Astro 121, Spring 2016
Week 7 (March 2)

Topic: Telescopes and imaging
Break: Stefan (after spring break: Randy)

Topics: This week we'll discuss telescopes: telescope designs, aberrations, image scale in the focal plane, angular resolution.

Reading for next week: There's a lot of highly detailed material out there; I've tried to come up with some things that give you a flavor of the complexities involved while still being accessible without a lot of prior work in optics. I'd suggest reading things in the order given here:

- Chromey, Chapter 5, through Section 5.4. Skim through Sections 5.1–5.2, which should be mostly review if you've had some optics. Also just skim through Section 5.5 to get a sense of the kinds of aberrations that exist.

- Chromey, Chapter 6, Sections 6.1 and 6.2. In both this chapter and the previous one, don't get bogged down in the lens/mirror equations, as we aren't going to be doing a lot of quantitative optics calculations (aside from diffraction limit and focal plane scale).

- Birney et al., Chapter 6. This is a less technical discussion, with clearer diagrams of different telescope designs.

- Berry and Burnell, Section 1.5. This discusses image sampling and includes the important Nyquist theorem. Note: Berry and Burnell call the focal ratio *N;* Birney calls this f/, and Chromey calls it $\Re$. I will refer to it as f/, since that seems the most common usage (although admittedly one has to be careful writing this in mathematical expressions given the slash).

- Kitchin, *Astrophysical Techniques*. Just look at the figures on pp. 72–76 to get a feel for the different types of aberrations.

- Roth, *Compendium of Practical Astronomy, Volume 1*. Look at the images of spherical aberration on p. 72, coma on p. 74, and note the Dawes criterion (not covered elsewhere) on pp. 104–105.

Problems

Note: several of these problems require extra information. While you might be able to find relevant numbers with a general Google search, often it may not be clear there what the details are, or how up-to-date those numbers are. I strongly encourage you to dig around on observatory web sites to get extra detail that will give you some insight into the characteristics of the telescopes discussed here. As a research astronomer, the website of whatever telescope or instrument you are interested in using is one of your most valuable sources of information.

1. The *plate scale* (a term from photographic days, but still used) or *image scale* of a telescope/camera system is the amount of angle on the sky that is imaged onto a particular linear size on the detector, e.g. a number of arcsec/mm.

    a. *Derive* (don't just look up) an expression for plate scale in units of arcsec/mm given the telescope diameter D in meters and telescope focal ratio f/. (The symbol f/ is often used for the ratio f/D; Chromey calls it $\Re$. For example a telescope with f/D = 8, i.e. focal length 8 times the primary mirror diameter, is referred to as an "f/8 telescope.") Show a diagram illustrating your derivation; it's fine to represent a telescope as a lens rather than a mirror – it's much simpler that way.

b. Convert this to units of arcsec/pixel, given a pixel size p in microns (which are the units usually used for CCD pixels). That is, come up with an equation for the plate scale in arcsec/pixel, given f/ and p in microns.

c. Use your expressions for a. and b. to determine these quantities, as well as the total field of view, for the van de Kamp telescope (f/7.8, 24-inch) and CCD camera (Apogee U16M), and for our rooftop 8" telescopes (Meade LX200GPS telescopes, with SBIG ST-10XME CCD camera). How well do these setups sample the seeing here (4" typical)?

d. Why do we almost always bin our CCD observations 2x2 when using the PvdK telescope? Can you think of any circumstances when it would be advantageous *not* to bin?

e. A telescope with a large f/ is referred to as a "slow" design, while a telescope with a small f/ is referred to as a "fast" design. Why? When might you want to use each kind? For this question, hold the aperture diameter fixed when comparing faster vs. slower designs. (Hint: you may find it helpful to think about having a detector with a fixed pixel size, and then determining how the rate of energy deposition *per pixel* varies with f/ when you are observing an extended object.)

f. Why is it hard to build a large-aperture, slow telescope?

2. Look at some CCD images taken with the van de Kamp Observatory telescope. Do you see any evidence of any of the aberrations shown in Fig. 5.34 in Chromey? Explain how you judged this.

3. The Hubble Space Telescope has had several cameras: WFPC/2 (for optical, replaced by ACS) and NICMOS (for near infrared); most recently, the Wide Field Camera 3 (WFC3) was installed, which works at both visible and infrared wavelengths.

   a. Calculate the diffraction limit of HST at 550 nm and at 2 microns.

   b. For each of these four cameras (WFPC/2, NICMOS, ACS, WFC3), calculate whether stellar images should be undersampled, critically sampled, or oversampled.

   c. Find HST images of stars (especially brighter stars) taken with the various cameras, and see if you can relate them to your answers to part b. What would you expect stellar images to look like, if taken with a telescope in space?

