

The invention of the telescope in 1609 changed our “world” view dramatically. The size of the observational universe increased while detailed observations of nearby objects changed the focus of astronomy from a mathematical science to a physical science. Among the problems facing seventeenth- and eighteenth-century scientists were the questions of how and why lenses focused or scattered light and the nature of light itself. In this exercise, you will learn about some of the properties of lenses and mirrors and see them in practice in the telescopes we’re using in class. You will also learn to recognize and understand the paths of light through simple optical systems you encounter every day.

Objectives:

- Understand reflection and refraction
- Learn the basic properties of lenses, mirrors, and optical systems
- Identification and analysis of basic optical systems
- Distinguish between types of telescopes
- Learn how to use our telescopes and interpret what you see

Equipment:

- 8-inch equatorial-mount telescope, e.g. C-8
- 8- and 10-inch Dobsonian telescopes
- stopwatch
- planisphere and red flashlight
- binoculars
- at least one of the following: 16-inch reflector atop RLM or 5-inch telescope, e.g. C-5

Set-Up:

The first part of this exercise should be done inside, where you can carefully review the properties of lenses, mirrors, and the different types of telescopes. Your instructor may want you to do the second part of the lab first and complete the other part at home. The second part of the lab is to be conducted either indoors or outside, at your instructor’s discretion. The portable telescopes may or may not be presented to you disassembled as they would be for transport so that you may learn how to assemble them for observing.

I. REFRACTION AND REFLECTION

You are already familiar with the dual wave/particle nature of light, dispersion, and diffraction. Here, we review two more properties of light that you should already be reasonably comfortable with: refraction and reflection.

When light passes from one medium into another, such as from air into glass, it is bent or *refracted*. This is because different media have different optical properties. We can characterize these properties via an *index of refraction*, n , which is an indicator of how severely the light will be bent as it passes through that particular substance. It is also an indicator of how fast light will travel through the medium. You have learned that the speed of light is $c = 300,000$ km/s. But it is very important to realize that this is the speed of light *in a vacuum*, that is, through virtually empty space with no air. Light travels at different speeds, v , through different materials as

$$n = \frac{c}{v} \qquad \text{Equation 1}$$

characterized by Equation 1. The index of refraction for a vacuum is, by definition, exactly one. Air has an index of refraction of very nearly one (1.000293); this is why we can use the speed of light in a vacuum for calculations in the laboratory and not worry about a correction for the speed of light in air. This is not the case, however for most other substances. Take glass, for example. Obviously, there are many different types of glass, but a typical index of refraction is around 1.5. Thus, light travels at a significantly different speed through that kind of glass.

Fermat's principle states that light will always take the shortest path between two points. This is why we see things like the example in Figure 1. The straw is not really bent at the interface between the liquid and air, but we see it like that because the index of refraction of the liquid is much higher than that of air. The light we see as the straw through the liquid is bent such that it travels the shortest possible distance in order to leave that medium. The outline of where the straw really is in the liquid is clearly a longer path through it than what we actually see.

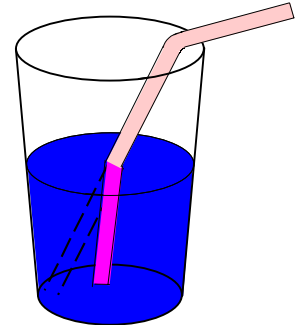
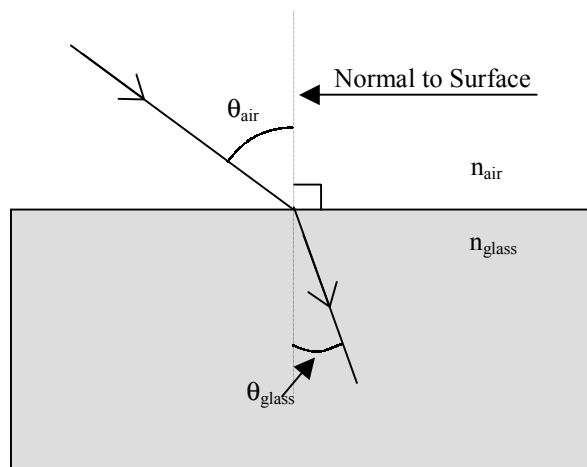


Figure 1. Refraction.

Snell's Law of Refraction (Equation 2) says that if we know the angle that the light enters a new medium, and the indices of refraction of the two media, we can calculate the angle that the light will be bent as it passes into the liquid. This is illustrated in Figure 2. The angles are



$$n_1 \sin \theta_1 = n_2 \sin \theta_2 \quad \text{Equation 2}$$

measured from the normal (perpendicular) to the surface. Thus we can determine the path that light takes from its point of origin to its endpoint.

