Supplement to lecture from Wed., Sept 16. Please read first two paragraphs (and the rest if you want to use this as the supplement it was intended to be) by Friday morning's class.

The Spectrum of Almost Anything

After a brief recount of what we have covered and will cover on Friday and Monday, I try to give a discussion of how ordinary and general the idea of "measuring a spectrum" is, and how you might get continuous, or line, spectra from all sorts of things that I just thought up as I wrote. You should try it yourself at the end.

WHAT HAPPENED on Wednesday? What's happening on Friday?
Today we covered about half of chapter 4 on spectral lines, most of the material in sec. 4.2 and 4.3. We'll finish this with some examples of atomic spectra like the pictures in your book, talk about how the same effects are seen in molecular spectra (sec. 4.4), and then get to the useful but difficult material on how spectral lines can be used to diagnose the object that we are observing, sec. 4.5. But none of this will make sense if you don't know what a spectral line is or how it comes about. The same is true for the rest of the course, so that's why I'm writing this supplement. It might be easiest to just think about light coming out of a star at first, even though the principles are general and some of the pictures in the book are of other objects. It is looking doubtful that we can make a dent in chapter 5 on Friday, so it is important that you read that material over the weekend so that I can cram it all into one lecture on Monday.

However the really important material for now concerns whether or not you are starting to understand spectral lines. If you have not read those sections in chapter 4, and today's lecture didn't click with you, perhaps you have not read 4.2 and 4.3 yet. Please, download and print out the lecture slides, go through 4.2, 4.3, 4.4, and 4.5 (and 4.1) before Friday, so that the lecture might clarify your understanding of this material, not as your first enounter with it. In case you were confused, or could use a rehash in order for it to make a little more sense, the main points concerning what went on in today's (Wed.) class is given below. Don't feel obliged to read it—there is nothing new there, or anything specific, just an overall summary of how I tried to explain what spectra were, the three types of spectra, and especially how they correspond to the structure of electron orbitals in atoms of various elements. Inbetween are a number of examples of things that have spectra that you could measure, so you will see that the case of light is not exotic at all, it is the same kind of thing we think about for everyday phenomena.

THREE KINDS OF SPECTRA OF LIGHT.
There are basically three kinds of spectra you encounter when you observe objects in the universe: A continuous spectrum, an absorption line or dark line spectrum, and an emission line or bright line spectrum. You are supposed to be able to explain the relation between these spectra and what atomic electrons are doing in a star's atmosphere.

WHY THESE ARE NOT ANYBODY'S "LAWS" (Kirchoff's, say)
These types of spectra correspond to the three "Kirchoff's laws" in sec. 4.1, but I think that to understand spectra this way leads to just memorizing a set of statements, not seeing the physical reasons for the phenomenon of spectral lines. Think back to Newton's law of gravity. In that case, you had to memorize a "law" in the form of a relation between the gravitational force, masses, and separation of two objects, but there was no way to EXPLAIN physically what "gravity" is. They are rules, rules that work well. However in the present case there is no real "law" to remember

("Kirchoff's laws"), but there IS a physical explanation behind the phenomenon, and THAT is what you need to think about and understand. Finally, in case you didn't hear me today, the textbook treatment in 4.1 introduces a pictorial representation of what we are talking about, but I have never encountered a student that really understood those light bulbs and prisms and opaque screens, etc. This is supposed to be like the situations in the universe that give rise to the three kinds of spectra named above, but the way Kirchoff came across them in his laboratory is not a very clear way to see what is really happening.

WHY THERE ARE SPECTRAL LINES OF LIGHT, IN A NUTSHELL:
Because we live in a quantum world.

So we strip off all the junk about Kirchoff's laws and prisms and why spectra look like long skinny rectangles in your book (they aren't!), and just ask about how gas in stars or in galactic gas clouds or anywhere emits photons, and absorbs photons, in terms of the quantized energy levels of electrons in various atoms, like hydrogen, or helium, or carbon, etc. THAT is the connection to make, the correspondence between the spectrum as a graph, like a blackbody (continuous, smooth) curve, showing how many photons are coming from an object in each wavelength (or frequency) interval, and the behavior and interaction of matter and photons at the level of individual atoms.

In a nutshell, you have to understand that the only way we can understand why there are spectral lines is to understand that the universe is QUANTIZED at the microscopic level: Electrons in atoms can only have specific, quantized (discrete) energies, and spectral lines correspond to light with just the right energy to be absorbed by one of those electrons. Alternatively, in a hot gas collisions push the electrons up to "excited states" or energy levels, and the EMITTED photons correspond to the electrons returning to various lower energy states—each time an electron changes its energy, a photon with a wavelength corresponding to that energy must appear or be absorbed. See if it makes more sense after the discussion below, where I offer an analogy using human heights, in which case you will easily see that there is no way to have a "spectral line" if the range of heights (or growth rates) of humans is continuous. However if you understand already, you could stop here.

