Chapter 5: Telescopes
The Tools of Astronomy

Outline

Summary

Chapter 5 begins with a discussion of optical telescopes. The two types, reflectors and refractors, are diagrammed and described, and the advantages of reflectors over refractors are discussed. Next, the importance of telescope size in improving light-gathering power and resolving power is explained. Students often confuse the purposes of microscopes with telescopes; both permit entry into a universe unseen by the eye alone. They must be constantly reminded that the microscope's function is magnification whereas the telescope's primary function is to gather as much light as possible. With regard to telescopes and telescope design "bigger is better."

Telescopes that are operated within the Earth's atmosphere are at the mercy of various possible atmospheric effects such as "seeing," reddening and extinction, and light pollution. These different types of adverse atmospheric effects are discussed as well as are the technological advancements available to mitigate those effects. The chapter ends with a discussion of radio astronomy as well as astronomy at IR, UV, and high-energy wavelengths.

Major Concepts

- Optical telescopes
  - Reflectors and refractors
  - Reflecting telescope designs
  - Advantages of reflectors
- Telescope size
  - Light-gathering power
  - Resolving power
- Seeing
- Detectors
- New telescope designs
  - Active and Adaptive Optics
- Radio and Radio Interferometry
- Space-Based Astronomy
  - Infrared
  - Ultraviolet
  - High-energy: X-ray and gamma ray

Teaching Suggestions and Demonstrations

Having the opportunity to observe with a telescope, even a small one, is probably the best way to engender student interest in telescopes. If possible, arrange some observing nights for your students. Seeing Saturn's rings or the Moon's craters for the first time through a telescope never fails to make an impression!

Section 5.1

You can begin your discussion of telescopes by bringing in several **lenses and mirrors** and showing students how these form images. One important idea is that a converging lens causes parallel light rays to focus at a point. ➲ **DEMO** Use a large demonstration convex lens to show how light is focused and images are produced. A plain light bulb can serve as the object. Mark a large black X on the bulb to aid students in seeing the image. Also try using a brightly colored bulb, such as green, to emphasize that optics are not "black and white" (a common misconception), but color. Image the object onto a screen. Vary the object distance to demonstrate how the image distance depends on the object distance. Show how, as the object distance gets longer, the image distance varies less and less and is eventually at the focal length for very distant objects.

A common student misconception is that larger diameter lenses produce larger magnifications. Show your students that two lenses with equal focal lengths produce images that are magnified the same amount, but that the image from the larger diameter lens is brighter and shows more detail, because the lens collects more light.

If you have an opportunity to do any night viewing, show a bright star through a cheap refractor; there is no better demonstration of **chromatic aberration** than this, it is so easy to see. Otherwise, begin discussing chromatic aberration by starting with the concept of focal point/plane. This can be shown with a simple diagram on the board or by showing Figure 5.5. Explain that a camera lens focuses the image at the focal plane, ask the students if they were designing a camera, where would they place the film? Surprisingly, the answers will be anywhere from "in front of the lens" to "behind the focal plane." Naturally, the film should be placed at the focal plane. Now, introduce chromatic aberration, where the focal plane is located at a different distance from the lens for each color. Colored chalk or markers are good for this if you are doing a diagram on the board. Draw a few colors with their respective rays converging at different points. Now repeat the previous questions "where do you place the film?" If one color is in focus, another will be out of focus. Discuss corrective methods for this such as thin coatings on the lens surfaces. These are generally expensive, which is one reason why "good" cameras are more expensive. Also, remind the students that mirrors do not suffer from this due to the fact that all colors reflect at similar angles while they are refracted at different angles.

Pass around a large **concave mirror** and have students look into it while holding it at varying distances. For instance, when you hold the mirror very close you will see a magnified, upright image of your face. This corresponds to the virtual image formed when the object is inside the focal length. With the mirror at a greater distance, the image is real and inverted.

➲ **DEMO** To create a makeshift **telescope**, stick two lenses on a meter stick with clay and sight through them. If possible, students can experiment with different lenses and different distances between them to investigate the types of images that are created. If you have access to an astronomical telescope, bring it to class and talk about its various parts. You can point out the primary mirror or lens, the eyepiece, and the mount. Show students how the telescope is positioned, and point out that once an astronomical object is found in the field of view of a telescope it won't stay there, unless the telescope has a tracking system. Although students are all well aware of the rotation of Earth, many are still amazed by how quickly stars move out of the field of view of a telescope. Discuss equatorial and alt-azimuth mount designs and the advantages of each. ➲ **DEMO** Before class, try to setup a telescope with either a clock-drive or a computerized goto system. Have it set to track an object such as the Sun or Moon. Have the students note the general position of the aim point, maybe even make a mark on the board or wall at which the telescope appears to be aimed. Have the students predict how much the telescope aim point will move by the end of class. At the end of class have the students note the new aim point. Remind them that, in reality, the telescope mount has simply adjusted for the Earth's rotation during that time interval.

