Topics: Radiation and matter...in detail: basic atomic structure (the Bohr atom), atomic processes, line broadening, radiation transport

Summary of reading:

- Ryden and Peterson, Ch. 5, first four sections, through p. 130 (but see my commentary below for what to pay extra special attention to and what you can pay less attention to).

Summary of work to submit:

- Nothing to submit for Tuesday’s class; though expect to do a calculation in class related to the hydrogen atomic energy level diagram and the wavelengths of photons produced (or absorbed) by electron transitions between particular levels.

Here are the things you should be thinking about:

The light we see/measure originated in some process involving matter (particularly/usually an electron). So, we want to understand the relevant properties of matter that affect the light we see. And then use observations of that light to infer the properties of the matter that emitted, absorbed, or scattered it.

There is a lot of material in this class preparation! The discussion will continue into Thursday, but let’s try to prepare to touch on all of it on Tuesday and then decide what we need to talk more about on Thursday.

Commentary on the reading:

Ch. 5 starts with basic information about atomic structure, focusing on the Bohr model of the hydrogen atom (extendable to any atom with only one electron; note eqn. 5.23 with its inclusion of $Z$, representing the charge (number of protons) in the atom’s nucleus).

Although the Bohr model is simplistic and leaves out a lot of important effects, it is a basically correct functional description of the quantum mechanical atom. Note the similarities in the derivation of its structure to circular orbits – a central $1/r^2$ force (here electricity rather than gravity); energy conservation considerations; angular momentum conservation. These factors combine to give the quantized energy levels that are one of the primary results of quantum mechanics. Unlike a satellite in orbit, an electron in an atom can only exist at specific orbital distances (and thus, energies). These energy levels are conveniently visualized in an energy level diagram, like that shown in Fig. 5. Electrons can move up or down between energy levels (but never to a point in between them) absorbing or emitting photons in the process.

Study the various atomic processes in the second section of the chapter. Note that some involve photons (with therefore, observable consequences) and some don’t (and so aren’t directly observable). But even the processes that don’t involve photons do conserve energy and so always involve some other particle (usually a free electron) that contributes or removes energy to balance out changes in potential and kinetic energy.

Review Kirchoff’s “laws” and color figure 3. And review the EM spectrum, the wavelengths associated with visible light, and the various units of wavelength. And the relationship between wavelength and photon energy – get comfortable with electron Volts (eV) as an energy unit.

One reason we’re learning about the Doppler shift now is that it can affect observed spectra in important ways; especially line (as opposed to continuous) spectra. A source that’s moving with respect to the observer will have its whole spectrum – including the positions of any spectral emission or absorption lines – shifted. And even a stationary source can be affected by the Doppler shift, if the individual atoms in it are moving...
with respect to each other. Specifically, any substance with a temperature greater than absolute zero has random thermal motions (we call that “heat”) which will impose a Doppler shift on every photon emitted or absorbed by those moving atoms. Taken together, this leads to each spectral line being broader than it otherwise would be. This is the thermal broadening described on pp. 125-6. That’s the most important part of the line-broadening reading; it’s where you should focus your preparations for class. The mathematical details of natural broadening (related to the Heisenberg uncertainty principle) are less important.

It’s important to get comfortable with the basic concept that when you see photons from more than one atom at a time, the individual Doppler shifts of each photon combine into a single observed spectral line that is broadened. Please feel free to ask/email me questions about this basic concept even before Tuesday’s class, after you’ve read about it, if you’re still confused.

Now, pay special attention to the Maxwell-Boltzmann distribution described there (it will be useful in other contexts, later). Roughly sketch out eqn. 5.40 for yourself. Make sure you understand what it represents (what’s plotted on each axis and what is the meaning of those quantities?) and how the shape will change if the temperature changes. And note the characterizations of the distribution on p. 125, like the mean velocity as a function of temperature. Finally, do you see, then, how the combined Doppler shifted photons from a Maxwell-Boltzmann distribution of atoms leads to a broadened (Gaussian shaped) spectral line (5.49) and the useful scaling relations (5.50 and 5.51)?

There are other important broadening mechanisms (bullet points at the end of the section), read about them, too. Note that one of them can be used to measure magnetic field strength.

Regarding radiation transport (sec. 5.4, Fig. 5.9, eqn. 5.61), the big picture is that an absorbing medium (e.g. a cloud of interstellar gas) absorbs some fraction of the light incident upon it from a background source. So we see that source as dimmer than we would otherwise. How can we relate the amount of dimming to the important properties of the cloud? Please think about how when you observe a spectral absorption line, the depth of line itself relative to the continuum tells us what fraction of the light is absorbed.

What governs the strength and shape of an absorption line? The properties of the medium doing the absorbing – the number density of particles, \( n \), the cross section (think, size) of each atom, \( \sigma \), and the thickness of the medium, \( \Delta x \). The unitless product of these three factors is called the optical depth, \( \tau \), and it is a critically important parameter in astrophysics. Optically thin media (with \( \tau << 1 \)) are transparent and optically thick media (with \( \tau >> 1 \)) are opaque. The ratio of the intensity of light entering a medium to that emerging from it after some of it has been absorbed is given by eqn. 5.61, \( I = I_0 e^{-\tau} \). If you can measure \( I/I_0 \) and know the cross section of the absorbing atoms, you can compute the column density, \( N \) (particles per square meter) of the absorbing medium. Think about the physical interpretation of this quantity. Another important quantity in radiation transport is the mean free path, which tells you the average distance a photon travels through a medium before it is absorbed. It is simply the distance that gives \( \tau = 1 \) for a medium.

Please think about for what values of optical depth the fraction of incident light that is absorbed will be proportional to the number of absorbers (the column density) and when and why that linear relationship breaks down.

Also! The intensity, \( I \), is a lot like flux – it has units of flux per solid angle. And solid angle is a square angle – the two dimensional analog of angular size – and so has units of square radians, which are called steradians. Don’t worry too much about this right now; but recognize that the important property of intensity is that unlike flux, which decreases as the square of the distance the light has travelled, the intensity does not change as light travels through space. Thus we can analyze the absorption, optical depth, etc. and not also have to
worry that the inverse-square-law decrease in brightness is also affecting our results.

What makes this radiation transport stuff interesting and extra useful is that just as light intensity can be a function of wavelength, so can the absorption cross section of an atom. In other words, line broadening can be incorporated into this picture. Please note that optical depth of a line is defined at line center. And further note that beyond the edges of an absorption line is the continuum. The continuum tells you what $I_o$ is which the line center tells you what $I$ is. Measuring $\tau$ from an observed absorption line is easy, then.