OPTIX Module 4 – Intermediate
Telescopes and CCD Cameras

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1 Objectives:

In this module you will learn

- how to set up a simple telescope;

- how to characterize the magnification of your telescope;

- what the characteristics of CCD cameras are;

- how to fit 2D functions to CCD images using Python;

Use this manual as you work through the module to keep track of your notes and thoughts. In addition, you will have to add a few printouts or add additional sheets of paper containing data tables, sketches, or additional notes. Please note that this is *not* your lab report and that you are expected to complete a full lab report written in *LaTeX* after you have completed this module. Keep in mind that this should be a publication style report, which means that it should place a big emphasis on your data and data analysis, and not so much on all the nitty-gritty details of how to assemble the apparatus. Keep this in mind as you work through this module. Your instructor can provide you with more information and will send you a template file that you can use for your report.

2 Tests and assessment:

In preparation for this module, read through the whole manual and answer the questions that are marked with a *. You should also watch the VIDEOs that are posted on our website (www.willamette.edu/cla/physics/info/NSF-OPTIX). They are meant to accompany this manual and will show you some critical steps of the module. When you come to lab, be prepared to discuss your answers to these questions with your class mates and your instructor.

In order to assess the success of this module, you will take a short assessment test before you start ("pre-assessment"), and another one after you have successfully completed this module ("post-assessment"). At this point you will also have the opportunity to provide us with feedback about the module that we will use to improve it for the next student generation. Thank you for your support!

3 Equipment:

For this module you will need the following equipment. You can find it in the box labeled "Module 4" that is located in one of the cabinets in the OPTIX lab. Please feel free to ask your instructor for help.

- Thorlabs CCD camera with USB connection

- Several converging lenses

- Several lens mounts, posts, post holders, table screws, and dogs

- Brass foil with pin holes on blue LED flashlight

## 4 Required background knowledge and things you need to do before starting this module:

In this module you will use many of the skills you learned in Module 1, including how to work with optics elements. You will also be using Python; if you haven't used Python before then please work through **PythonStart.py**, which is on the WISE folder for this module. **Make sure to read through the *whole* manual before coming into the OPTIX lab, and mark anything that you find difficult to understand. In addition, answer all questions that are marked with a yellow star like this: *.**

5 Setting up a simple telescope

A telescope is used to observe very distant objects like stars. There are two important concepts to understand when thinking about imaging light from such distant objects. (1) Even if we treat them as point sources of light, the rays that reach our eye (or telescope) after traveling all that distance are, for all intents and purposes, parallel to each other. We can thus treat the light that reaches us from such an object as collimated. (2) Because these objects are so distant, what we perceive when we look up at the night sky are not the distances between the stars, but instead the differences in angle from our vantage point.

This second point will be especially important for us when we describe the magnification that results from a telescope. Rather than talking about how much the distance between two stars is magnified, we will describe a telescope's magnification by thinking about how the perceived angle between the objects changes. For example, in the figure below, the magnified image of the two stars causes us to perceive a greater angle between the two objects.
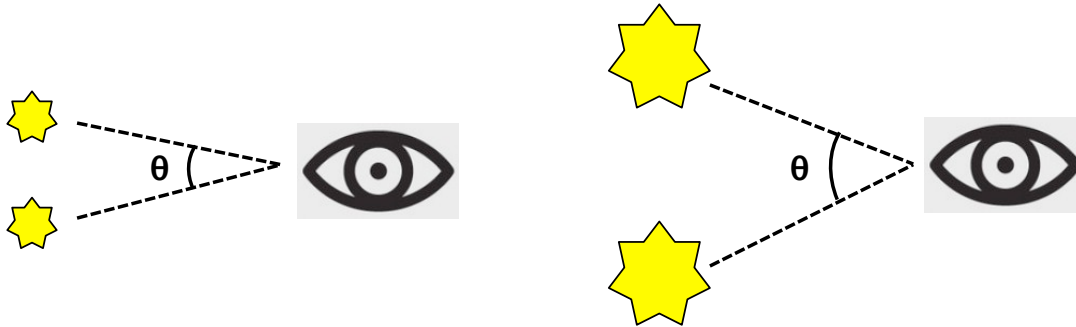
Figure 5.1: *On the left, for the unmagnified image of the night sky, the two stars subtend an angle θ. However, when the image is magnified (for example by a telescope), this angle increases.*

When we talk about the magnification of your telescope in the next sections, we will be referring to the ratio of the angular distances perceived with and without the telescope. This will be very different from how we think about microscope magnification.

