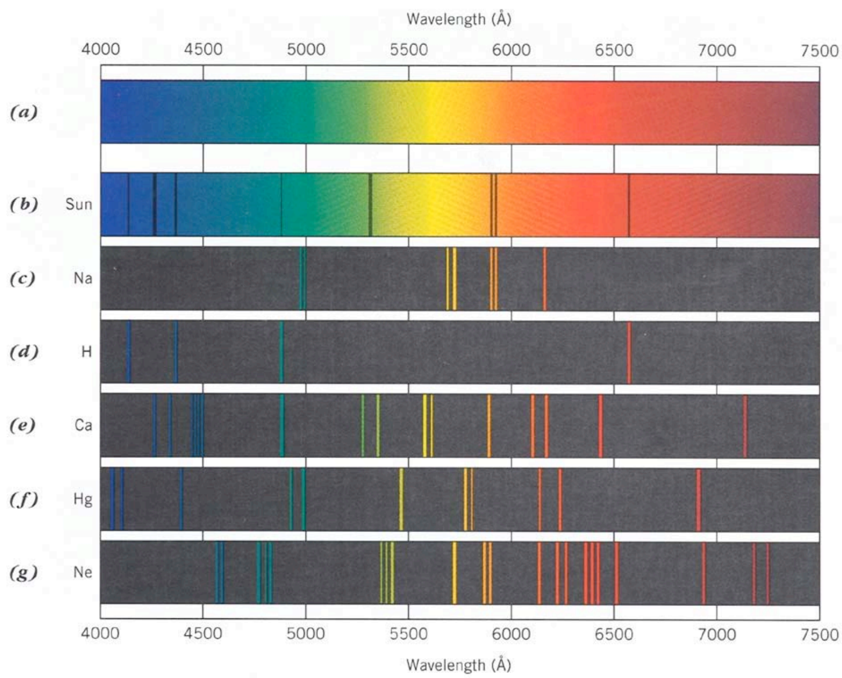
Here are spectra of two real astronomical objects, a comet (top) and star (bottom)--by the time you take the next exam, you should be able to explain why these look so different.



The wavelengths, shapes, and strengths of these "spectral lines" are the keys to understanding many of the physical properties of planets, stars and galaxies.

Spectra are usually displayed as long strips with varying color and dark or light vertical “lines” in them. Remember when you see these spectra that they are just representing the kind of device (“spectrometer”) that is being used to spread the light into its component wavelengths. (If you saw a photograph of a forest with lots of trees, you wouldn’t be confused into thinking that the squareness of the photo has anything to do with the properties of the forest.)

For example, here is the Sun’s spectrum, along with a blackbody of the sun’s temperature (top--why are there no lines?), and the spectra of individual elements as observed in the laboratory. Each spectral line is a “chemical fingerprint” telling you which elements, and how much of each element, is contained in the object you are observing.



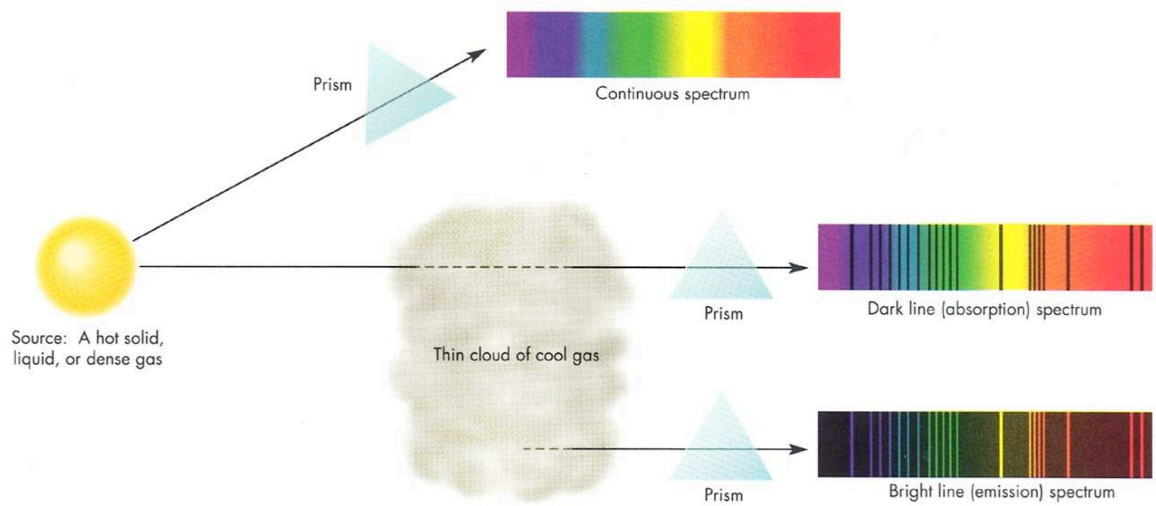
Continuous spectrum

Solar absorption lines

Emission lines from a number of individual elements

<u>Your goal</u>: to understand physically how these spectral lines come about due to the internal structure of atoms and molecules, and how they can be used to learn about many physical properties of astronomical objects, like their temperature, radial velocity, composition, even rotation speed and (in a few cases) magnetic field strength.