➲ **DEMO** Bring out the concave mirror again and have students imagine designing a telescope around it. Trace the light path from an imaginary or real source and position yourself to observe at the prime focus. Students will notice that you are then blocking the incoming light! Ask them to think of ways to overcome this problem and show Figure 5.6, which illustrates different **reflecting telescope** designs. As pointed out in the text, all large modern telescopes are reflectors. Challenge your students to come up with reasons for this fact before you go over the excellent list given in this section.

➲ **DEMO** Many departments have old, unused refractors and Newtonian reflectors. Take one of each into class and disassemble them in front of the class. For the refractor, first remove the eyepiece and the focusing rack and pinion and explain the purpose of the eyepiece. (It is only necessary for visual observations. The telescope works fine without one.) Next, remove the primary lens and show how it looks just like the demonstration lenses used earlier. Next, turn the tube vertically and drop something through it like a pencil. The tube is empty! The lens is really the telescope and the tube just helps support it and keeps the eyepiece aligned with the lens. The tube can also keep stray light from entering the telescope. Demonstrate the Newtonian in a similar fashion. Emphasize the basic simplicity of telescopes and the simplicity of their purpose: to collect large amounts of radiation (i.e., light, infrared, radio, etc.) and concentrate (focus) it into a usable image. That's about it!

Figure 5.4 should be used to establish the basic differences between a reflector and refractor. Then Figure 5.6 can be used to distinguish between the different foci for reflectors. Discuss the advantages and disadvantages of each focus with respect to the size of the telescope. Prime focus is not useful for small telescopes because too much light will be blocked. Newtonian is very good for small telescopes because the focus is near the top where it is easy to view. But this focus is difficult for large telescopes because the viewer or instrument will be very high off the ground and in an awkward position. Cassegrain focus is very useful for all sizes of telescopes. Coudé focus is really only useful when the light must be analyzed by a large, permanently mounted instrument.

Satellite dishes are commonly seen on campuses and at homes. Have students look at one and note the similarities in design to optical reflectors. Are they Newtonian, Cassegrain, or prime focus? Usually they are prime focus. If you have access to a small dish, bring it in to show the class.

Section 5.2

New **detector and telescope designs** have been motivated by the desire to obtain better images, to view ever fainter objects, and to overcome the limitations of seeing. Look at the history of telescope design as a progression of improvements, many of which have been ingenious. Discuss

CCDs, active optics, and adaptive optics, and ask students what limitations these new technologies are helping to overcome and how.

➲ **DEMO** If you have one available, show a photographic plate to your students; they will be unfamiliar with plates (as are many astronomers now). Set it on an overhead projector so that the images (which are very small in most cases) can be seen. Although the photographic plate is not efficient in using light (efficiencies of less than 1% are common), a plate records many images. A typical astrographic or Schmidt plate may record 100,000 to over one million star images.

If a plate is not available, select a slide of a very rich star field and project it onto a large screen. Estimate the number of stars in the field by counting the number of stars in a small region and multiplying by the number of regions in the picture.

➲ **DEMO** Demonstrate a photodetector. Particularly useful are those with a digital display. These are commonly available at low cost. Show how the signal strength varies with light intensity. Although photodetectors are much more efficient (typically around 15%) than plates, they measure only the light from one star at a time. They also measure the light much more accurately than does a plate. Astronomers used to have to choose which they wanted, lots of star images with low quality information on each or high quality information on single stars.

Although the CCD cannot be effectively demonstrated in class, describe how they allow astronomers to combine the best qualities of the plate and photodetector. They are very efficient (about 75%), they record a field of stars, and they allow accurate determinations of the brightness of each star or object in the field. A very good way to describe CCDs is through the use of a standard digital camera. Ask the class how many own a digital camera. Usually a good portion of the class will say that they do. If you have one, bring it to class and take pictures of the class while discussing the fact that the sensor that collected the image is a close cousin to the CCD arrays used for astronomy. This is also a good opportunity to discuss the “pixel,” where each CCD element corresponds to an image pixel on the output screen on the back of most digital cameras.