A similar law exists for the reflection of light from a surface such as a mirror, but it is much simpler. The Law of Reflection simply states that the angle of incidence, α , is equal to the angle of reflection, β , as measured from the normal to the surface. This is illustrated in Figure 3. In panel (a) we see simple reflection off a "first surface" mirror, meaning the first surface the light hits is the reflective surface. In panel (b) we see reflection off a "second surface" mirror. Here, the

Figure 2. Snell's Law of Refraction.

light passes through the first surface of the mirror and is refracted before it bounces off the back surface, which is the reflective surface, and is refracted again as it exits the material. The angles with the "1" subscripts are equal and the ones with the "2" subscripts are equal.

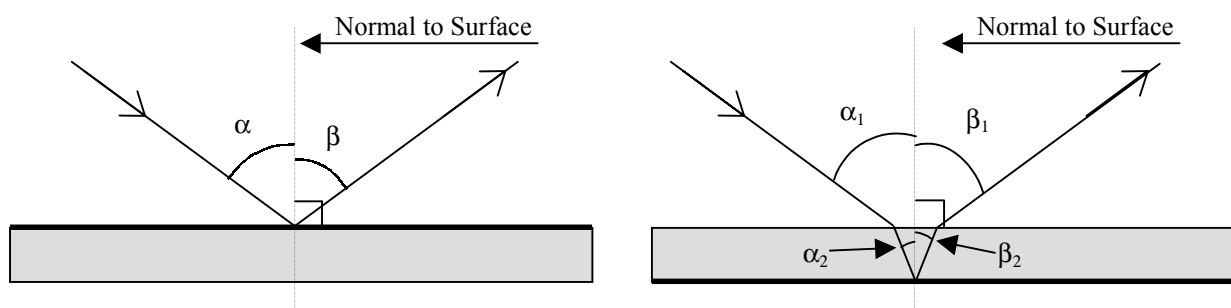


Figure 3. The Law of Reflection. (a) A first surface mirror. (b) A second surface mirror.

ANSWER THE FOLLOWING QUESTIONS IN YOUR LAB NOTEBOOK.

1. If the index of refraction of olive oil is 1.45, what is the speed of light through the oil?
2. Imagine a bottle of oil and vinegar salad dressing that has separated with the oil on the bottom. Sketch the geometry of the layers inside the bottle and include the air. If you know $n_{oil} = 1.45$, $n_{vinegar} = 1.3$, and that light enters the vinegar at an angle of 29° from the normal, at what angle will the light enter the oil? (Hint: draw it on your diagram.)
3. I insert a first surface mirror into a light path at an angle of 54 degrees. At what angle will the light reflect off the mirror (as measured from the surface normal)?

II. LENSES AND MIRRORS

There are two basic types of lenses: *convex* or converging and *concave* or diverging. A convex lens takes parallel light rays and focuses them to a point, as in Figure 4(a), while a concave lens will take the same rays and spread them out like in Figure 4(b). When the light source is an

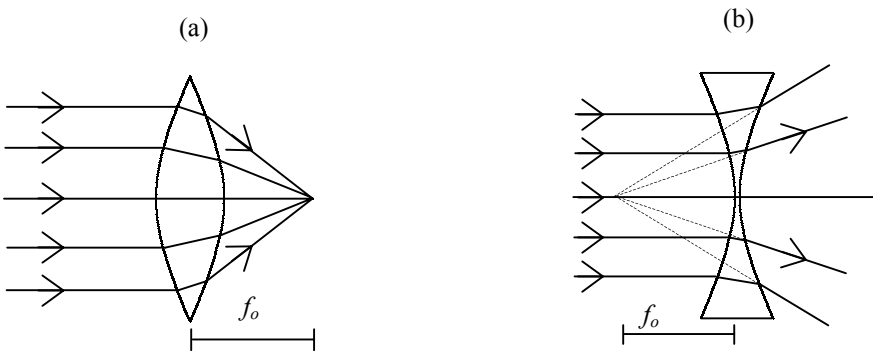


Figure 4. Converging (a) and diverging (b) lenses.

infinite distance away from the lens, light rays move in parallel lines coming into the lens and are focused at a characteristic distance from the lens called the *focal length*, f_o . The distance between the object (d_{obj}) and lens and the image (d_{img}) and lens are related to the focal length by Equation 3,

with the geometry as shown in Figure 5. Note that the image in Figure 5 is inverted. Astronomers must keep this particular effect in mind as they analyze their data. The image received at the telescope will be inverted relative to the actual orientation of the objects (Figure 6).