Kirchoff's laws--you should be able to understand why the ideas are usually presented this way, with prisms and striped colorful "spectra." But it is a rather confusing way to explain what is going on, so we will not refer to this setup much . Just note that "prism" is supposed to represent an instrument, called a "spectrometer."



If the light from the hot "star" or blackbody doesn't pass through any low-density gas, then the spectrum is featureless--it is a "*continuous spectrum*."

If that continuous spectrum passes through a cool cloud of gas, the cloud can absorb particular wavelengths, and you get an *absorption spectrum*.

But if the gas is hot, say at least a few thousand degrees, it can emit spectral lines, an *emission spectrum*.

How does this occur? The answer lies in the structure of atoms.

Structure of Atoms (and molecules)

This structure is why there are spectral lines. The important ideas are:

➨ *Quantized* electron orbits (see Figs. 4-8 to 4-10)

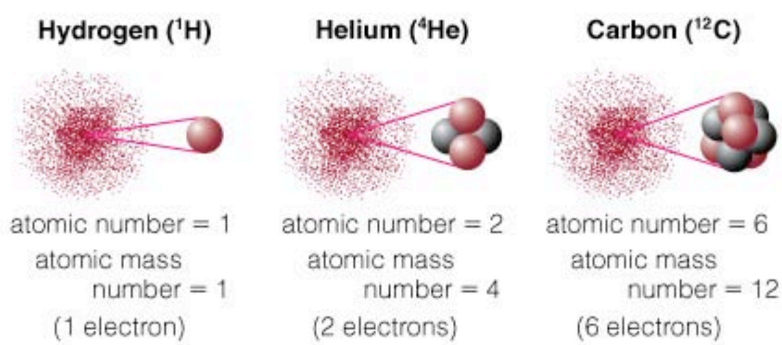
➨ Ground state--all systems like to be in this lowest-energy state.

➨ Excited states--an electron could get boosted to a higher energy by collisions *or* by absorbing a photon. Former: emission line; Latter: absorption line (will explain)

➨ Ionization -- electron gets yanked off its parent atom either by collision or by radiation

First we'll review the structure of atoms.

Nucleus contains protons and neutrons (most have equal numbers). We will discuss the electrons as if they are in well-defined orbits about the nucleus, but actually they are in "clouds" or "orbitals," where the probability of finding electrons is large.

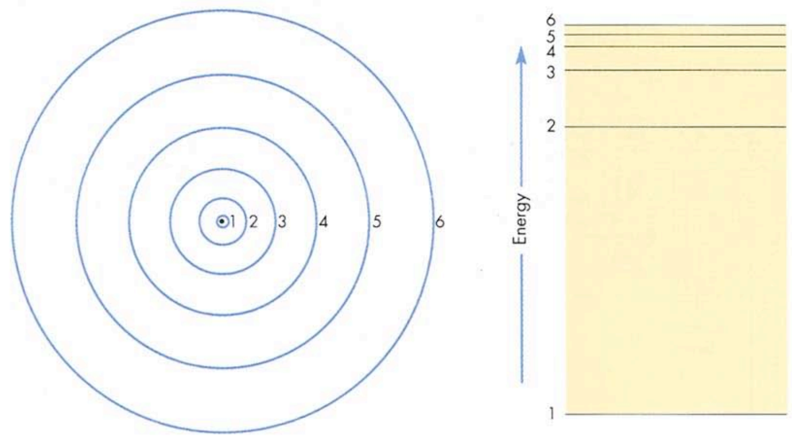


- Molecules: consist of two or more atoms (e.g. H_2O, CO_2). But their levels are much different from atoms, so we will discuss them separately (later).

•Here is an illustration of the energy levels of hydrogen atoms. (Note: this is very simplified--actually the electrons are in "probability clouds" called "orbitals" and even this is an approximate way of looking at it.)

Electron Distances and Energy Levels

A, The electron in a hydrogen atom can exist only at certain distances from the nucleus. **B**, Each of the possible electron distances corresponds to a different energy level.