For decades, astronomers did not build larger and larger telescopes because they knew their detectors were wasting most of the light the telescopes were collecting. Emphasis was placed on building new and more efficient detectors instead of larger telescopes. With the availability of CCDs, the emphasis is now on larger telescopes because the CCD is utilizing most of the light collected by the telescope. Note also that a 25cm (10-inch) telescope with a CCD can now detect what a 125cm (50-inch) telescope could with a photographic plate. Amateur astronomers are now capable of doing significant research with their small telescopes!

➲ **DEMO** Demonstrate how a Geiger counter works. Set the audio level high enough for the students to hear. Hide a small radioactive source ahead of time and find it with the Geiger counter. Place the Geiger tube at the end of a pipe, preferably lead. The angular resolution of the detector can be increased in this way. Sweep across the source in a series of scans to show how an “image” of the source might be produced by a similar detector in space. Although this is the old way of imaging X-ray and gamma-ray sources, it does demonstrate how this radiation has to be dealt with differently from other forms of electromagnetic radiation because of its higher energies.

Section 5.3

Students will likely know that larger telescopes are better, at least for research purposes, but many will probably think that the reason has to do with magnification. It doesn't; instead, larger-diameter telescopes have improved **light-gathering power** and **resolving power**. Light-gathering power is proportional to the square of the diameter and is important because so many astronomical objects are faint. The angular resolution of a telescope is inversely proportional to the diameter (for a given wavelength of light), which means that larger-diameter telescopes are capable of seeing more detail. Have students calculate the resolving power of the telescope you brought into class and compare it to one of the Keck telescopes. They can also calculate how much brighter an image in the Keck telescope would be compared to an image of the same object viewed with the smaller telescope for an equal exposure time.

➲ **DEMO** To introduce diffraction-limited optics, shine a laser through a pinhole and project the diffraction pattern on the wall or a screen. It is often difficult for students to see how the diffraction pattern demonstrated using a laser and a pinhole relates to the diffraction-limited optics of telescopes. Telescopes are about 1,000 times bigger than pinholes and therefore the diffraction pattern will be 1,000 times smaller. But the image quality produced by a telescope allows the pattern to be seen.

Remind the students what the "size" of an arc second is. It is the breadth of a thin hair (0.05 mm) viewed from a distance of 10 m or a penny viewed from 3.6 km. Discuss **angular resolution** of telescopes. ➲ **DEMO** Try the following demonstration which tests the resolving power of the human eye. On a plain sheet of white paper, draw two black dots 0.5 cm in diameter and separated by 1 cm. They should look something like this.

● ●

Now hold this pattern at a distance from a student so that they can just distinguish the two dots as two dots and not blurred together as one. Use the following table to give the resolving power (in arc minutes) at various distances. Humans with perfect vision have a resolving power of about 1 or 2 arc minutes; most classrooms will not be big enough for a person with good vision to see the two dots blur together. So try this experiment with students who have vision that is less than perfect! Have them remove their glasses and test their resolving power.

Distance (ft)	**Resolving Power (arc minutes)**
110	1
55	2
40	3
30	4
20	5
10	10
6	20
4	30
3	40

Have the students notice how their resolving power improves when they wear their glasses. Point out that this is analogous to the repair of the Hubble Space Telescope; it had less than good vision until corrective optics (glasses!) were installed. Its resolving power was dramatically improved.

Section 5.4

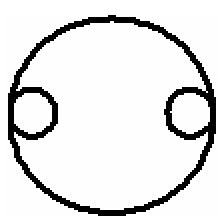
"Stars twinkle, planets don't" is a saying your students may well have heard regarding how to tell planets from stars in the night sky. "**Seeing**" is the phenomenon responsible for the old trick. Stars twinkle as their point images are bounced around by the changes in temperature and density in the atmosphere. Planets have disk shapes, and as the disks are moved slightly they continue to overlap, giving a more constant image. ➲ **DEMO** A simple demonstration of the effects of seeing is to place a hot plate set on high just under the light projected by a slide projector (or a hair blower set on high directed into the beam). Show a slide with lots of stars in it and watch how the images become distorted.

Section 5.5

Radio telescopes have both advantages and disadvantages when compared to optical telescopes. For instance, radio astronomers do not need to wait until nighttime to observe! Angular resolution of radio telescopes tends to be poor, however, because of the long wavelength of radio waves. Discuss how this shortcoming has been addressed through technologies that allow larger dishes and through interferometry. Most importantly, radio telescopes give us a whole new view of the universe, as many of the objects that are bright in the radio portion of the spectrum are not necessarily bright in the optical. Also, radio waves penetrate dust clouds, so we can investigate objects even if they are obscured in the optical.