4. At what wavelengths is the Keck telescope limited by diffraction rather than atmospheric seeing?

5. Chromey, problem 5.8, on observing Mars with different telescopes.

6. Up until about the 1960s, all major telescopes were equatorial mounts. Now many are alt-az mounts. Why do you think this is?

7. Alt-az telescopes have a hard time observing objects that are within a few degrees of the zenith (and thus will sometimes be limited in their control software from pointing there at all). Why? (Hint: think about the telescope tracking as the object moves.) See also Chromey problem 6.1, which is essentially the same question.

8. Calculate the length of the Sproul refractor. Why do you think it has such a focal length? What is the focal length of the van de Kamp telescope? How does this compare to its overall length?

9. Rules of thumb, round 3. (Time to find that third hand!) The diffraction limit of a telescope is typically written as 1.22 λ/D. But that's in radians, which aren't very practical. Show that the diffraction limit in arcseconds is roughly 1/4 λ/D where λ is in microns and D is in meters.

10. Chromey 6.9, on the detection threshold for HST vs JWST.

Data analysis:

To give you some direct experience with photometry, we'll do some photometric measurements of our own with the van de Kamp telescope.

For this assignment we'll do some time-series photometry (e.g. of an eclipsing binary, an RR Lyrae variable star, a Cepheid, or an extrasolar planet) in a single filter. Another sort of target would be OK, too, but talk to me about it first. I think an RR Lyrae would be one of your best choices, due to the relatively short period and relatively large amplitude. With our telescope, differential photometry of any star that is 13^{th} magnitude or brighter (in g', r', V, or R) will have no problem detecting variations of 0.1 mag or less quite easily, and can go to 10x smaller amplitudes with careful analysis.

Some resources for finding targets:

- You can go to Vizier and search for catalogues of eclipsing binaries, Cepheids, or RR Lyraes. Then you can narrow down by RA/Dec, period (shorter is probably better – shoot for a period less than a day if it's an RR Lyrae, or try to observe an eclipse if it's an eclipsing binary), etc.

- I have put together a tool that lists upcoming extrasolar planet transits, at http://astro.swarthmore.edu/transits.cgi . There you can see when there are upcoming transits. Note that these are much smaller-depth events than a typical eclipsing binary, and thus harder to detect. You may want to stick with an easier target for your first attempt… But if you do choose this, go for a transit depth of at least 10 milli-magnitudes (i.e. 0.010 mag).

- NASA's K2 mission (the extended part of the Kepler mission) has measured light curves of many thousands of stars. A lot of them are uninteresting, but there are many interesting ones in there, too. You could look through some of the K2 light curves and see if there is anything of interest there to follow up. Note that you won't be able to do photometry that's as precise as K2, so you'll want to choose a target with relatively large variations (e.g. an eclipsing binary or sinusoidal variable). How to find targets in this category:

  - The fields observed by K2 are shown here: http://keplerscience.arc.nasa.gov/k2-fields.html Data from fields 0 through 6 have been released to date.

  - Light curves of stars from fields 0 through 5 can be viewed via links here: https://www.cfa.harvard.edu/~avanderb/k2.html. When you look at the curves, you'll see that they have a lot of systematics in them. So it can be hard to pick out a target of interest just from browsing through light curves. (And there are thousands of them in each campaign!) Which is why you might want to look at:

  - The list of approved programs for K2: http://keplerscience.arc.nasa.gov/k2-approved-programs.html. For each field, this gives a list of proposals that were accepted from scientists who proposed targets that K2 might observe. By looking through the list of proposal titles for a given field, you can get a sense of which proposals might have targets you're interested in (e.g. if it mentions "eclipsing binaries" in the proposal title). You can then click on the proposal title to get a sense of the science, and you can click on the number of accepted targets in the right-hand column to get a list of the IDs of the targets observed. You can then search for these IDs at the previous link to see the light curve of that star.

After break, you will do a more formal writeup of this project. For this coming seminar (March 2), I would like you to turn in the following:

- What target(s) you observed;
- What filter(s) and exposure time you used, and why;
- The coordinates of the target(s).
- A finding chart, i.e. an image of the field that is roughly 30' x 30'.
- A light curve (magnitude or flux vs. time) for your target.
- An explanation of how you did the photometry (aperture size, sky annulus, comparison stars, etc.). I'm not looking for a detailed cookbook of software-related commands here, but rather a summary of the relevant parameters that governed what magnitudes actually came out. One way to look at it is that you should give enough information that someone could reproduce your results if they were using the your images but *different* software. In general, that's what you need to strive for in scientific research writing – what information is necessary for someone to reproduce your results?