A Possible distances of the electron in a hydrogen atom **B** Energy levels for the hydrogen atom

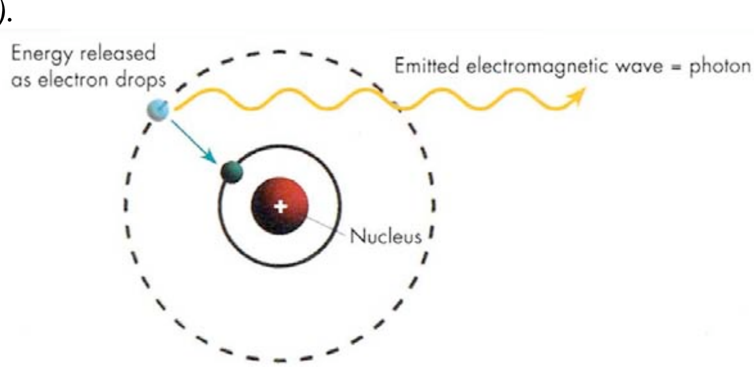
If an electron gets "kicked" up to a higher-energy orbit (either by absorbing a photon, or by a collision with another atom), known as an "excited state," it will always try to return to the lowest possible energy state ("ground state"), very rapidly, **and in the process, emit a photon that has exactly the energy difference between those two energy levels.**

This is an important sentence to understand--it is the basis for understanding all spectral lines. It explains why they are "sharp," at a single well-defined wavelength.

This basic principle is important enough to word again:

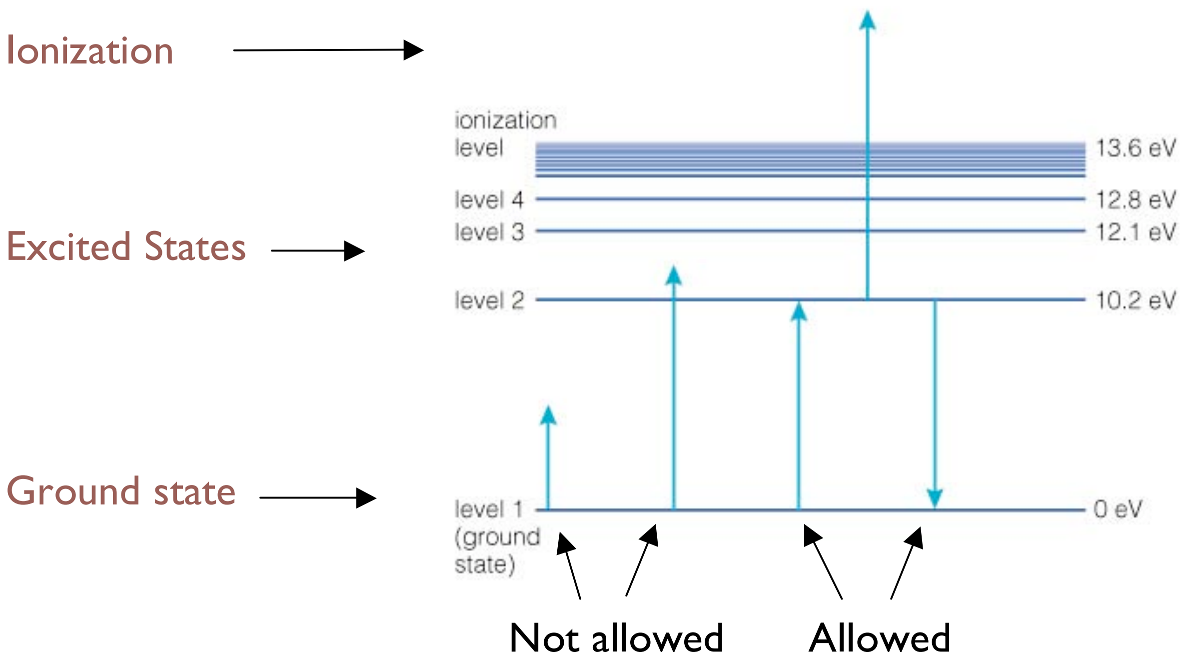
Electrons can be "***excited***" to higher levels *either* by collisions (e.g. in a hot tenuous gas—these will give emission lines) or by absorbing photons (e.g. in the atmospheres of stars—these will give absorption lines).

The atom is now in an "excited state." Once in an excited state, they decay back to a lower level, emitting a photon of a *well-defined energy that corresponds to the change in energy of the electron).*



How the excited state got excited (collisions or photon absorption) is what determines whether you get an emission line or an absorption line.

Let’s look at the transitions of electrons in hydrogen. Note that we are using hydrogen as our example just because is it so simple.