Section 5.6

This demonstration is usually effective for conveying the concept of interferometry. Remind the students that the resolving power of a telescope is not directly related to the surface area of the primary optical component, but rather the largest dimension (diameter). It is this fact that gives interferometry its strength. ➲ **DEMO** To explain, start with a single lens of mirror of 1 foot in diameter, if available. Alternately, you can us a piece of cardboard cut into a circle about 1 foot in diameter to represent a "mirror." Now, take a smaller lens/mirror or a second piece of cardboard cut into a circle about 3 inches in diameter. Ask the students which "mirror" has the higher resolving power. They will answer unanimously that the larger "mirror" does. Now, take another small lens/mirror or piece of cardboard, also cut into a 3-inch diameter circle and hold it and the other small piece of cardboard so that they are separated by nearly the diameter of the large piece as shown in the image blow.



Now, ask the students which has the higher resolving power, the large "mirror" or the two smaller "mirrors." They are equivalent. Now, separate the two smaller mirrors by many feet and repeat the question. Now the power of interferometry becomes clear.

Section 5.7

Space-based observatories are designed to overcome the limitations imposed by the Earth's atmosphere. Even though visible light penetrates the atmosphere, optical telescopes have to deal with the effects of seeing. Optical telescopes placed above the atmosphere are opening new doors into previously unavailable views of the Universe. **Other astronomies**, including infrared, ultraviolet, and high energy (X-ray and gamma ray), are likewise opening up new realms in astronomical observing. Spend time going through Table 5.1 to compare the general considerations for observing in each different wavelength range and the types of objects observed. Note the wavelengths that do not penetrate the Earth's atmosphere at all. The only way to capture X-rays, for example, is to view them from above the Earth's atmosphere. Even on high mountaintops, there is enough atmosphere above to block the X-rays. We are left with only one alternative and that is to view X-rays from space. You should definitely take the opportunity here to show slides of some of the currently active space-based observatories such as *IRAS* or *XMM-Newton*. While discussing these, remind the student (if you have not already mentioned this) that placing satellites in space is not for the purpose of getting closer to the objects that they are looking at. Even as close as the Moon is, a satellite in orbit is much less than 1% closer, let alone objects like planets or stars, which are many, many magnitudes further away.

Section 5.8

Figure 5.40, showing the Milky Way Galaxy in five different wavelength ranges, is an excellent illustration of the wealth of information available through observations in different ranges. Point out the electromagnetic spectrum icon that indicates the wavelength range of each photo. These icons are used throughout the text, and students should pay attention to them as they view images of astronomical objects.

Student Writing Questions

1. The next great observatory will have telescopes that can observe from the radio part of the spectrum through to ultraviolet light. You have been given the choice of locating this observatory on a high mountain peak on Earth, in Earth orbit, or on the far side of the Moon. Write a proposal that justifies the best site for this observatory. (You may want to read ahead for some information about the Moon in Chapter 8.) Don't worry about what the cost of running an observatory might be at any of these locations, just concern yourself with the most ideal observing location.

2. In this question, you can now worry about the cost of running an observatory at one of the locations given in the first question. What will make one location more expensive than another? Cost-benefit ratios are often discussed in this regard, i.e., are higher costs justified by some significant benefits? What would you propose?

3. The Hubble Space Telescope is operated from Earth. What would be the advantages or disadvantages of having humans working at the telescope while in orbit? Do you think this would be cost effective?

4. What do you think the next generation of telescopes will be? What can't be done now that needs to be done? Where will this be done from, Earth or space? Will the costs be worth it?

5. About 80 years ago a single photograph of a galaxy might have taken two or three nights of observing (exposing) at a 60-inch telescope. Today that same telescope could accomplish that task in just a few minutes. 80 years from now we will likely have similar comparisons. Why, then, should scientists struggle to do their research if all they need to do is wait until the future when it will be done so much faster and easier? Why should research be funded today if tomorrow it can be done faster, better, and probably cheaper?

Answers to End of Chapter Exercises

Review and Discussion

1. The two reasons why larger telescopes are better than smaller telescopes are greater collecting area and better angular resolution. The primary purpose of a telescope is to make faint objects bright enough to detect. Larger telescope mirrors collect more light and bring it to a focus. It is also necessary to see detail in the image formed by the telescope, to resolve two objects that appear close to each other. Larger telescope mirrors produce less diffraction, which blurs an image and limits resolution.