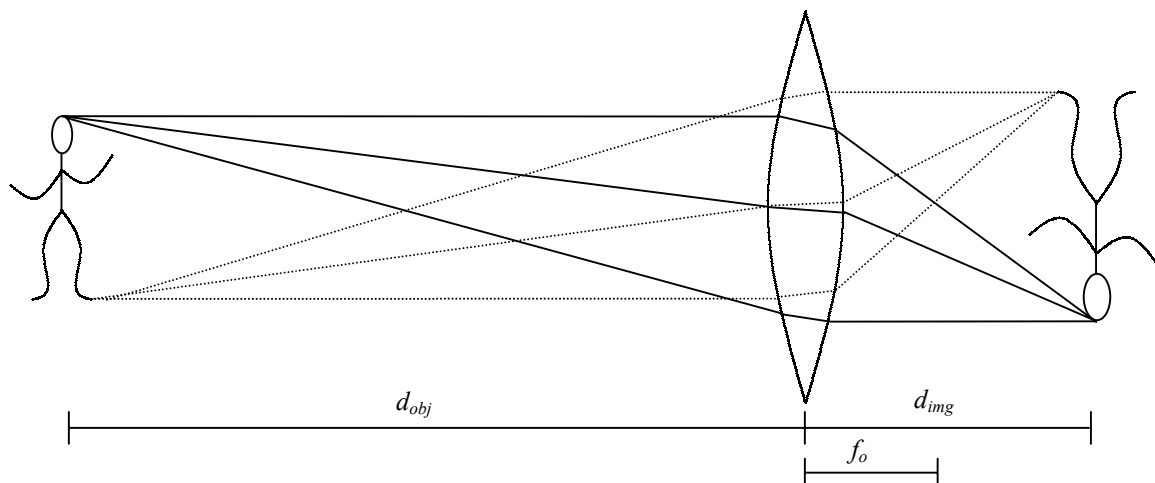


Figure 5. Inverted image produced by ray-tracing.

$$\frac{1}{f_o} = \frac{1}{d_{obj}} + \frac{1}{d_{img}}$$

Equation 3

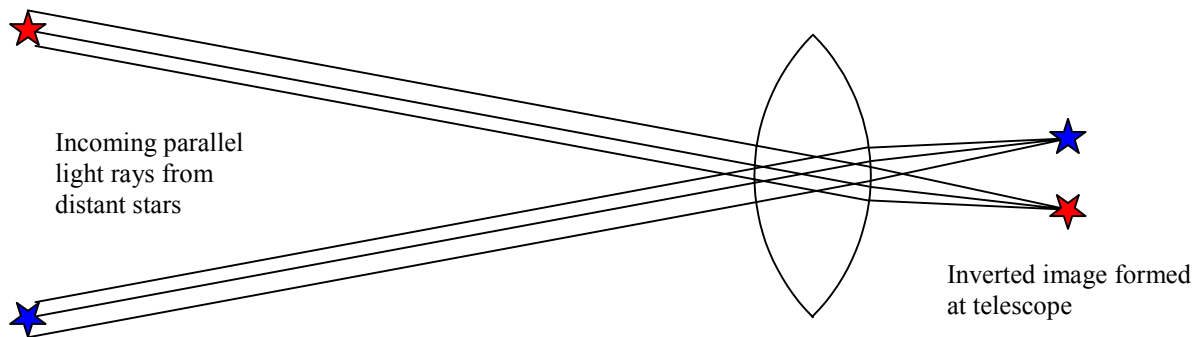


Figure 6. Inverted image formed at telescope.

Using simple similar triangles, you can determine the relationship between the image size (h_{img}) and object size (h_{obj}), and image and object distance (d_{img} , d_{obj}). This relationship is shown in Equation 4 and the geometry illustrated in Figure 7.

$$\frac{d_{img}}{d_{obj}} = \frac{h_{img}}{h_{obj}} = \text{Magnification}$$

Equation 4

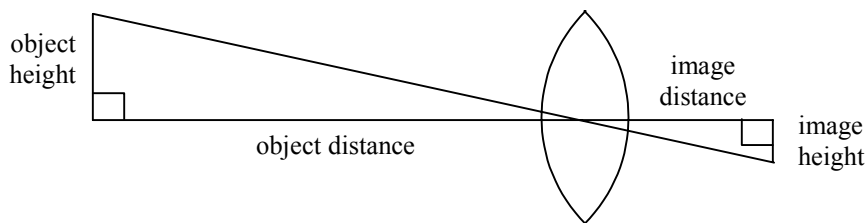


Figure 7. Magnification.