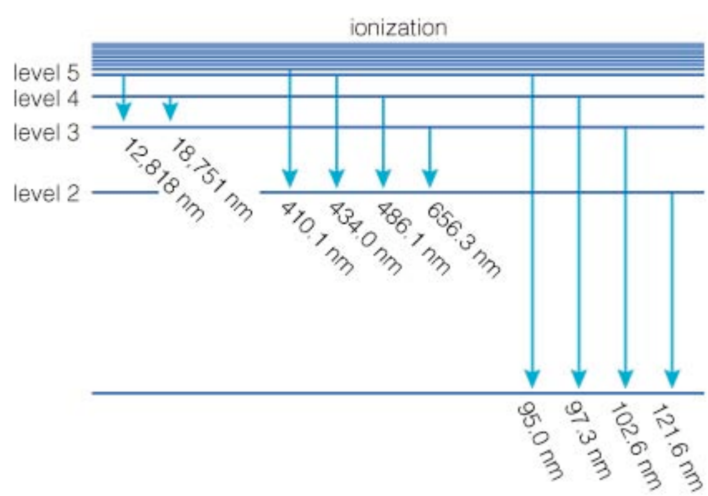


When one of these excited states decays, we get photons that are “chemical fingerprints.” These wavelengths uniquely identify this atom as hydrogen.

⇒ Remember, we can’t “see” different substances in stars, we ONLY have these spectral line signatures, so they are very important.

This is how we will obtain the abundances of different chemical elements in stars to piece together the history of our Galaxy.

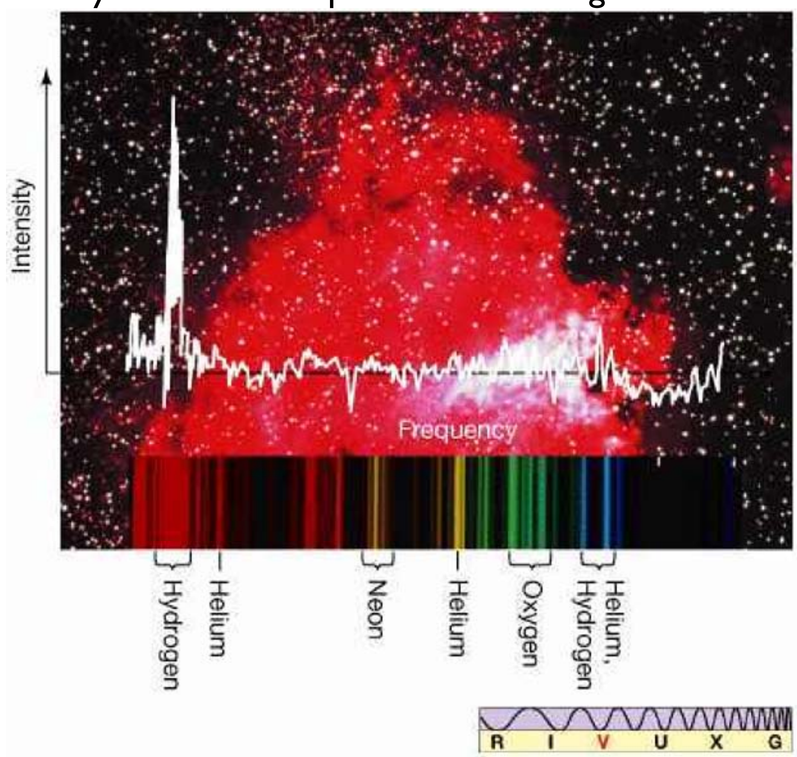
Now consider what happens when an excited level decays back to a lower energy level: A photon must be emitted to make up for the change in energy between levels.



Here is what some of these downward transitions (“emission lines”) look like in the spectrum (hydrogen only):

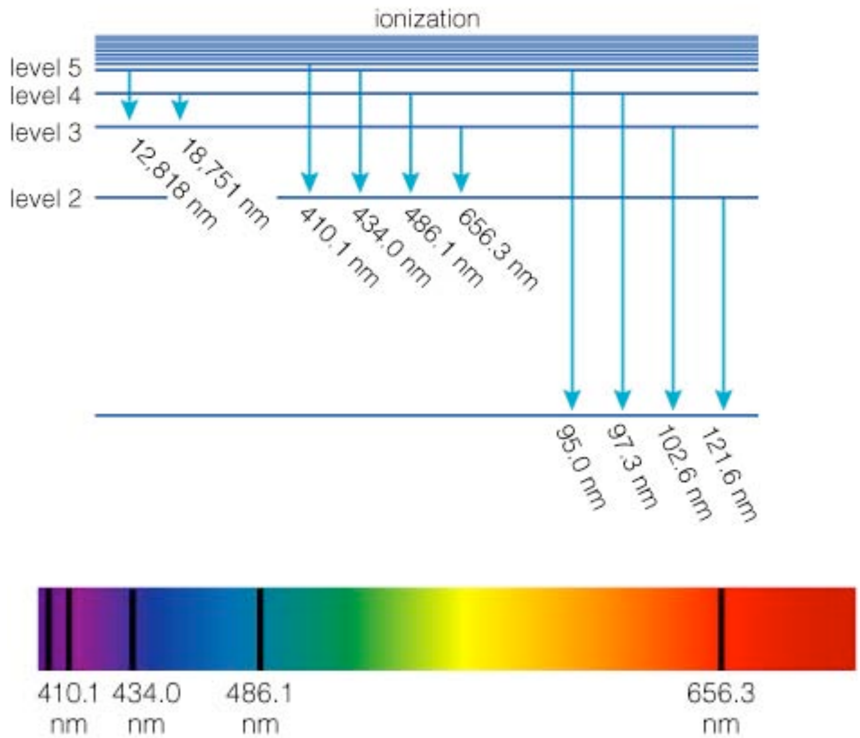
Each type of atom (helium, sodium, neon below) has a unique spectral fingerprint:

A real life example (from your textbook): *Emission line spectrum* from a gas cloud heated by hot stars. What is the physical process that causes the excitation of atoms that followed by emission of a photon as in this gas cloud?



ABSORPTION LINES (will discuss in more detail in class)

More difficult to understand: Why these downward transitions produce emission lines, while if the excited states were excited by photons, as in a stellar atmosphere, you get absorption lines. I will explain this in class, but the essential idea has to do with the excited state getting excited by *absorbing* a photon that would have otherwise made it to your telescope; the photons emitted upon the decay of the electrons are emitted in *random directions*. So in this case you get:



REVIEW:

Emission and absorption lines can be understood in terms of the discrete nature of the energy levels of atoms and molecules, and the fact that when atoms and molecules undergo *transitions* between these different levels, a photon can be emitted or absorbed.

This material is covered in sec. 4.1, 4.2. Before the causes of these "lines" were understood, they were described by "Kirchoff's laws"; but you don't have to memorize these "laws," only understand why they come about. I will show you more pictures to illustrate this.

The most basic idea is that electrons can be "excited" to higher levels (after which they decay back to a lower level, emitting a photon of a *well-defined energy that corresponds to the change in energy of the electron) either* by collisions (e.g. in a hot tenuous gas—these are emission lines) or by absorbing photons (e.g. in the atmospheres of stars—these are absorption lines).

We only discussed hydrogen because of its simplicity, but the same principles apply to all atoms. They just have more electrons, and so have many more complicated possibilities for spectral lines. (Example: iron shows something like 100 thousand absorption lines in the Sun's spectrum.)

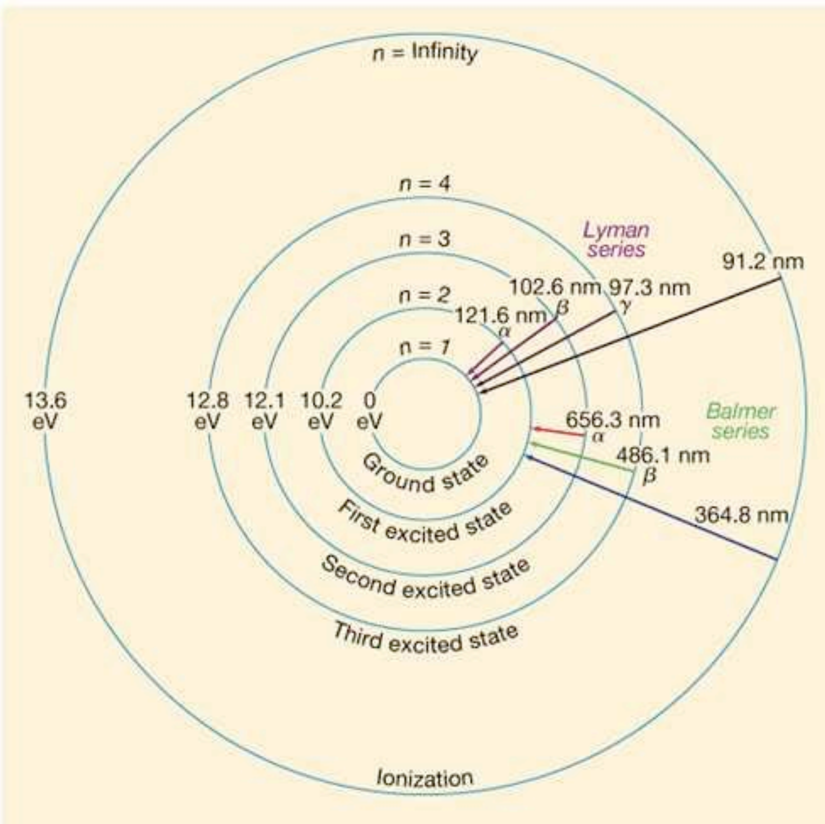
(You will not need to understand the *specifics* of "More Precisely 4-1" for the exam, but I do expect you to get the basic idea. Read Discovery 4-1, but I will not test you on it.)