Your first task in this lab will be to set up a model of the night sky and an observer looking up at the stars. But before we do this, we will need to learn a bit about the plano-convex lenses you will be using for much of this module.

5.1 Introduction to plano-convex lenses

Most of the lenses we will be using in this lab are plano-convex, meaning they have one convex spherical surface and one flat surface. These lenses are particularly effective for the purpose of turning a point source into collimated light or focusing collimated light to a point. These lenses are more effective than bi-convex lenses, which you may have learned about when you were first introduced to lenses. Bi-convex lenses consist of two convex spherical surfaces, typically of the same radius of curvature. When using the thin lens approximation, these lenses are expected to bring collimated light incident upon them to a single point one focal length away from the lens. In practice, however, the thickness of these lenses results in an effect known as spherical aberration, in which not all the rays come to focus at the same point. Specifically, the rays near the center of the lens do not come to focus at the same point as rays near the edge of the lens (see Figure 5.2).

A bi-convex lens that has a long focal length is created from surfaces that have a very large radius of curvature. As a result, these lenses can be made quite thin. Conversely, lenses that have a short focal length tend to be thicker, and thus suffer from more striking spherical aberration. For example, in Figure 5.2, the thinner lens has a radius of curvature that is 4-times that of the thicker lens. As you can see, the spherical aberration is much worse for the thicker lens.
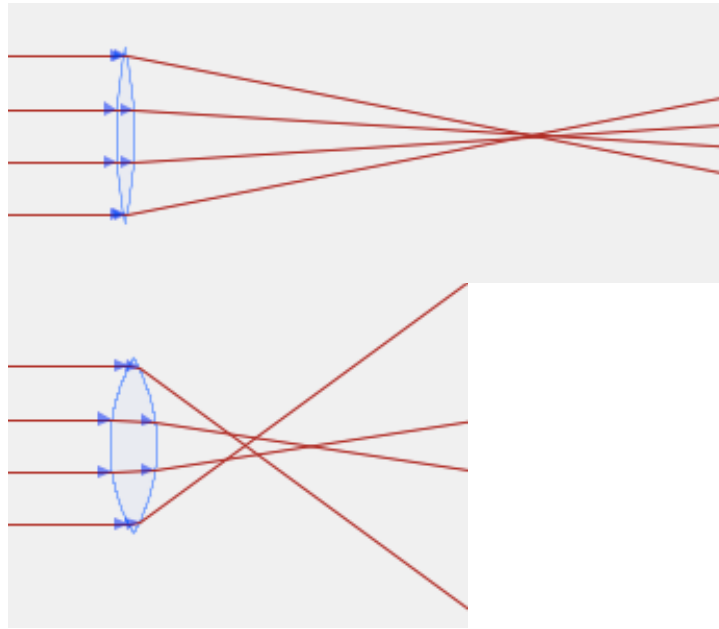
Figure 5.2: *Bi-convex lenses result in spherical aberration, which is more severe in the case thicker lenses with shorter focal lengths.*

* Plano-convex lenses must be oriented appropriately in order to reduce the effects of spherical aberration. Determine the correct orientation (i.e. whether the parallel light rays should be on the flat or the curved side of the lens) using the program OpticalRayTracer. You will want to look at a single lens bringing the rays of light to focus. Play around with the different parameters, focusing especially on the **Sphere Radius** for the left and right sides of your lens, which can be adjusted in the **Design** tab. You may also want to increase the number of rays you are looking at, which you can adjust in the **Configure** tab. You should observe that the incorrect orientation of the lens actually makes the spherical aberration worse.

Sketch below the correct orientation of a plano-convex lens that should be used to focus a collimated beam, and include a printout of the images that allowed you to determine this.

5.2 Setting up a model of an observer looking at the night sky

Your night sky will consist of a brass plate with small holes drilled in it taped over a blue LED flashlight. The brass sample contains ten lines of two holes each that are arranged in a "V" shape. The diameter of each hole is about 10 μm, and the distance between the two neighboring holes increases by 100 μm from row to row, from about 100 μm in the first row to about 1000 μm in the last row. Sketch the sample in the box below.