ANSWER THE FOLLOWING QUESTIONS IN YOUR LAB NOTEBOOK.

4. What kind of lens would you use to disperse light?
5. I have a convex lens with a focal length of 25 mm, a screen, and an object to sight. If I place the lens three focal lengths away from the object, where should I place the screen so that I may see the focused image? Sketch the geometry and indicate relevant distances.
6. What is the magnification of the object? Is the image larger or smaller than the actual object?
7. An optical system is a combination of lenses and/or mirrors that work together for a specific purpose. Name at least three different optical systems you encounter in everyday life and give the purpose of each. Sketch the optical path for one (I'm not looking for exact distances and artwork here; simply put the principal components where you think they are and indicate how the light moves through the system).

III. TELESCOPES

There are two general types of telescopes: reflecting and refracting. A refracting telescope uses two convex lenses to collect the light and focus it down to an image. Reflecting telescopes gather the light by means of a primary mirror, which reflects it to either a secondary mirror or to a lens that focuses the image for observing. Reflecting telescopes are the most commonly constructed systems today, since mirrors are easier to support rigidly against flexing than a lens, which can be held only around its perimeter since the light must pass through it. Also, mirrors focus all colors of light at the same point. Lenses do not bend and focus all colors of light the same way; this defect – called *chromatic aberration* – is one of the main disadvantages of optical systems using lenses.

Figure 8 gives the basic design of a refracting telescope. The long-focus objective lens “gathers” the light from the object and focuses it down while the short-focus eyepiece lens allows you to examine the image formed by the objective lens.

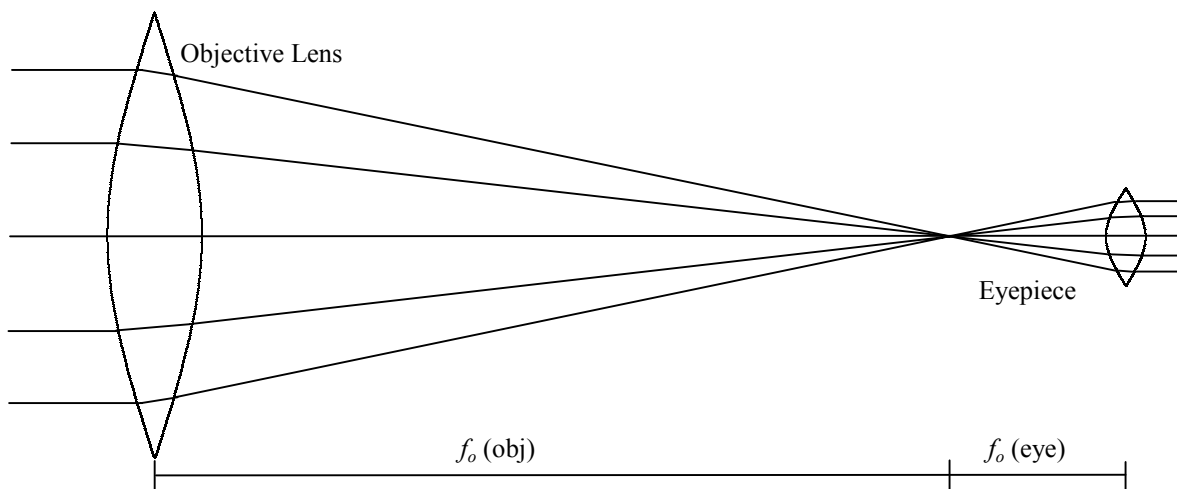


Figure 8. A refracting telescope.

In a reflecting telescope, the primary mirror acts as the objective, “collecting” the light and sending it to another optical component, usually either a lens or another mirror. Notice in Figure 9 that the mirror is not flat, but curved. They can be spherical, parabolic, or hyperbolic in curvature. Spherical and parabolic mirrors are more commonly used than hyperbolic surfaces.

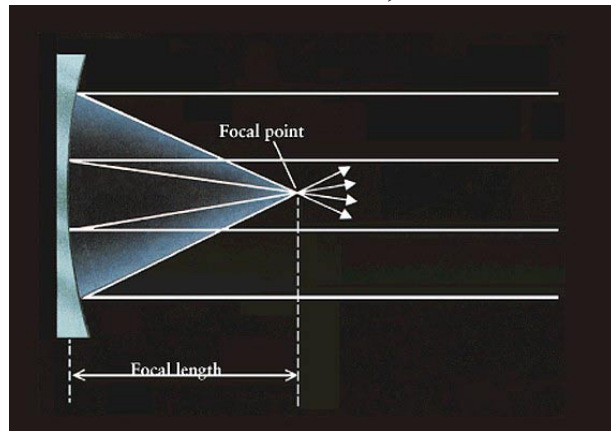


Figure 9. Curved mirror showing focal point.