Lyman, Balmer series of lines

You *should* be able to understand and explain the relation between the different electron transitions that can occur in hydrogen (e.g. Lyman series, Balmer series, …) and the patterns of spectral lines that are seen in the spectrum. The reason is that much of astronomy is based on detecting and analyzing these spectral lines, and also because H is really the only system that we can explain so simply (or explain at all in most cases).

Lyman series: spectral lines that correspond to all electgron transitions that begin or end on the lowest electron orbital.

Balmer series: same, but begins or ends on next-highest (in energy) orbital.



Now on to emission and absoption of light by molecules, then what specific properties of objects we can learn from their spectral lines.

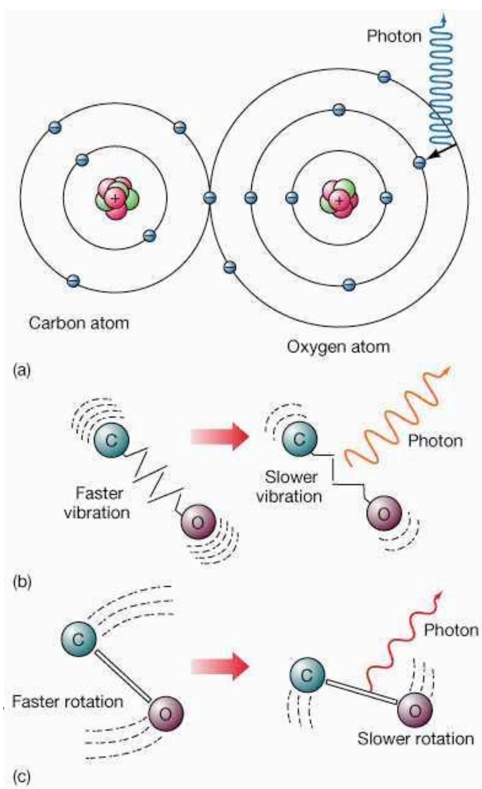
ENERGY LEVELS OF MOLECULES

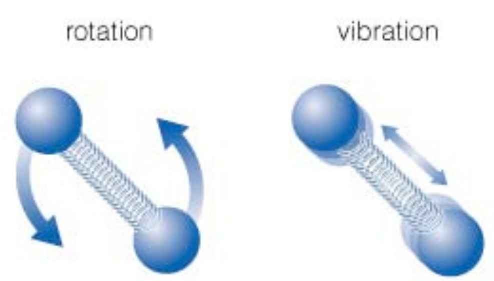
Molecules—More than one atom bound together, like H_2O, CO, O_3, SiO_2,… The energies by which they are bound are typically smaller than the energies of electrons bound to nuclei. This means *they can only exist at relatively low temperatures* (less than roughly 3000 ^{O}K); at higher temperatures their bonds are broken by collisions with other particles. (High temperature means rapidly moving particles, so lots of kinetic energy when they collide.)

So we see spectral lines of molecules *only* in the coolest stars (Sun = 6000K, so only very weak molecular lines), planets (surface temperatures ~ few hundred K), and in the gas clouds between the stars, where stars form (temperatures ~ 10 to 100 K).

Molecular energy levels, transitions (sec 4.4 in textbook)

Besides electron transitions (like in atoms), molecules also vibrate and rotate (see Fig. 4.13).



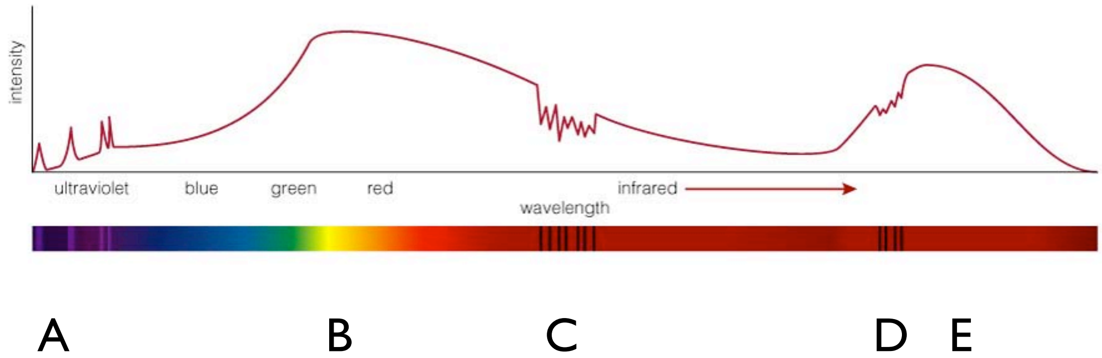


e.
rgy transitions in a molecule.