You will be conducting your experiment on one corner of the optics table. Mount the blue flashlight and place it on the optics table as far from your corner as possible.

The observer will consist of the provided CMOS camera (which will represent the observer's retina) and a single plano-convex lens (which will be the eye's lens). When the eye is most relaxed, the lens is least rounded and thus has the longest focal length, which corresponds to the diameter of the eyeball or the distance to the retina from the lens. Thus a relaxed eye is able to create a focused real image of a distant object on the retina. For close by objects, the image location is further than the distance to the retina, so the image on the retina is out of focus. To bring these objects into focus, muscles in your eye can flex the lens to increase its curvature, shortening its focal length and making the image location equal to the retina location.

To model the relaxed eye looking at your two stars, choose one of the 1-inch-diameter plano-convex lenses provided to you (from among the 50-100 mm focal length lenses described in the *Equipment* section).

Set up the camera and lens near the corner of the table farthest from the stars. Please note, you will need to know the orientation of the lens within the mount in order to orient the lens correctly to minimize spherical aberation. Figure 5.3 shows an example diagram of a 100-mm focal length plano-convex lens.

You now have your model of an eye looking at distant stars. Start live collection of the camera using the ThorCam software. The holes are small and don't let much light through, so you will need to adjust the exposure time to close to its maximum value and turn the room lights off (you may leave the green lights on). Once you have a clear picture of the holes (they should form a V shape), adjust the LED such that the pairs of holes are vertical and the V expands to the right. Using the snapshot button, capture a jpg-image of the stars with the camera (adjust the position of the LED if necessary). This image represents what the stars look like to the naked eye. We will analyze this image later, so save it to the computer.

In the next sections, you will be incorporating a telescope between the lens and the stars. Be sure that your camera and lens are securely attached to the table, and *do not adjust the position of either throughout the next few sections*.

5.3 Introduction to the Keplerian telescope

A Keplerian telescope consists of two lenses: the objective lens (which is closer to the distant object) and the eye lens or eyepiece (which is closer to your eye). The objective has a longer focal length than the eyepiece, and the two are separated by the sum of their focal lengths. Basically, the objective lens forms a real image of the distance star inside the telescope, which is then viewed with the eyepiece.
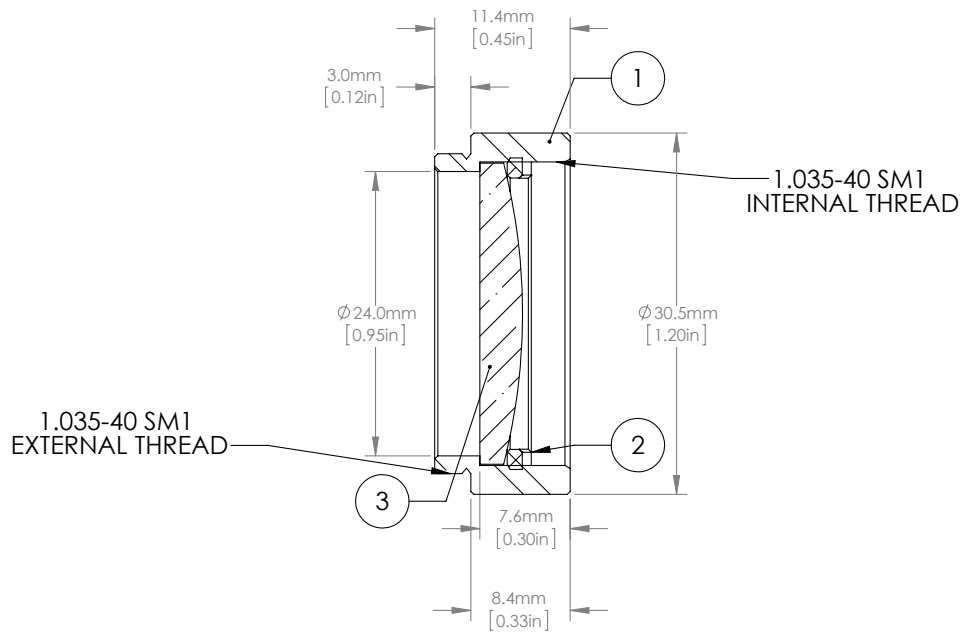
**Figure 5.3:** *Orientation of a lens within its mount.*

* Draw a picture of a Keplerian telescope that is built from plano-convex lenses. Orient the lenses appropriately to minimize spherical aberration. Now, consider star light incident on the telescope from a star that is located along the optical axis of the telescope. Draw a few rays of light from this source of collimated light as they pass through the telescope.