THE DISTRIBUTION (SPECTRUM) OF HUMAN HEIGHTS AS AN ANALOGY FOR SPECTRA OF PHOTONS.
I introduced what is intended to be a simple analogy that is closer to everyday experience in order to help you remember what spectral lines are. I can't go over the entire thing here, but to remind you, it had to do with counting the number of people at (say) a football game, or a shopping mall, or anywhere, and making a histogram or bar chart showing how many people are present as a function of their height. If you draw a smooth line through the tops of each bar in a bar graph with lots of bars (say a hundred, or a thousand, or them), you get a curve that still shows the number of people as a function of their height. THIS IS JUST LIKE SPECTRA, EXCEPT IN THAT CASE WE ARE COUNTING HOW MANY PHOTONS HAVE THIS OR THAT WAVELENGTH, instead of how many people have this or that height.
As discussed today, that curve will have a sharp peak at around 5-6 feet, because there aren't very many humans that are MUCH smaller (babies maybe) and not many that are much taller (basketball players), although in the latter case we don't exactly know why there couldn't be

people with heights of 10 feet; they would not be very popular, so perhaps they have been weeded out of the population by the homogenizing evil that we call society.

MORE EXAMPLES, especially musical instruments and radio stations.
This is not complex. We like to think that everything can be labeled with certain properties, like the ages of (most) things, or the number of pieces of paper in all the desk drawers in the world (think about it), or the intensity of a sound as a function of the frequency. Concerning this last example, think—do most musical instruments have a continuous sound spectrum? Compare a piano with a violin with the hiss of noise coming from a radio inbetween broadcast frequencies, and see if you get the difference between discrete and continuous frequencies.

And notice that the intensity of sound you hear on a radio if you continuously “turn the knob” is only strong for very well-defined frequencies at which there are radio stations broadcasting at various strengths and located at various distances from you. That is precisely the same as spectral lines, except of course this has nothing at all to do with the quantum nature of the world, only that radio stations have to remain well-separated or you would hear them all at once. Once you understand spectral lines for light, come back to this and explain why the radio example is an emission spectrum, and whether there is a continuous spectrum underlying the spectral lines.

Size spectrum of particles on a beach.
Or imagine you had nothing else to do but measure the sizes of pebbles on the beach; the “size spectrum” of the pebbles would be a curve in a graph showing the relative number of pebbles at different heights, with size increasing to the right, so grains of sand on the far left, boulders, if there are any, on the far right. Again, start by imagine making a bar graph or histogram, then let the number of bars get large and just draw a curve through the tops of them—that is the “spectrum.” Maybe you can already tell that at a beach most of the particles will be grains of sand, so the “spectrum” will be very high at small sizes and then decline rapidly for grains as large as 0.001 inches, or 0.01, or 0.1 inches, because those pebbles will be increasingly rare. Now you draw a smooth curve through the points representing your histogram, and you have the “continuous spectrum” of sizes. But you may have noticed that on some beaches erosion has left a population of pebbles that have about the same size. They would appear as a “peak” in the size spectrum, an “emission line.” The “line” would have a width that is the range of sizes of these eroded pebbles, such as 1.4 to 1.7 centimeters. That is the “width of a spectral line.”

LINES IN THE SPECTRA OF LIGHT SOURCES ARE TELLING US THE WORLD IS QUANTIZED
Now think about a photon spectrum as being the result of counting the number of photons that have different wavelengths (or frequencies). In this case the telescope and an instrument called a “spectrometer” counts the photons, basically by seeing how bright the object appears at each wavelength, which is the definition of the photon spectrum. Is it a smooth curve? That is a continuous spectrum. But stars, and planetary atmospheres, and the interstellar medium, have spectra that are riddled with thousands or millions of very specific wavelengths where some of the photons are missing, maybe low by a factor of ten, or a hundred. This will appear as a sharp “dip” (a “line”) superimposed on the continuous spectrum. We could understand these “spectral lines” in the case of the radio stations, but it would be awfully weird in the other cases.

The quantized energy levels of electrons in atoms give us a way to understand how this could possibly happen—think about how strange it is. In the analogous “height distribution” of people in a mall, spectral absorption lines would correspond to having a deficit of people IN A VERY

NARROW HEIGHT INTERVAL, like 5.2025 to 5.2030 feet. What if you noticed that out of 100,000 humans, the number in that interval should be 250, but you only count 6—how could that be? For human heights it could not be, and you must have made an error—there is no process that that doesn't result in CONTINUOUS growth (or shrinkage!), so having a "growth spurt" right at 5.2025 feet that takes humans across this interval would be too weird to explain. Yet some other examples above did have "quantized" or at least discrete, "spectral lines." Now is a good time to go back if you didn't get it the first time.

For light, we see the same kind of thing, but in this case we are missing photons over a very small interval of wavelengths. The strange case of the "missing photons" was extremely difficult to understand until the 1920s, and then only because we (think we) understand that photons can only be absorbed and emitted at very specific wavelengths. This is because electrons in atoms can only exist in very particular energy levels—the energies of electrons in atoms are QUANTIZED. If we didn't know that spectral lines are due to the quantum nature of the microscopic universe, we might have to suggest it in order to explain those lines.

A suggested exercise: Try to imagine the spectrum of wind speeds measured by some instrument in a given place, like a "weather vane," or at the body of a jet airliner.

What does the spectrum of wind speeds mean, in everyday words? What might we learn from it?

Think about "clear air turbulence," those sudden unexpected turbulent winds that cause the plane to shake and the passengers to tremble because they have seen too many realistic movies about plane disasters. Is it like a spectral line? Something else? What would be the analogous phenomenon if you were listening to the pitches in a musical piece?

Had enough? OK, I'll stop there, except to suggest that you think up an original example of some down-to-earth phenomenon for which you could measure a "spectrum" and think about whether it could have spectral lines, and whether they would be emission or absorption lines. If you can do that, you will be successful in all your future endeavors, for your entire life, all your past failures and inadequacies will be reinterpreted as triumphs, and more. Much more.