ASTR469 Lecture 10: Telescopes and Optics I (Ch. 6)

Assess yourself/study guide after lecture & reading (without peeking at notes)...

1. Try drawing a ray diagram of the human eye.

2. What is the resolving power of your eye? That is, at what angular scale can you no longer separate two dots? Your outstretched pinky finger is about one degree across.

3. If a lens's focal length is 10 mm and its entrance pupil diameter is 5 mm, is this a fast or a slow lens?

4. Consider (qualitatively): what would happen to the surface brightness (intensity per sterradian) of an object if the detector is placed in front of or behind the focal plane?

5. Determine (quantitatively) what happens to the surface brightness of an object that is magnified to 2x its present image size (by what factor does the surface brightness change)?

6. Consider Snell's law. If you could make a lens out of a material with $\mu < 1$, would a concave or convex lens focus the light?

1 Telescopes

Over the next few weeks we'll be discussing a few ideas relating to telescopes and methods in collecting light at various wavelengths. To start off with, let's ignore the wavelength aspects and discuss some general ideas about telescopes.

First, a very basic terminology: there is a "detector" that actually measures the light (e.g. the retina in your eye), and often some kind of other apparatus that directs the light to the detector (your eye's pupil and lens). Today we will focus on the ideas surrounding optics of the light-directing mechanisms. Detectors differ more significantly as a function of wavelength, and we will talk about them in turn over the next few weeks.

And why might we need to manipulate astronomical light?

1. To raise our sensitivity to faint objects.

2. To improve resolution or magnification of an object.

2 Incident light and optics

Most telescopes have a large "primary" mirror or lens, which acts as the primary light catcher. Recall in our discussion of quantifying light that the units of flux were

$$[F] = \left[\frac{\mathrm{W}}{m^2}\right] \tag{1}$$

... in other words, you'll get some energy flow rate per square meter. Recall that if you had a lot of square meters, you'd collect lots of light. That is the point of a primary telescope surface. As a matter of general principle, a telescope with a larger primary surface will be the more sensitive one, because it is simply gathering more photons.

But, your actual detecting sensitivity also depends on the properties of your detector (how efficient it is at registering incident light, whether it has hardware or software issues) and your environment (light pollution, air quality, cloudiness). Obviously, your primary mirror would ideally be on par with the quality of other components of your telescope and environment.

The purpose of the primary is to focus light into the detector, or alternately to redirect light into other reflecting/refracting surfaces (like a secondary mirror, an eyepiece, or your eye!).

Let's discuss the two main optics principles used in the design of telescope surfaces.

2.1 Refraction/Refractors

Refracting telescopes use lenses to focus light. The first telescopes were refractors. They are no longer popular; the lenses are extremely heavy, optics make the telescopes get really long, and there are numerous aberration effects that distort images (discussed in your book; we may also discuss these next lecture).

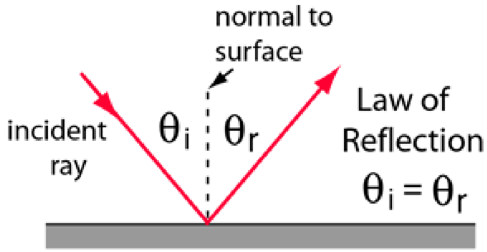

Figure 1: Graphic showing the law of reflection.

Refracting telescopes rely on Snell's law, which we saw in our discussion about refraction in the atmosphere bending starlight. As a reminder, Snell's Law says

$$\mu_1 \sin(\theta_{\rm I}) = \mu_2 \sin(\theta_{\rm R}) \ , \tag{2}$$

Where a ray of light coming from medium 1 into medium 2 will start off coming in at angle $\theta_{\rm I}$ and be redirected towards the normal line, with a new angle $\theta_{\rm R}$. Recall that the index of refraction, μ, is the ratio of the velocity of light in a vacuum to that in the medium, $\mu = c/v$ (note: in Griffiths and some other EM books the symbol n is commonly used instead of μ).

In lenses, the change in index of refraction bends the light. Convex lenses that look like () focus light, conccave lenses that look like)(broaden light.

2.2 Reflection/Reflectors

All modern telescopes are reflectors. All radio telescopes are reflectors. They do not normally suffer from the same aberrations that refractors do. Although there can be problems in their optics that need to be corrected (we will likely discuss these next lecture), these are minor compared to those of lens-based refracting telescopes.

Reflectors operate under the principles of the law of reflection, which states simply that with respect to the normal line to the reflecting surface, an incoming ray of light will have an incident angle equal to its reflected angle: $\theta_i = \theta_r$, as shown in Figure 1. If the surface is flat, there will be no change to the image, as the simple ray diagram in the image shows.

2.3 Basic lens/reflector properties

For an image to be without-distortion after passing onto a (spheroidal) telescope mirror or lens, it must be "in focus." For this to happen, two things must be true:

- **The incident light rays from one point must be parallel.** It is important to note that our targets of observation are far enough away that they can be considered "plane waves"; that is, the light rays hitting our telescope are all parallel to one other.