The energies of these motions are also quantized, leading to more kinds of spectral lines in different wavelength ranges.

Vibrational transitions—these transitions are usually in the infrared part of the spectrum.
Rotational transitions—seen in the radio part of the spectrum.
==> Why do electronic, vibrational, and rotational molecular spectral lines occur in such different spectral regions?

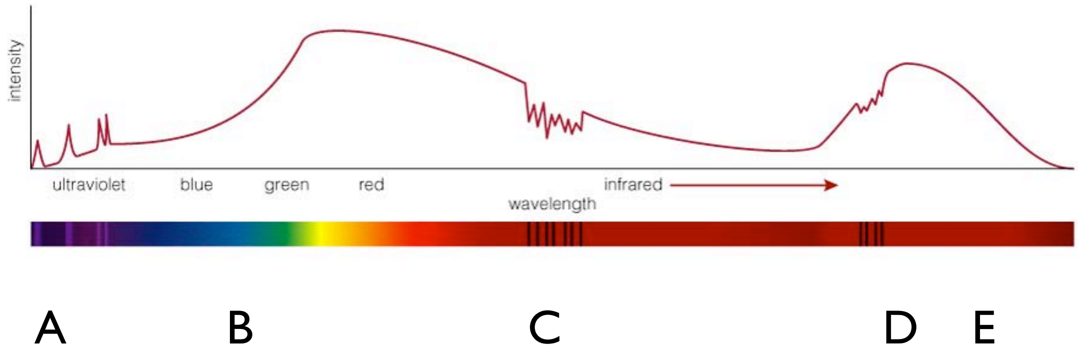
Here is an instructive review question. Look at the following spectrum:



1. Which letter(s) labels absorption lines?
2. Which letter(s) labels the peak (greatest intensity) of infrared light?
3. Which letter(s) labels emission lines?
4. Follow the continuous spectrum from small (ultraviolet) to large (infrared) wavelengths. From Wien's law, you should have an idea how the peak in the continuous spectrum tells you the surface temperature of an object. Can you think of how it is possible for this object to have two peaks?? (One is between green and red, the other in the infrared.)

What might you conclude about the temperature of the object from the peak in the visible? From the peak in the infrared? See next page.

By carefully studying the features in a spectrum, we can learn a lot about the object that created it:



Reflected sunlight: continuous spectrum of visible light like Sun's (peaks at yellow color) except some blue light has been absorbed: object must look red (i.e. it reflects red light much better than blue).

Thermal Radiation: Infrared spectrum peaks at a wavelength corresponding to a temperature of 225 K. This is the temperature of the object itself, not reflected light from the sun.

Carbon Dioxide: The infrared absorption lines are the fingerprint of CO_2 in the atmosphere of the object.

Ultraviolet Emission Lines: Indicate a hot upper atmosphere.

THIS WAS A SPECTRUM OF THE PLANET MARS. Notice what a large range in wavelengths was used for this "diagnosis" and the number of different types of features (reflected continuum, thermal continuum, molecular spectral absorption lines, ultraviolet emission lines).

What can be learned from a spectral line?

First: the identity of the element (or molecule) giving rise to it.

Each chemical element has a particular, recognizable spectral line signature at particular wavelengths. This pattern of wavelengths is like a map of the possible transitions of electrons within atoms corresponding to each chemical element. These wavelengths are known by heating gases of all the different elements in the laboratory and recording the spectra.

So it is easy to identify the chemical element causing a given spectral line, just from the line's central, or peak, wavelength.

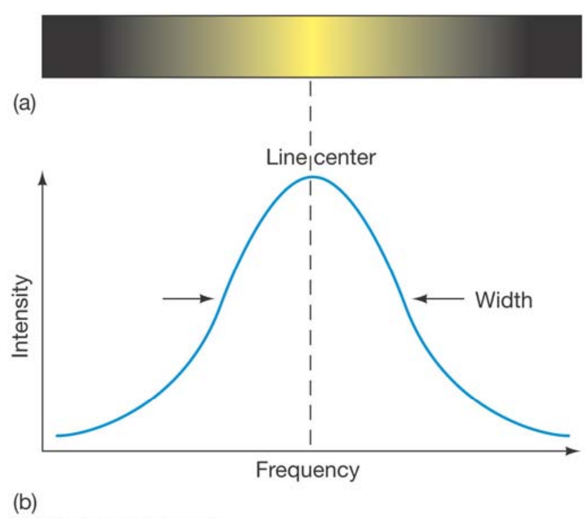
It is *not* easy to estimate the relative abundance, or concentration, of an element using spectral lines, although that is one of the primary things that astronomers determine, for hundreds of thousands of stars (and later in course: galaxies).