A curved mirror has a focal length, just as a lens because it either focuses or disperses light depending on whether it is concave or convex. Figure 9 shows a converging parabolic mirror and its focal length. In Figure 10 are some examples of reflecting telescope designs and the paths of light through them. Design (a) is a Newtonian reflector. In this design, a curved primary mirror focuses the light but just before it reaches the focus, a flat first surface (secondary) mirror is inserted in the optical

path to “pick off” the light and send it out a hole in the side of the telescope tube. Figure 11 shows a Newtonian design with the eyepiece lens in place. Design (b) is a prime focus reflector, named so because the image is formed at the focal point of only a primary mirror. Design (c) of Figure 10 is a Cassegrain focus reflector. In a Cassegrain style telescope, the secondary mirror is curved and helps to focus the light down to a point just outside the base of the telescope tube, through a hole in the primary mirror. Design (d) is a coudé focus reflector. Here, a tertiary mirror (flat) is used to pick off the light from the secondary (curved) mirror and send it to another instrument, usually in a different room entirely, such as a spectrograph room. Most large reflectors are designed so that they may be used at different foci, depending on the instrument the astronomer needs and how it is designed to be used.

The two most important properties of a telescope are its light-gathering power and its resolution. Faint objects cannot be seen with the naked eye because the pupil of the eye is limited in its ability to enlarge and, therefore, has limited light-gathering ability. The large lenses and mirrors in telescopes gather larger quantities of light. The amount of light collected depends on the area of the objective; remember that the area is proportional to the size of the objective, or $A \propto r^2$, where r is the radius of the objective. So, if you have two telescopes with the same optical properties, but Telescope A has three times the diameter of Telescope B, then Telescope A has nine times the light-gathering power of Telescope B.

Another important capability of a telescope is its ability to resolve detail. This depends on the diameter of the objective and the quality of both the eyepiece and the objective. When sources of light are close together, they may appear to blend into one; stars which appear as one to the naked eye may actually be double or triple stars. The resolution of a telescope is the ability to distinguish objects that are too close for the eye to separate. The resolution of a telescope in

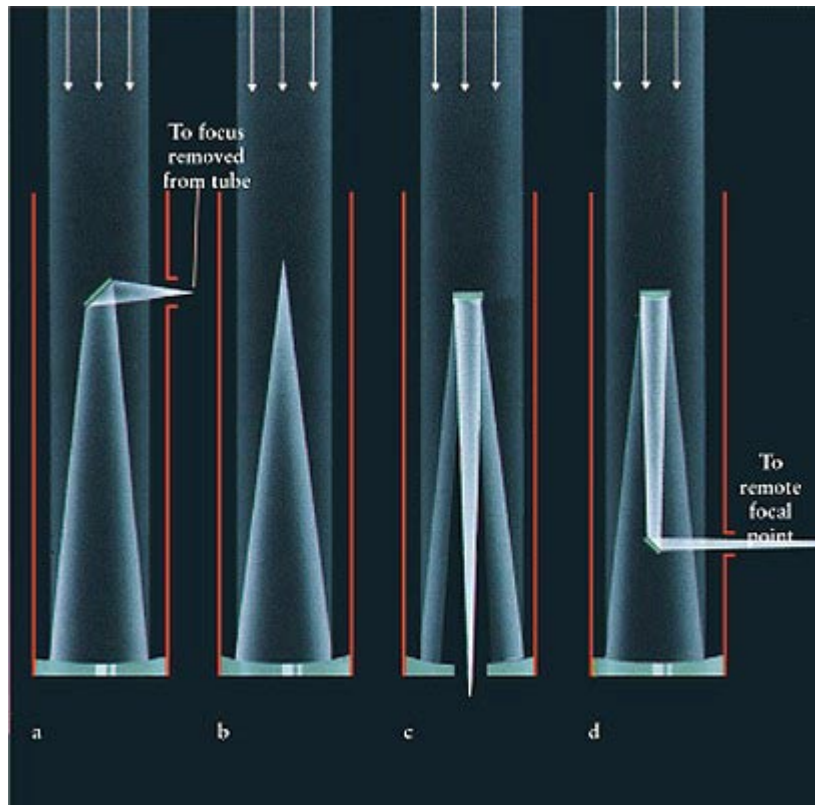


Figure 10. Basic reflecting telescope designs.