   Currently, there seems to be a sudden interest in building large telescopes. The last large telescope was built in 1948, the Palomar Observatory 5-meter telescope. For about 4 decades astronomers did not seem interested in building larger telescopes. Why did this suddenly change? The answer is that the detectors of light used by astronomers were very inefficient; they wasted most of the light received by the telescope. A photographic emulsion is no better than 5% efficient, 95% of the light is wasted. Other detectors were not much better than 10% efficient. Astronomers were not limited by the size of their telescopes but by the inefficiencies of their detectors. When CCD detectors became available, astronomers could use up to 75% of the light, so little light was wasted. Now, to see fainter objects, they had to start building bigger telescopes.

2. The largest telescopes are reflecting telescopes, primarily because of 3 distinct disadvantages of the refracting telescope. When light passes through a lens, light of different wavelengths focus at slightly different places. This is known as chromatic aberration and can produce seriously out of focus images. It is not easy to correct when making large lenses. Note, however, that camera lenses are quite successful in correcting this aberration, otherwise all your color photos would be rather blurry. A second problem is the glass lens absorbs certain wavelengths of light that the astronomers need to observe. In the infrared, for instance, glass is not transparent like it is for visible light. In the infrared, the glass lens blocks light from entering the telescope. Lastly, it is difficult to keep a lens bigger than about one meter from bending in its support. Glass is flexible and lenses can only be supported around their edge. When a large glass lens bends due to its own weight, its curvature changes and so does the focus, thus ruining the image.

3. The Keck telescopes are 10-m reflectors and are the largest in the world. They are atop Mauna Kea in Hawaii, as are several other large telescopes. Another example is the VLT (Very Large Telescope) in Chile.

4. The Earth's atmosphere smears out images seen in telescopes. "Seeing" is the blurring in the image of an object, such as a star, as its light passes through the Earth's atmosphere. Instead of the star image being very small, limited by the diffraction of the telescope, the image is blurred to many times this size. The atmosphere of the Earth is not homogeneous, it is turbulent and contains layers of varying temperatures and density. Light passing through these layers is refracted into many slightly different paths. Fortunately for astronomers, the Earth's atmosphere is really rather thin and so the images are not completely blurred to uselessness.

5. The *Hubble Space Telescope* is not affected by seeing because it orbits above Earth's atmosphere. It can also observe at wavelengths that are absorbed by Earth's atmosphere. Its disadvantages are several; it is a very complex telescope to operate and astronomers must use it remotely. If something goes wrong, they cannot easily fix it. Because the Hubble orbits close to Earth, half the sky is blocked by Earth. Because it orbits quickly around

Earth, objects may be observable for only part of the time; the rest of the time they are blocked by Earth.

6. A CCD, or charge-coupled device, has thousands of individual detectors arranged in a grid, each much more sensitive than a photographic plate. The light level of each detector is read out by computer. A CCD's primary advantages are its high sensitivity to light, its linear response to light (twice as much light produces twice as much signal, unlike a photographic plate, which is highly non-linear), and the ease with which the image can be processed by computer software.

7. Image processing takes advantage of fast computers available today. Since the image is really nothing more than an array of picture elements stored in the computer's memory, it can be manipulated electronically/mathematically. The particular manipulation algorithm will be dependent on the desired enhancement or the particular defect to correct for.

8. A 2-m telescope will definitely have its resolution limited by Earth's atmosphere. This size of telescope is diffraction-limited at about 0.05". But the blurring due to the atmosphere is at least 10 times this, at best, and usually closer to 20 times or 1.0".

9. Active optics is a method in which the telescope's optical system is continually adjusted to compensate for effects like mirror distortion, temperature changes, and bad seeing.

10. Adaptive optics are just now being developed that change the shape of mirrors in the telescope in order to compensate for atmospheric distortions.

11. The resolution of a telescope depends on the wavelength of the light observed; the longer the wavelength, the lower the resolution. Radio waves are very long relative to visible light. Since larger telescopes produce higher resolution, radio telescopes must be very large, compared to optical telescopes, in order to have a useful resolving power.

12. Conditions in some objects produce radio waves but little or no visible light. Some objects produce both but by different mechanisms. Radio astronomy allows all these objects to be studied. The radio emissions reveal a great deal of information about the objects that could not be learned by observations in visible light.

