Astro 121, Spring 2014
Week 11 (April 10)

Topic: Spectroscopy (part 1)
Break: Catherine

Reading for next week:

Chromey, Chapter 11, covers all the important topics, but there is so much in that chapter that we're going to split this over two weeks. For this week, read the first part of Chapter 11, as follows:

- We'll cover all of sections 11.1 and 11.2 (though we won't really talk about prisms). You have probably seen the grating equation before, but I'd really like you to understand it, inside and out, and you should (eventually) be able to talk through a derivation of it without referring to the book.

- We won't talk much about section 11.3, but you should understand the basic idea of what happens when a spectrometer does not have a slit vs. when it does have a slit. As you'll see in 11.4, a slit causes you to lose light, so it's important to understand why we bother with it.

- Section 11.4 is a short but very important section, and we'll spend some time on it. This overlaps with the Walker reading that's needed for one problem I assigned. But hopefully Walker will make much more sense once you've understood Chromey.

A few notes on the reading:

➢ Chromey refers to "spectral purity" (p. 370), and then mentions in passing that "Astronomers commonly refer to the spectral purity as the resolution." I do indeed call this "resolution," as do most astronomers I know - so you'll probably hear me using that term. But you should know that it's the same thing as "spectral purity." I'll try to refer to "spectral resolution" to distinguish it from "spatial resolution," which we've talked about previously.

➢ Also on p. 370, in the middle, Chromey brings in a term involving 2.3 detector elements, in defining resolution (purity). But then on p. 385, he shifts the criterion to 2.0 detector elements (pixels), which I think makes more sense. (What's special about 2 pixels? It's something we've discussed already in a different context.)

You may want to follow up with one or more of the alternate sources listed below, picking and choosing as needed for the topics you don't understand, or if you just want to get another look at a particular topic. I do think Chromey is good on this topic, though.

As with some of our previous topics, there's a lot of highly detailed material out there. Each of the following references has some useful material, but also may have the potential to be confusing. Here is a range of references, in roughly decreasing order of priority; look at several of these as needed, but don't feel compelled to read all of them. You may also find it useful to consult a basic optics book (or the *Diffraction Gratings Handbook*) to remind yourself about multiple-slit diffraction.

- Walker, *Astronomical Observations*. pp. 151–169. (Note that I ask you about some of the equations from this in a problem below, so you'll need to at least look at this one.)

- Berry and Burnell, Chapter 9. This is a pretty gentle start, giving some of the basic terminology and an overview of several kinds of spectrographs.

- McLean, *Electronic Imaging in Astronomy,* Section 5.2, pp. 167–176. This is the opposite of Berry and Burnell—just dives right in with some of the highlights, presented fairly quickly without a lot of extra information. The level of math here is more like what we're interested in, though.

- Birney, Chapter 12.

- Kitchin, *Astrophysical Techniques*, pp. 310–322; pp. 347–355. Don't get bogged down in the math, especially in the first section. However, this does give an idea of how the way the various orders appear on the chip is a function of grating properties. The first section defines some terms, though we don't care (much) about prisms.

- Palmer, *Diffraction Gratings Handbook*, Chapter 2. This book is a free publication by a leading manufacturer of diffraction gratings. It has a nice overview of the basic physics of diffraction gratings. I've put my copy of this in the lab.

- Howell, *Handbook of CCD Astronomy*. Chapter 6. Below, I haven't asked you explicitly about detector and data-reduction aspects of spectroscopy, but read over this chapter to get a feel for them, and we'll talk about them in seminar if we have time. We'll also be doing some spectroscopic observing soon.

- Roth, *Compendium of Practical Astronomy, Volume 1*, pp. 300–313.

Important concepts and problems to complete:

1. *Parts of a spectrograph*. What is the role of each of the following elements of a spectrograph? Telescope, slit, collimator, disperser (grating or prism), camera, and detector. (The first and last should be obvious, but they are there to give the complete list in order.) Roughly diagram the path of two different wavelengths of light through the spectrograph, showing how the light passes through each element of the spectrograph. Note that the use of the word "camera" here is distinct from how we've used it before; I sometimes refer to a "CCD camera", but there that's not what it means.

2. *Spectrograph efficiency*. Walker arrives at an expression for the efficiency of a spectrograph fairly quickly (in just two pages) because he glosses over a lot of hidden assumptions about how a spectrograph is put together. If you understand those assumptions, then you understand spectrographs fairly well, but it takes a bit of work. So: derive equations 5.3, 5,4, and 5.6 in Walker, and give a diagram with your derivation. Some hints:

    a. Ignore the r factor (given in Eq. 5.5); also note that Walker's k variable is simply the pixel size of the detector.

    b. Think about where the collimator must be placed, and what diameter it must have, if it is to be able to intercept light from the entire primary mirror. Use this to derive a relationship between $f/_{\text{telescope}}$ and $f/_{\text{Collimator}}$. (Note that Walker's notation is different here.)

    c. Think about what the diameter of the camera mirror must be if it is to intercept all of the light from the collimator. Use this to derive a relationship between the diameter of the collimator and the diameter of the camera.

d. Now you have all the pieces you need to get Walker's equations. But it still takes some thinking. Feel free to come see me if you're stuck. (This is true with any problem, of course, but with this one in particular I think there's a bit more likelihood of getting stuck…)

3. *The grating equation*. Derive the grating equation, $m\lambda = \sigma (\sin \alpha + \sin \theta)$ where α is the angle of incidence and θ is the angle of reflection, σ is the spacing between grooves in the diffraction grating, λ is the wavelength of light, and m is an integer. (Do this for the two-slit transmission case, which is a little easier to think about than a reflection grating, though the latter are what is generally used in astronomy.) Note that the angles are defined so that all angles on one side of the normal to the grating are positive, and all angles on the other side are negative. Why isn't the angle of all of the outgoing light from the grating slits equal to the angle of the incoming light?

4. *Thinking more about how a grating works*. Why doesn't reflection off a (continuous) mirror produce a spectrum? You could think of it like a reflection grating, which is really just a bunch of mirrored strips laid side-by-side. So a mirror is a reflection grating with an infinitesimally small spacing between facets. Why doesn't that give you a spectrum? Try to answer this both mathematically (using the grating equation) and physically (explaining what is or isn't happening in each case).

5. *Blazing*. What does it mean to blaze a grating? Why is it done? (Try to answer this in a way that isn't just quoting directly from Chromey – explain what is going on in your own words, and compare to the alternative.)

6. *Spectral resolution or spectral purity*. How is it defined? What factors does it depend on? (It's not only the properties of the grating or prism, though those do matter.) In practice, how could you measure it? What is the equivalent of Nyquist sampling (discussed previously) when we're talking about spectra rather than images?

7. *The slit*. If you took a spectrum of a star without using a slit in your spectrograph, what would that spectrum look like? (To help with seeing this, please sketch the resulting spectrum using colored pencils or pens.) What sets the spectral resolution of such a spectrum? Look on-line to find examples of slitless spectra of extended objects—I know Chandra has taken some of supernova remnants. What is "long-slit" spectroscopy, and what is it used for? Find some examples (e.g. in ADS) of long-slit spectra.

8. *Echelle spectroscopy*. What is an echelle spectrograph? What are the basic optical elements in an echelle spectrograph, and how do they differ from a simple single-order spectrograph? What are the advantages and disadvantages of an echelle?