- **The detector must be in the focal plane of the last optical piece.** Both reflectors (mirrors) and refractors (lenses) have the ultimate goal of getting light focussed

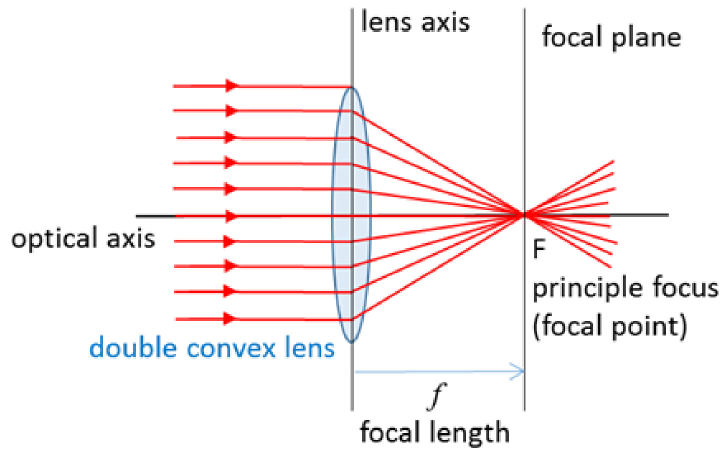

Figure 2: Terminology for a refracting lens. Curved mirrors follow the same terminology. The point of a lens is to take lots of light from an object and redirect it to a single point on the focal plane. Note that the **aperture** size of this lens is defined by its cross-sectional surface area for incident light (in this case, considering the lens as a circle compared to the incident plane wave, its aperture size would be $A = \pi r^2$, with r being half the lens's vertical height in this diagram.

into one point. It is thus useful to define the focus. The geometry and labelling for the optics of a lens is shown in Figure 2, however the same terminology applies for reflecting telescopes.

Importantly, *any plane wave incident on a spherical surface will be reflected, in-focus, onto the focal plane.* See Figure 3 to see how this works.

3 Characterizing Telescopes

We can characterize at telescope's optics with its aperture size (usually given by diameter D), and the focal length, f, which as you saw in class is a characteristic of the surface curvature (and in the case of lenses, also depends the material's μ).

3.1 f-number, $\mathcal{N}$

We can characterize each lens or reflective surface with something called an "f-number":

$$\mathcal{N} = \frac{f}{D} \tag{3}$$

where f is the focal length of the lens or mirror, and D is the diameter. This is a convenient way to quantify the curvature of your lens compared to its size. However, it is (annoyingly) used to sometimes quantify the sensitivity of a lens.

For a fixed curvature (one spheroid), decreasing the diameter leads to larger f-numbers **(thus, larger $\mathcal{N}$ means less sensitivity for a fixed curvature).** Note: "fast" lenses have low

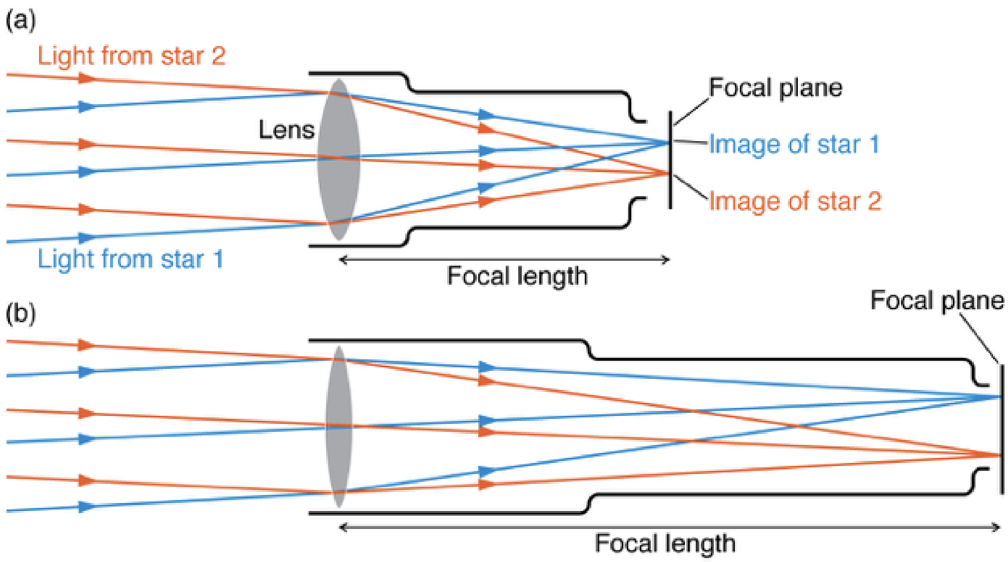

Figure 3: Plane waves (orange and blue) coming in from different stars in the sky. Note that each plane wave is focussed onto the focal plane. Imagine the image you would record on a detector at the focal plane; because of the optics, star 2 would appear to be below star 1 (note how the curved optics inverts the image).