Spectral line analysis:

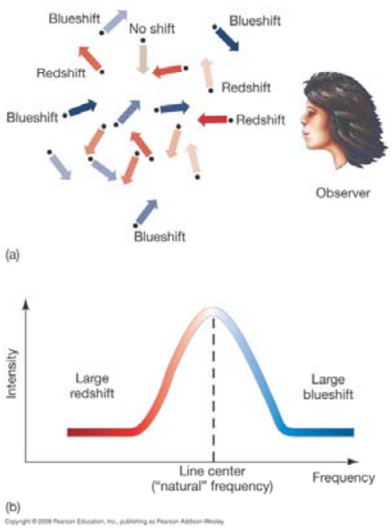
Wavelength—besides the identity of the atom or molecule, get radial velocity from Doppler effect. (Review this if it is not clear; notice that without spectral lines we would not be able to get the speeds at which most objects in the universe move! Later you will see that most of our current understanding of the beginnings of the universe comes from using spectral lines to get speeds from the Doppler effect.)

Intensity (or "strength")—gives composition (or "abundance") of emitting gas, and its temperature. An important thing to understand (later in course) is why the intensities of spectral lines are usually more sensitive to the temperature than the abundances of the elements that cause the lines.

Width and shape ("line profile")—a number of effects broaden spectral lines:
[See book for illustrations; brief descriptions on next page.]



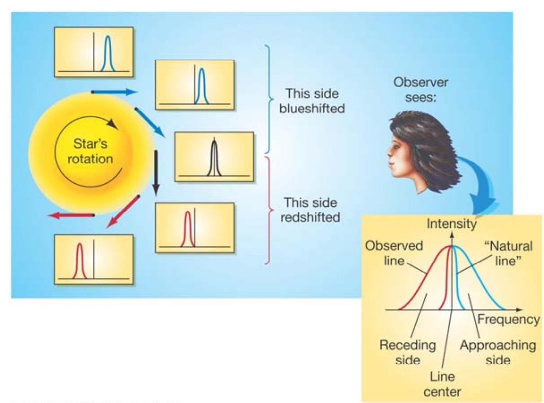
Effects that Broaden Spectral Lines and Give More Information



Thermal motions (see. Fig.4-17): The huge number of individual atoms (or molecules) within the gas you are observing are all moving in random directions with a range of speeds that depends on the temperature. When each of these atoms emits or absorbs a photon, the wavelength is shifted by the Doppler effect according to the speed of that atom. But what you see are the photons from a huge number of atoms in some volume of space (say 10^{23} of them), so what you get is a "broadened" line that is really 10^{23} individual Doppler shifted lines so close together in wavelength that you can't distinguish them.

Turbulent motions: Turbulence is random motions, like for individual atoms, but now for large blobs of gas, like winds in the atmosphere. When you look at some gas in the atmosphere of a star or planet, these motions are much smaller than the region you can resolve, so the Doppler shifts from each of the randomly moving blobs are all blended together, like the case for thermal motions.

Rotation (see Fig. 4-18): You will have to look at an imaginary picture of a star rotating, to realize that one side is moving away, the other moving toward you, so redshift, blueshift, and everything in between. We can't resolve the surface of any star (besides the sun), so these different Doppler shifts from different parts of the star's surface are all blended together. ***This is virtually the only way we can obtain the rotation rates of stars*** *(except for the sun).*



Atomic collisions : difficult to explain why (the physics is subtle), but collisions make the energies of energy levels "fuzzy," so the wavelengths emitted or absorbed are at a range of wavelengths, not a single wavelength.

Magnetic fields: again, can't explain the reason without lots of physics, but magnetic fields split electron energy levels into closely space sublevels, meaning that energy differences between two electronic energy levels correspond to several closely-space wavelengths. *This is one of few ways we have to measure magnetic field strengths in astronomical objects.*

Notice that many (not all) of these are directly due to the Doppler effect. If you can explain these spectral lines and their broadening and what you can learn from this in terms of the Doppler effect, then you probably understand this material. See table on next page, from textbook.

TABLE 4.1 Spectral Information Derived from Starlight

Observed Spectral Characteristic	Information Provided
Peak frequency or wavelength (continuous spectra only)	Temperature (Wien's law)
Lines present	Composition, temperature
Line intensities	Composition, temperature
Line width	Temperature, turbulence, rotation speed, density, magnetic field
Doppler shift	Line-of-sight velocity