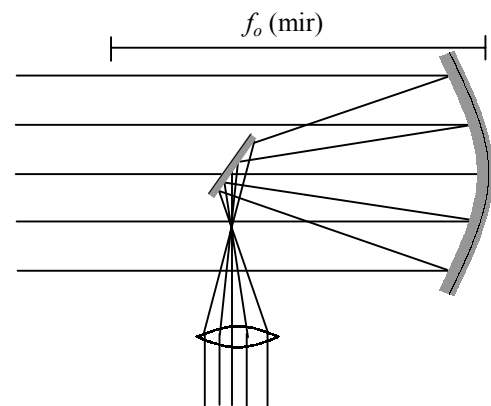


Figure 11. A typical Newtonian reflecting telescope with eyepiece (lens).

arcseconds is given by Equation 5, where λ is the wavelength and D is the diameter of the objective. This gives the minimum angular separation that can be observed with that system.

$$\Delta\theta = 2.5 \times 10^5 \frac{\lambda}{D} \quad \text{Equation 5}$$

Another important quantity to be familiar with when working with telescopes is the “ f -number” or “ f -ratio.” This is the focal length of the objective divided by the aperture diameter (objective) as in Equation 6.

$$f / \text{ratio} = \frac{f_{\text{obj}}}{D} \quad \text{Equation 6}$$

One of the most overemphasized capabilities of a telescope is its magnification. We have already discussed one way to determine the magnification of an optical system. However, this isn't always the easiest (or most practical) method. More often, the magnification of an astronomical telescope is given by dividing the focal length of the objective by that of the eyepiece (Equation 7). The focal length of a telescope (objective) is not easily changed. In fact,

$$M = \frac{f_{\text{obj}}}{f_{\text{eye}}} \quad \text{Equation 7}$$

some cannot be changed at all. Others can be changed to accommodate different instruments at the focal planes but this is a nontrivial engineering task that requires skilled engineers and technicians to accomplish. If you are viewing through the telescope with eyepieces, it is much easier to alter the magnification (and field of view) simply by changing the eyepieces. They come in many different focal lengths for just these reasons. The focal lengths are usually stamped on or etched into the side of the eyepiece for ease of identification.

One final important property of a telescope is its *field of view*, FOV. This is the angular size of the piece of the sky seen through the telescope. Since the FOV is an angle, it is measured in degrees, arcminutes, or arcseconds. For a given telescope, the greater the eyepiece focal length, the greater the FOV. If you choose an eyepiece with double the focal length, you also double the FOV.

ANSWER THE FOLLOWING QUESTIONS IN YOUR LAB NOTEBOOK.

8. Give an example of chromatic aberration you have learned of in this course before this exercise. (Hint: think spectroscopy lab.)
9. Does a reflecting telescope have an objective? If so, what is it?
10. How much more light can Telescope X gather than Telescope Y if Y has half the diameter of X?
11. What is the angular resolution of our 16-inch telescope in the optical regime (take the median optical wavelength to be 5500 \AA)?
12. If you purchase a 24-cm refractor and the box says it's an $f/3$ telescope, what is the focal length of the objective? Is this a lens or mirror?
13. Name the basic designs of the telescopes in Figure 12.

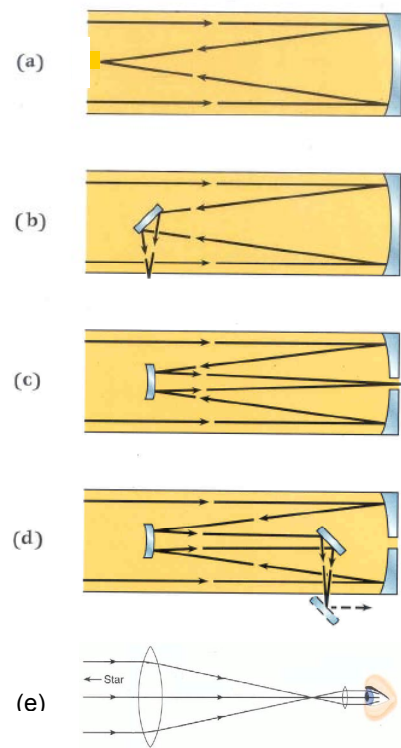


Figure 12. Telescope schematics.

IV. USING THE TELESCOPES

Please remember that telescopes are precision instruments; be careful using them. Ask your instructor for help when you are in doubt about what to do.