13. Even large radio telescopes have poor resolution when compared to optical telescopes. To improve their resolution would require radio telescopes of enormous size, at least kilometers in diameter. The technique of interferometry synthesizes a telescope of this size by separating several radio telescopes by this distance and simultaneously observing the same object. Using some rather complex computer processing, the individual images are combined to synthesize what would have been observed by a telescope the size of the separation between the telescopes. Radio interferometry can now reach resolutions that are far better than optical telescopes.

14. Interferometry is not limited to radio astronomy but is much more difficult at infrared and optical wavelengths. The twin Keck telescopes, for example, recently became fully operational for optical interferometry.

15. Ground-based optical telescopes have resolutions around 1 arc second. The Hubble Space Telescope has a resolution of 0.05 arc second. Radio interferometers have reached resolutions of 0.001 arc second.

16. Because anything that is warm emits strongly in the infrared, the telescopes and instruments must be cooled to low temperatures to reduce the amount of interference from them. Some infrared observations must be conducted above much of Earth's atmosphere because the atmosphere absorbs certain wavelengths of the infrared radiation coming from space.

17. The Earth's atmosphere blocks almost all ultraviolet light, so there are no ground-based ultraviolet observatories.

18. X-rays will not reflect off a mirror. However, X-rays will reflect off surfaces at low grazing angles. An X-ray telescope is made of sets of nested cylindrical mirrors positioned at the correct angle to both reflect X-rays at grazing angles and focus the X-rays to an image. (See Figure 5.36.)

19. Many objects emit their peak amount of radiation at wavelengths other than visible. When the universe is observed at new wavelengths, these different objects suddenly become visible, and astronomers are then able to study them. Generally, observing at many different wavelengths increases the total amount of information available to astronomers.

20. With 1° resolution, the smallest objects visible to the eye would have to be about 60 times bigger than they are now. Reading or any close work would be very difficult or impossible. If we could only see in the infrared, many things would look very different from how they look now. Instead of seeing some objects by reflected light, we would see them by the infrared light that they emitted owing to their warmth. This question is open-ended, and much more could be added to this response.

Conceptual Self-Test

1. F
2. F
3. F
4. F
5. T
6. T
7. T
8. T
9. F
10. F
11. C
12. D
13. D
14. B
15. C
16. C
17. A
18. D
19. B
20. C

Problems

1. A 10' angle is equal to 600". But there are 2048 pixels along this angle, so each pixel corresponds to 0.293" or about 0.3". A typical seeing disk of a diameter of 2" would consist of 2" / 0.293" per pixel = 6.8 pixels.

2. $\lambda_{max} = \dfrac{.29\text{cm}}{5.5\text{K}} \times \left(\dfrac{1\text{m}}{100\text{cm}}\right) \times \left(\dfrac{10^6 \mu\text{m}}{1\text{m}}\right)$, so $\lambda_{max} = 527\mu\text{m}$, which is longer than the 3 to 200μm operating range.

3. The amount of light collected by a telescope depends on the area of the mirror, and the area depends on the *square* of the diameter. A 6-m telescope is 3 times bigger in diameter than a 2-m telescope, so it has $3^2 = 9$ times the light-gathering power. The larger telescope will gather light 9 times faster than the smaller telescope, so what the 2-m telescope can accomplish in 1 hour, the 6-m can accomplish in 1/9 hour or 6.7 minutes. A 12-m telescope has 6 times the diameter of a 2-m telescope and therefore 36 times the area. It gathers light 36 times faster. What the 2-m telescope can gather in 1 hour, the 12-m can gather in (60 min)/36 = 1.7 minutes.

4. The angular resolution of a telescope gets poorer as wavelength increases. The angular resolution in arc-seconds is proportional to the wavelength. (a) 3.5 μm = 3,500 nm. 3,500/700 = 5, so the wavelength is 5 times longer. The resolution should be 5 times poorer or 0.05" × 5 = 0.25".
(b) Similarly, for the ultraviolet, 140 nm/700 nm = 0.2 and 0.05" × 0.2 = 0.01".

5. The mirror diameter is 8.1m. Using the formula for angular resolution (a) = 0.25 (0.7 μm / 8.1) = 0.022", (b) = 0.25(2 μm / 8.1) = 0.062".