* A Keplerian telescope is called an afocal system (look up what this means). Based on your drawing above, explain why this is the case.

Before we set up your telescope on the table, we need to think about how close the telescope needs to be to your "eye." To do this, we need to introduce two new concepts. The first is the *aperture stop*. This is the aperture which allows light into the telescope; rays which do not pass through this aperture cannot enter the telescope. In our simple telescope, the aperture stop

is simply the objective itself.

The second new concept is the *exit pupil* which is the aperture through which every ray that enters the telescope will exits the telescope. This is a virtual aperture (not a physical aperture), whose location and size are determined by properties of the telescope which we will discuss below. If we think about the aperture stop as an object from which all rays entering the telescope emanate, then the exit pupil will be the real image of this object made by the eyepiece. This can be visualized by looking at what happens when collimated rays from multiple directions enter the objective lens (see Figure 5.4).
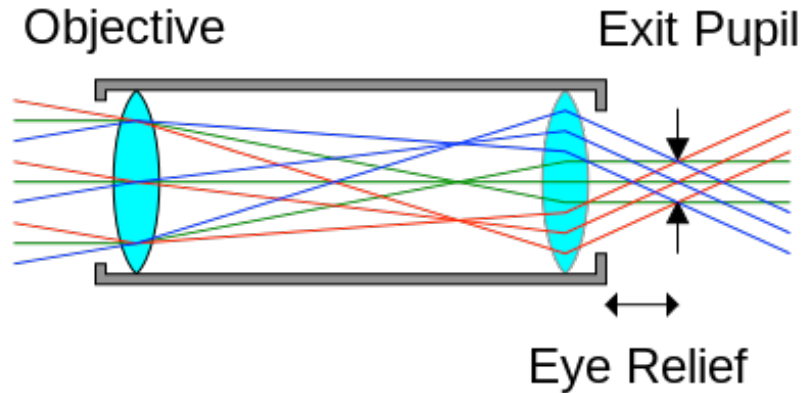
Figure 5.4: *All collimated rays that enter the objective, regardless of their angle, will pass through the exit pupil [?].*

Using the thin lens equation, calculate the location of the exit pupil as a function of the focal lengths of the objective and eyepiece. In other words, calculate the location of the image of the objective lens made by the eyepiece lens.

The distance to the exit pupil, which you calculated above, is called the *eye relief*. To capture all the light entering the telescope, your eye must be placed at this distance from the eyepiece, and the size of the exit pupil should be similar to (or smaller than) the entrance to your eye. If you place your eye away from this plane, then you will begin to lose rays at more extreme angles relative to the optical axis. This will result in *vignetting* of your image, in which your image appears brighter in the middle and darker toward the edges.

5.4 Imaging with a Keplerian telescope

Using the 1-inch-diameter 200-mm focal length and 100-mm focal length plano-convex lenses, set up a Keplerian telescope to image your two LED stars.

Before setting up the telescope on the table, sketch your setup, including both the telescope and the camera with its associated lens. Be sure to orient the plano-convex lenses appropriately and indicate distances between all lenses in your system.

Without moving the positions of the camera or its lens, set up the telescope in the appropriate place on the table. Use a ruler to roughly determine the position of the two lenses. You can also use the holes in the table, which are separated by 1 inch or approximately 25 mm, to estimate the distances between the lenses. Use the camera's live feed to image the LEDs. Do a final alignment of the telescope lenses so that the "stars" are brought into focus.

Take a second picture of the stars, now with the telescope. Save this image; we will be analyzing it in the next section.