You should have two additional handouts: one on the operation of the 16-inch reflector atop RLM and another on the parts and operation of an equatorial-mounted telescope, specifically an 8-inch Celestron (commonly referred to as a “C-8”). You should look over these handouts and be familiar with the parts of the telescopes. Your instructor will briefly orient you and, if the portable telescopes are disassembled, will show you how to put them together so you can use them to observe. You may also be using a smaller version of the C-8 which has a 5-inch primary. We commonly refer to this telescope as a “C-5” despite the fact that you may be using the one that isn’t made by Celestron. It has all the same parts and works in the same way as the C-8, with the only difference being the smaller mirror.

One type of telescope you will be using that is not covered in the separate handouts is a Dobsonian-mount telescope. This is a Newtonian reflector that is very popular for its simple mount and ease of use, especially for novices and children. The Dobsonian telescopes you will use are already assembled and break down into only two pieces for transport: the base and the tube itself. The tube simply lifts in and out of its saddle, requiring no tools (unlike the Celestron).

The Dobsonians are designed specifically for amateur viewing and so do not have setting circles like you will find on most other larger telescopes. Ours do not have clock drives or pointing computers and software, so they are mainly for pointing at random objects in the sky and viewing the pretty picture. Once you become an experienced observer, you will discover you can readily find more and more objects, things that you once found difficult to observe.

The base of a Dobsonian swivels and the tube pivots in its saddle, so to move it, you need only rotate the base and push the tube up or down until you are pointed in the right direction. Each telescope has a wide-field finderscope attached to its side which you can use to sight the general field of view. Once you have done this, you can look through the telescope’s eyepieces to zoom in on the object in question.

One other important piece of information to know: the f /ratios of the telescopes you’ll be using. The 16-inch is $f/11.6$, and both the C-8 and C-5 are $f/9.8$.

A. EXERCISE 1: DETERMINING THE FIELD OF VIEW

If you cannot observe outside, your instructor may opt to omit this section or do the indoor alternative at the end of the section. Ask him/her which you are to do.

You will use a stopwatch to measure how long it takes for a star near the celestial equator to pass across the region viewed through the eyepiece when the telescope drive motor (if that telescope has one) is turned off. Then, convert that time into an angle. This will be the diameter of the field of view.

If this exercise is conducted outside, everyone may not be using a telescope with a drive motor, nor will everyone use the same size aperture. To speed up the activity, you should use all the available telescopes your instructor indicates, i.e. the 8- and 10-inch Dobsonians as well as the C-8 and C-5. Nor will everyone will be using the same eyepieces. Thus, it is *extremely important* to record what instruments and eyepieces you used to make your measurements. Also, the telescope must be aligned properly. If it is,

the star will remain in the field of view while the clock drive is on. Because you want the star to traverse the diameter of the field, it is important that the declination remain constant.

Choose a reasonably bright star near the celestial equator. Do not forget to record what star this is! If your telescope has a clock drive, unplug it and watch which direction the star appears to drift across the FOV. Compare this direction to how the stars move through the sky when you look at it with your eyes. Is the motion in the same direction? Then move the telescope, placing the star *just outside* the FOV on one edge (you should know which one!). This will cause the star to appear in the FOV when the drive is off. When the star reappears in the eyepiece, start the stopwatch and record the starting time. When it passes out of view on the opposite side, stop the stopwatch and record the ending time. Calculate the transit time of the star across the FOV. Enter these values in a table similar to that in Table 1. Make more than one measurement and compute the average.

Eyepiece	Transit Times								FOV
	Start Stop	Transit Time	Start Stop	Transit Time	Start Stop	Transit Time	Mean	Std Dev	

Table 1. Sample data table.

Do not forget to record important observing information: date, time, conditions, instruments/eyepieces used, etc.

Convert the transit time into an angular distance traveled using what you know about the rotation of the Earth. Your answer is the size of the FOV. Repeat these observations using a second eyepiece with a different focal length.

Indoor Alternative: THIS OPTION CAN ONLY BE DONE USING A TELESCOPE WITH A CLOCK DRIVE. Your instructor will set up a light source close to the direction of the celestial equator (close to due east or west) which you can focus the telescope on. Turning the drive on will simulate the motion of the earth and cause the light to pass in and out of the FOV. Complete the exercise using this configuration.

ANSWER THE FOLLOWING QUESTIONS IN YOUR LAB NOTEBOOK.