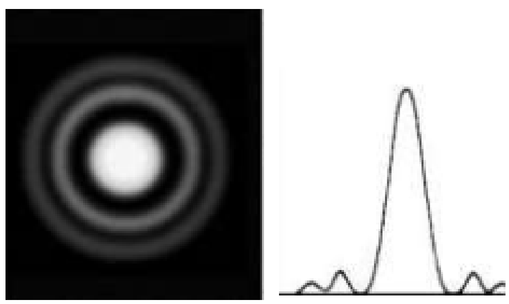

Figure 4: The light distribution (left) and a cut through the peak of this intensity distribution for an Airy disc. The first minimum in the function to the right occurs at $1.22\lambda/D$.

$\mathcal{N}$. $f/2$ is fast, while (for telescopes) $f/8$ is slow. Note that the f-number is usually written in the format $f/\mathcal{N}$. For instance, the f-number of the human eye varies from about $f/8.3$ in a very brightly lit place to about $f/2.1$ in the dark.

3.2 Resolving power

How well can we resolve two objects closely separated on the sky? This comes down entirely to the primary aperture diameter, and has to do with *diffraction* of light.

Light will diffract through an aperture, just like a plane wave through a circular slit. Imagine sending in a perfect plane wave from a single point-like source into a perfect aperture; the "Airy disc" and Airy pattern define the distribution of light of the best focussed spot of this light. An Airy pattern will be shown in lecture.

We can model a cut through the peak of the Airy disc with the square of the "sinc" function, such that the intensity distribution looks like:

$$I \propto \mathrm{sinc}^2(x) = \frac{\sin^2(x)}{x^2} \tag{4}$$

This gives the pattern shown in Fig. 4.

This spreading out of light defines how well we can actually tell two compact astronomical objects apart. There are different criteria we can apply to say "well, we can still actually tell these apart," but the most common is the Rayleigh Criterion, which says that as long as one object has an Airy disk that's sitting further away than the first minimum of another object, that you can resolve the two objects. The first minimum of an Airy disc is this much away from the peak:

$$\theta = 1.22\lambda/D\,, \tag{5}$$

where λ is the observing wavelength, D is the primary surface diameter, and θ is given in radians. This tells you how far apart you need to have two objects to be able to resolve them.

Related to the Airy disc is the "point spread function" (PSF). In addition to the Airy disc, the PSF takes into account broadening along the entire optical path, as well possibly as any atmospheric effects.

The light from stars falls on a single location at the detector - they are point sources. They appear spread out due to the point spread function such that all stars will have the same "size" in the observed image.

3.3 Magnification

It should be clear in Figure 3 that the image of the two stars is further apart for the object with the longer focal length f. This is true; longer focal lengths lead to greater magnification.

There's a trick we can pull with optics to help it easier to change our magnification, and that's using an eyepiece. See Fig. 5. Magnification of a lens depends on the focal lengths of your primary and secondary eyepiece.

$$m = f_1/f_2\,. \tag{6}$$

For example, if our primary has $f = 50\,\mathrm{cm}$ and eyepiece has $f = 2\,\mathrm{cm}$, magnification is 25 times. You can change this easily by changing the eyepiece (if your telescope has an eyepiece). Greater magnification will come from eyepieces with a shorter focus.

Magnification isn't necessarily a scientifically great thing to do because you don't get more light with more magnification! That's because the primary aperture is still the same size, and the primary defines how much light you're collecting. In fact, the intensity of light as measured per steradian on your detector *decreases* with increasing magnification. If the object is low surface brightness, you may want low magnification as well.

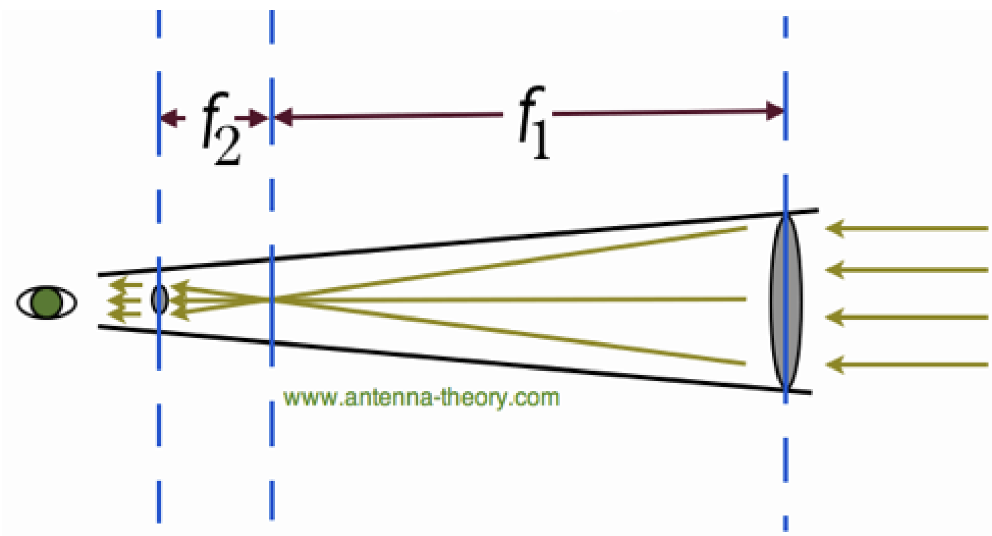

Figure 5: Use of an eyepiece.