6 Analyzing your telescope

Telescopes have three main goals: 1) light collection, 2) resolution, and 3) magnification. The light collecting capabilities are directly related to the size of the aperture stop (i.e. the objective lens). Without a telescope, your ability to collect light from a distant object is limited by the size of your pupil. But the telescope can collect light from a much larger area, allowing you to image very dim, faraway objects like galaxies. In the next section, we will explore the magnification capabilities of a telescope.

6.1 Telescope Magnification

As discussed earlier, the magnification of a telescope is related to the angle subtended by the object being viewed. Specifically, angular magnification of an object is defined as the ratio of the angular size of the image subtended at the eye seen through the telescope to the angular size of the object subtended at the eye without the telescope. Let's come up with a relation that will allow you to calculate the magnification of a telescope.

Imagine that there is a star on the optical axis of the telescope. This star will remain on the optical axis when viewed with or without the telescope. Now imagine a second star that is located at an angle θ_o with respect to the first star, as seen without the telescope. When the light enters the objective of the telescope, it makes an angle θ_o with the optical axis (see Figure 6.1).

In the figure below, we see the effect the telescope has on the light from the star. As indicated, the angle θ_E is the angle at which the light exits the eyepiece and then enters your eye.
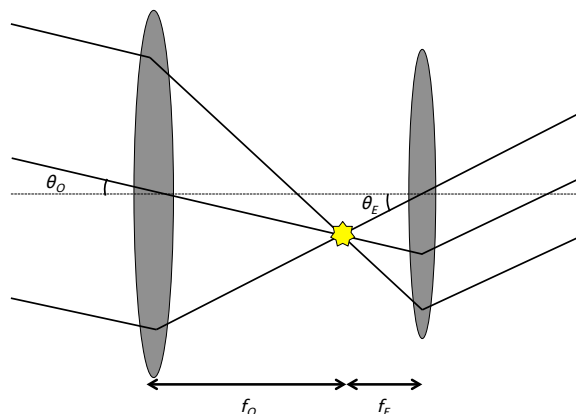
Figure 6.1: *The effect of a telescope on light from a star that is entering at an angle with respect to the optical axis.*

Using the figure above, come up with a relation for the angular magnification ($M_\theta = \frac{\theta_E}{\theta_o}$) in terms of the focal lengths of the two lenses. Using this relation, determine the magnification of the telescope you set up.

Now let's test your calculation using your measurements of the stars with and without the telescope. Open up your first image, without the telescope, in *Fiji*. Click the line button and draw a line between the center of two of the stars. Then, click the *Analyze* pull-down menu, and select **Measure**. The resulting measurement window will give you the distance between the stars on the CMOS/retina in pixels. Record your measurement in the box below. Repeat the process for your second image (collected through the telescope), and record the distance measurement in the same box.

* One way to calculate the angular magnification of the telescope is to calculate the ratio of the distance between the two bright spots with and without the telescope. Explain why we are justified in making this connection between distance and angle. Perform the calculation below. How does your calculation compare to your expected magnification based on the focal length of your two lenses? If it is different, explain possible reasons why.

If you have time, explore the various problems that can occur when the telescope is not designed properly. First, let's look at what happens if you use the plano-convex lenses in the wrong orientation. Rotate both lenses of your telescope so that the curved-sides face the wrong direction. If necessary, adjust the positions of the lenses slightly to bring the LEDs into focus as much as possible. Include a snapshot of your image on the next pages. Do you notice any changes to your image? Explain why or why not.

Now let's explore vignetting. Explain how you can deliberately introduce vignetting into your images without changing the magnification of your image. Make the necessary changes to your optical system until vignetting visibly alters your image of the stars. How did your image change? Explain why. Include a snapshot of your image on the next pages.

7 Introduction to CCD and CMOS cameras:

Digital imaging is primarily based on either the Charge Coupled Device (CCD) or the Complementary Metal-Oxide-Semiconductor (CMOS), either of which is capable of counting photons that are incident on them. In a digital camera, light is focused onto a solid-state "chip", which consists of a 2D array of photon detectors. These semiconductor detectors use the photoelectric effect to count the photons incident upon them. Incoming photons knock electrons into the conduction band where they contribute to a current that can be read electronically. Review semiconductors and sketch this process in the box below.