- 14. Recall your comparison of the direction the stars drifted across the FOV to how they move through the sky when you look at them with your eyes. Explain the reasons for any differences or similarities.**
- 15. Why did you make more than one measurement per set-up and take an average? Be specific!**
- 16. Is the field of view greater with a shorter or longer focal length eyepiece?**
- 17. Describe why the field of view changed when you used different eyepieces.**
- 18. Would the Moon be completely visible in either of the eyepieces you used? How do you know?**
- 19. Your transit time was for a star near the celestial equator. How would the transit time change for a star at a higher declination (closer to the celestial pole)?**

B. EXERCISE 2: MAGNIFICATION AND LIGHT-GATHERING POWER

If you cannot observe outside, your instructor may opt to omit this section or do the indoor alternative at the end of the section. Ask him/her which you are to do.

You will be observing M42, the Orion Nebula, through an 8-inch telescope and either the 16-inch or 5-inch telescope (your instructor will tell you which), looking for changes in magnification and intensity.

First, to analyze light-gathering power, look through both telescopes you are supposed to use for this part (either 8-inch and 5-inch or 8-inch and 16-inch), but do not record anything in your notebook. Pay attention to relative sizes, positions, colors, intensities, structures, and anything else you can observe. [*Note that the “other” telescope you use – either the C-5 or 16-inch – should have the same focal length eyepiece as one of the two in the 8-inch scopes.*]

Now, look through the two telescopes again, this time taking your time and making sketches and notes in your notebook. You will probably need to look more than once. Record as much detail as possible; this will be important in answering questions later. Do not forget to record the vital “standard” observing information!

Next, to analyze different magnifications, go back to the two 8-inch telescopes. They have different eyepieces, thus different magnifications. Look through these as much as necessary and make sketches and notes to record what you observe.

ANSWER THE FOLLOWING QUESTIONS IN YOUR LAB NOTEBOOK.

- 20. Which telescopes did you use for the light-gathering part? Through which one could you see more detail? Is this what you expect? Justify your answer.**
- 21. You know that changing the focal length of the eyepiece on a telescope changes the magnification. What else does it change?**
- 22. How does changing the focal length of the eyepiece (but NOT the telescope) change the magnification?**
- 23. How does changing the focal length of the telescope (but NOT the eyepiece) change the magnification?**
- 24. Can you see fainter objects with higher or lower magnification (or does it matter)?**
- 25. Calculate the magnification for each of the set-ups you used in this exercise.**

Indoor Alternative: You will be given two images of NGC 7635 (the Bubble Nebula) taken with different telescopes. Each telescope had a different aperture and because of the different focal lengths, had a different scale. Answer the next 4 questions only if you do the indoor alternative.

ANSWER THE FOLLOWING QUESTIONS IN YOUR LAB NOTEBOOK.

- (a) Which of the telescopes gave a higher apparent magnification?**
- (b) Which one gave the widest angle shot?**
- (c) Which telescope produced a deeper image (that is, which allowed you to see the faintest structure in the nebula)?**
- (d) Which telescope would you use to take images of a large angular diameter nebula? A distant galaxy? Explain why.**

C. EXERCISE 3: RESOLVING POWER

If you cannot observe outside, your instructor may opt to omit this section or do the indoor alternative at the end of the section. Ask him/her which you are to do.

You will observe θ Taurus with your eyes, binoculars, and one other telescope. Be sure to make careful sketches and notes of what you see in each case.

First, observe θ Taurus with your eyes. Use your planisphere to locate it (your instructor may help you or give you a finder's chart). Record the brightness, size, and color of the star and any other details you note. Relative comparisons to other nearby stars may help.

Next, look at the star through both binoculars and a telescope. Again, record your findings. Do you note anything special?

Do not forget to record the "standard" important observing information on weather, instruments, date, etc.

ANSWER THE FOLLOWING QUESTIONS IN YOUR LAB NOTEBOOK.

26. If the separation of the stars is $5'36''$ which of these methods (eyes, binoculars, telescope) should have resolved the stars? Did they? If not, why? (Take the diameter of a dark-adapted pupil to be 5 mm.)

Indoor Alternative: Your instructor will set up a light source with stars etched into a mask in front of it. You will estimate using your naked eye from the opposite end of the hallway how many stars are there. Move closer to the "stars," about half the distance, and make the same estimates. Next, return to your original position and use binoculars to estimate the number of stars. Get a lab partner to measure the diameter of your pupil and also measure the diameter of the lens in the binoculars. Measure the distances from the "stars" to your two observing positions. Record all the information in an organized format in your lab notebook. Answer the next 3 questions only if you do the indoor alternative.

ANSWER THE FOLLOWING QUESTIONS IN YOUR LAB NOTEBOOK.

- (a) What was the limiting resolution of your eyes? (Use a median optical wavelength of 5500 \AA .)**
- (b) What is the limiting resolution of your binoculars?**
- (c) How much better are the binoculars than your eyes at resolving things?**

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