6. First, find the angular separation of the stars:

$$\frac{\text{angle}}{360^\circ} = \frac{(2\text{ A.U.})(1.5\times10^8\text{ km/A.U})}{2\pi(200\text{ lt yrs})(9.5\times10^{12}\text{ km/lt yr})}$$

yields an angular separation of 9.05×10^{-6} degrees = 0.033". Use this as the angular resolution:

$\text{resolution} = 0.25\dfrac{\lambda(\mu\text{m})}{\text{diameter(m)}}$ so diameter = 0.25(2μm)/(0.033") = 15 m.

7. The Hubble Space Telescope has a mirror diameter of 2.4 m. Observing at 400 nm, it can therefore achieve an angular resolution of 0.25(0.4 μm)/(2.4 m) = 0.042". If the stars in the previous problem have an angular separation of 0.033" at 200 light-years, then the distance at which their separation will be 0.042" is (0.033/0.042)(200 light-years) = 160 light-years.

8. The CCD records 90/5 = 18 times as much light as a photographic plate. If it took 1 hour to photograph an object, it should take the CCD 1/18 as long or 60 min/18 = 3.3 minutes.

9. Use the last formula in *More Precisely 1-4* and use arc seconds instead of degrees. 57.3° = 206,000". *Diameter* = 380,000 km(3" / 206,000") = 5.5 km; *Diameter* = 380,000 km(0.05" / 206,000") = 0.092 km = 92 m; *Diameter* = 380,000 km(0.001"/ 206,000") = 1.8 m.

10. This is exactly the same problem as the previous problem but with a new distance, 2.5 million light years. *Diameter* = 2.5 million LY (3"/ 206,000") = 36 Ly; the other two answers are 0.6 Ly and 0.012 Ly (= 760 A.U.)

11. The Arecibo telescope is 300 m in diameter. Comparing the areas of the two telescopes, square their diameters. $(300)^2 / (105)^2 = 8.2$, so Arecibo collects 8 times more radio waves and is 8 times more sensitive.

12. Area is proportional to diameter squared: $2 \times (10\text{ m})^2 = 200\text{ m}^2$. Taking the square root of this to get the diameter of a single mirror of equivalent area gives 14.1 m. Similarly, $4 \times (8\text{ m})^2 = 256\text{ m}^2$. Taking the square root of this to get the diameter of a single mirror of equivalent area gives 16 m.

13. (a) First, convert 5 GHz to wavelength: 3×10^8 m = 5×10^9 Hz × λ. λ = 0.06 m. Converting this to microns gives λ = 60,000 μm. The 5,000 km baseline is 5×10^6 m. Applying the formula for angular resolution:

$$\text{angular resolution} = 0.25\frac{60{,}000\ \mu\text{m}}{5\times10^6\ \text{m}} = 0.003''$$

(b) Applying the formula again for the case of the interferometer gives:

$$\text{angular resolution} = 0.25\frac{1\ \mu\text{m}}{50\ \text{m}} = 0.005''.$$

14. Calculating the theoretical resolution of these telescopes will not help, since they do not image in the same way regular telescopes do. The text notes that the gamma-ray telescopes have about a one degree resolution, compared to one arc seconds for *Chandra*. The latter is the one to use.

15. 1 keV = 1.6×10^{-16} J. The frequency is equal to $f = 1.6\times10^{-16}$ J / 6.63×10^{-34} = 2.4×10^{17} Hz. The wavelength is given by λ = 3×10^8 / 2.4×10^{17} Hz = 1.2×10^{-9} m = 1.2×10^{-3} μm. Angular resolution would be 0.25 (1.2×10^{-3} μm / 1.2 m) = 0.00026". Certainly *Chandra* is not diffraction limited.

Resource Information

Student CD Media

Movies/Animations

Light and Data Path

Interactive Student Tutorials

Mirrors in Telescopes
The Optics of a Simple Lens
Chromatic Abberation

Physlet Illustrations

Image Formation by Lens
Telescope Designs
Image Formation by Mirror

Transparencies

T-40	Figure 5.1	Reflecting Mirror	p. 106
T-41	Figure 5.4	Reflectors and Refractors	p. 108
T-42	Figure 5.5	Chromatic Aberration	p. 109
T-43	Figure 5.6	Reflecting Telescopes	p. 109
T-44	Figure 5.12	Sensitivity	p. 116
T-45	Figure 5.16	Resolution	p. 119
T-46	Figure 5.27	VLA Interferometer	p. 127

T-47	Figure 5.28	Interferometry	p. 128
T-48	Table 5.1	Astronomy at Many Wavelengths	p. 137
T-49	Figure 5.40	Milky Way Galaxy at Multiple Wavelengths	p. 136

Materials

An assortment of lenses and mirrors can be very helpful in demonstrating the concepts in this chapter. Edmund Optics can be found online at www.edmundoptics.com. It is a great source for lenses, prisms, and other optical components. Meter sticks and clay will allow you to construct very simple models of telescopes.