A digital image is a 2D array of pixel values, with each pixel value corresponding to the photon count in a particular detector over a fixed time, called the "exposure time". High counts correspond to bright pixels and low counts to dim pixels, thus forming a black and white image. Note that CCD images count all photons equally and do not distinguish between photons of different frequency (as long as they are sensitive to that frequency of light). For color images, filters are applied to each pixel that let through only one color of photon; thus there are pixels that count only red photons, pixels that count only blue photons, and pixels that count only green photons. These color counts can be combined to make a color image. In this module, we will only be working with gray scale images.

Digital cameras, which are about 70 times as sensitive to light as film cameras, have led to a revolution in imaging. Unlike photographs, digital images are easy to take and can easily be analyzed using a computer. Digital cameras are one of the most versatile and sensitive light detectors in the optics laboratory, and it is important to understand their operation and uses.

Turn on the computer and log in. Start Python by double clicking on the snake icon on the desktop. It is slow, but once it starts up click to launch *Spyder*, which is the Python editor. Download the program **Module4.py** from the class WISE site and open it in Spyder. This program shows you how to open an image file and read it into a 2D *numpy* array of pixel values using PIL (Python Imaging Library). The program also demonstrates how to display the image in false colors, with high pixel values being displayed in red and low pixel values in blue. Finally, the program shows how to plot a "slice" through the image at a fixed y value (note that the image is plotted so that the first index designates the y value and the second index the x value. Also note that the (0,0) value is in the upper left hand corner of the image.) Make sure you understand this program well before you continue.

Open your images of the "stars" with without the telescope using the Python program and examine the plots. You may have to adjust the row number plotted so that the "slice" goes through roughly the middle of the peak. The camera software also allows you to make histograms of the pixel values and to see vertical and horizontal profiles of the video feed.

You probably noticed that the peaks corresponding to the stars in the images look like 2D Gaussian functions, i.e. a hump with a bell curve radial profile . Thus, we will now attempt to fit some of the stars with a 2D Gaussian using Python program imported from *astropy*, a set of programs useful for working with astronomical images. For more information, go to the webpage `http://docs.astropy.org/en/stable/modeling/`. You will need to do a 2D fit of your image to the model *models.Gaussian2D*. You can also check out the webpage `http://docs.astropy.org/en/stable/api/astropy.modeling.functional\_models.Gaussian2D.html` for more help. Summarize what you've learned in the box below.

The file **Module4.py** also shows you an example of how to do the 2D fitting in Python. First, with the line starting with 'g_init=', you need to provide guesses for the parameters of the fit: the amplitude, the center of a peak ('x_mean' and 'y_mean'), and the width of the peak in the x and y directions ('x_stddev' and 'y_stddev'). You should be able to determine good guesses for these parameters for a few of the stars by examining your plots. In order to make more accurate guesses, you probably want to look at a subarray of the image array. You can achieve this by "slicing" the array. Fr example, `sub = imarray[100:200,300:400]` would give you a part of the array consisting of pixels with values between 100 and 199 of the first index and between 300 and 399 of the second index. Note that `imshow` plots the first index on the y axis and the second index as the x axis.Your guesses don't have to be perfect, but they should be realistic. Record your guesses in the box below.

The line starting with 'g=' determines the best-fit model and sets it equal to the function called 'g'. You can read the fit parameters as 'attributes' of the model g (i.e. apply the fit parameters to 'g'). For example, the best fit amplitude is given by 'g.amplitude' and the best fit 'x_mean' is given by 'g.x_mean'. If you type the command 'print(g)' it will give you all of the best fit parameters of the model for the same stars for which you recorded guesses. Record them in the box on the next page and compare them to your estimates from the previous box.

You can also use 'g' as a function to plot the best fit model, as shown in **Module4.py**. In the box below, compare your original data to the fitted 2D Gaussian by discussing their similarities and differences. Also add a printout of your data with the fit to this manual.
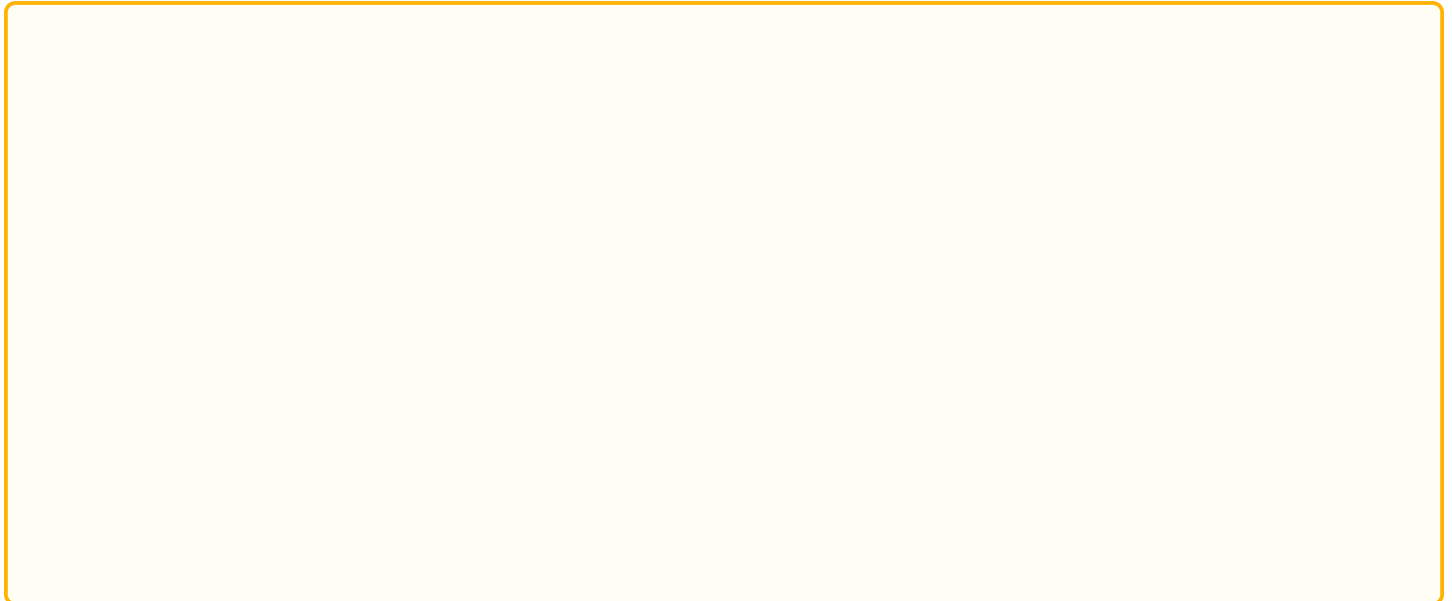
We typically think of a lens as a device that refracts light, but it also can be thought of as an aperture through which light passes, and thus necessarily diffracts. You can think of this diffraction as introducing spread into the rays we normally draw in a lens diagram, so that a single ray will become "thick". Thus a lens cannot actually focus parallel rays to an infinitely small point, but will instead focus light into a "blob" whose intensity falls off with distance from the center. The profile of this "blob" is called the point spread function. This is what you just observed in the last exercise. In fact, aberration and diffraction both contribute to the fact that a point source does not show up as a point in an image, but rather as a "blob" with a finite radius. If the sources are really points, then the point spread function is entirely due to the optics and should be roughly the same for all the peaks (they can, however, have different amplitude, which corresponds to their brightness). In the space below, discuss the results of your fits of the stars in the different images. Do the stars in an image all have the same point spread function? How does the point spread function change between the images with and without the telescope? If so, why?

Finally, is it possible that two point sources can be close enough together that they appear as a single point source, in other words, that you can't resolve the two point sources? Examine the closest together point sources in both images and discuss your conclusions in the space below. What do you think determines whether two point sources can be resolved?

How do you think the focus of an optical system affects the point spread function? Go back to your system and move the camera a small distance to take the image slightly out of focus. Fit some of the stars as before. In the box below, discuss whether the point spread function changed as you expected.

Let's connect this to images that we are more used to seeing, like the ones that we take with our phones. We can think of any object as being made up of a collection of small pieces that act like point sources. In the box below, discuss why images look blurry if we blow them up too large. Why do images look blurry if they are out of focus?

And that's it! You made it successfully through the first module and are now qualified to perform the more advanced modules. Please leave us any comments, suggestions, or concerns in the box below, so that we can optimize this module for future student generations. Thanks!