A laser and pinhole will allow you to demonstrate circular diffraction patterns.

The refracting telescope kit from Project Star (www.starlab.com) provides lenses, tubes, and lens holders for constructing simple telescopes.
If you want to do extensive demonstrations with optics, the "Blackboard Optics™ Basic Set" from Klinger (item KO4100 or KO4100M) is one example of an assembly of lenses, mirrors, and ray projectors that can attach right to your blackboard. An additional accessory set (KO4100A or KO4100AM) provides components for more demonstrations and experiments in optics.

Suggested Readings

Andereck, B. and Secrest, S. "The Magic Magnifier." *The Physics Teacher* (May 2001). p. 301. Describes the construction of a simple telescope out of PVC pipe and lenses.

Balinius, S. "View from the Mountaintop." *Astronomy* (September 2003). p. 60. Historical overview of Mount Wilson Observatory, initiated by G. E. Hale for Solar work. Hubble also made important discoveries there.

Berman, B. "Big Eye on the Universe." *Astronomy* (April 2003). p. 38. An article about the telescopes at Mauna Kea, showing many nice examples of what can be seen through some of the instruments located there. Also includes a map of Mauna Kea, which would be a nice accompaniment to readily available images of the site.

Deans, Paul. "2MASS treasure hunt." *Sky & Telescope* (Dec 2000). p. 54. Showcases results from the near-infrared sky survey conducted by twin 1.3-meter telescopes in Arizona and Chile (2MASS).

di-Cicco, Dennis. "A CCD camera buzzword primer." *Sky & Telescope* (Aug 1997). p. 109. Provides a guide to the terminology associated with CCD cameras.

Elvis, Martin. "NASA's Chandra X-ray Observatory: a revolution through resolution." *Sky & Telescope* (Aug 1999). p. 44. Gives a detailed overview of X-ray astronomy and the characteristics and capabilities of the Chandra X-ray Observatory.

Huebner, J., Gibbs, D., and Ryan, P. "Projecting Chromatic Aberrations." *American Journal of Physics* (September 2000). p. 869. Describes apparatus for demonstrating chromatic aberration to a large class using an overhead projector.

Leonard, Peter J.T., Wanjek, Christopher. "Compton's legacy." *Sky & Telescope* (July 2000). p. 48. Reviews results of the high energy gamma ray sky obtained during the nine-year mission of the Compton Gamma Ray Observatory.

Miller, D. “Retinal Imaging and Vision at the Frontiers of Adaptive Optics.” *Physics Today* (January 2000). p. 31. Good discussion of the potential for adaptive optics to correct for aberrations, diffraction and the eye's defects.

“Millimeter wavelengths saved for astronomers.” *Sky & Telescope* (Nov 2000). p. 32. A short description of the conflict between radio astronomy and radio communications.

Milonni, P. “Resource Letter: AOA-1: Adaptive Optics for Astronomy.” *American Journal of Physics* (June 1999). p. 476. Provides a guide to the basic concepts and the literature on adaptive optics for astronomy.

Naeye, Robert. “Back to the future.” *Astronomy* (Oct 1999). p. 40. A showcase of spectacular images from the Hubble Space Telescope.

Saegusa, Asako. “Celebratory pictures from Subaru.” *Nature* (Sept 23 1999). p. 314. Showcases some of the first images from the Subaru Telescope on Mauna Kea.

Schomaker, W. “Big Glass.” *Astronomy* (May 2003). p. 38. Good overview of modern, large telescopes around the world (and beyond).

Sincell, Mark. “Making the stars stand still.” *Astronomy* (June 2000). p. 42. Describes how adaptive optics work to compensate for atmospheric distortion of astronomical images.

Smith, Robert W. “Ten years and counting: HST in orbit.” *Sky & Telescope* (Apr 2000). p. 28. Provides a nice review of the key results from the first ten years of the Hubble Space Telescope.

Terrance, Gregory. “Exploring the digital darkroom.” *Astronomy* (Sept 2000). p. 76. An overview of image-processing techniques for images obtained with CCD cameras.

Notes and Ideas

*Class time spent on material: Estimated:*_______ *Actual:*______________

Demonstration and activity materials:

Notes for next time: