

The Sky and Telescopes

Coordinate Systems and Timescales

COORDINATE SYSTEMS

Altitude and Azimuth. The **altitude** is defined relative to the **horizon**, and is the angle from the horizon to the object. The altitude of an object on the horizon is 0° , and the altitude of an object directly overhead is 90° . The point directly overhead (altitude = 90°) is the **zenith**, and a line running from north to south through the zenith is called the local **meridian**. **Azimuth** is the angle around the horizon from north and towards the east. An object in the north has azimuth 0° , while an object in the west has azimuth 270° . The altitude and azimuth of an object are particular to the observing location and the time of observation.

Right ascension and declination. **Declination** (dec) is like latitude on the Earth, and measures the angle north and south of the **celestial equator** (an imaginary line in the sky directly over the Earth's equator). The celestial equator lies at 0° , while the **north celestial pole** (i.e., the extension of the Earth's rotation axis) is at 90° . Declination is negative for objects in the southern celestial hemisphere, and is equal to -90° at the south celestial pole.

Right ascension (RA) is analogous to longitude. The **ecliptic** is the plane of the solar system, or the path that the Sun follows in the sky. Because the axis of the Earth is tilted, the ecliptic and the celestial equator are not in the same plane, but cross at two locations, called the equinoxes. One of these locations, the **vernal equinox**, is used as the zero point of right ascension. Right ascension is measured in hours, minutes, and seconds to the east of the vernal equinox. There are 24 hours of right ascension in the sky, and during the 24 hours of the Earth's day, all

of them can be seen. Each hour on Earth changes the right ascension of the meridian by just under 1 hour.

Figure 2-1 shows a diagram of the important points in the sky. Imagine that you “unrolled” the sky and made a map, much like a map of the Earth. All of the following are labeled on the map, and many are explained in more detail later in the chapter:

- (a) ecliptic
- (b) celestial equator, 0 degrees dec
- (c) autumnal equinox, 12 hours RA
- (d) vernal equinox, 0 hours RA
- (e) summer solstice, 6 hours RA
- (f) winter solstice, 18 hours RA
- (g) direction of the motion of the Sun throughout the year.

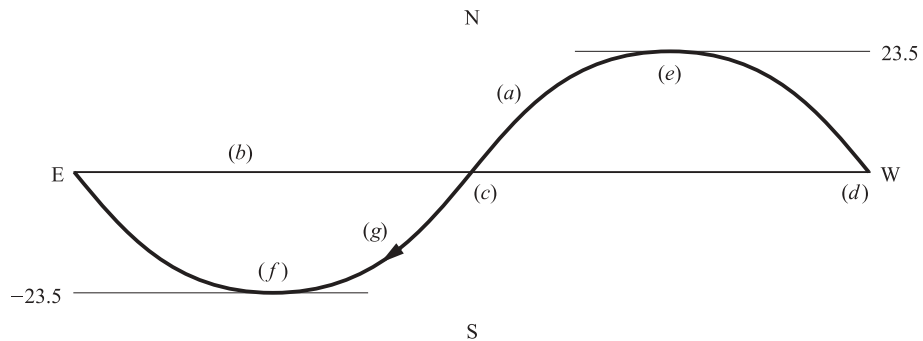


Fig. 2-1. A diagram of the sky. The path of the Sun is indicated by the curved line.

THE DAY

The Earth rotates on its axis once per day, giving us day and night. Astronomers define three different kinds of “day,” depending upon the frame of reference:

1. **Sidereal day.** The length of time that it takes for the Earth to come around to the same position relative to the distant stars. The sidereal day is 23 hours and 56 minutes long. Specifically, it is measured as the time between successive meridian crossings of the vernal equinox.
2. **Solar day.** The length of time that it takes for the Earth to come around to the same position relative to the Sun. It is measured as the time between successive meridian crossings of the Sun. The solar day is 24 hours long. The “extra” four minutes come from the fact that the Earth travels about 1 degree around the Sun per day, so that the Earth has to turn a little bit further to present the same face to the Sun.

3. **Lunar day.** The length of time that it takes for the Earth to come around to the same position relative to the Moon. Since the Moon revolves around the Earth, this day is even longer than the solar day—about 24 hours and 48 minutes. This is why the tides do not occur at the same time every day, because the Moon is the primary contributor to the tides, and it is not in the same location in the sky each day.

TIDES

The Earth experiences one full set of tides each day (two highs and two lows), everywhere on the planet. Tides are caused by gravity. The Sun and the Moon both contribute to tides on Earth.

When the Sun, the Moon, and the Earth are all in a straight line, the tides are largest. This is called a spring tide (spring for jumping, not spring for the season). When the Sun, the Moon, and the Earth are at right angles, the tides are smallest. This is called a neap tide.

Tides are slowing the Earth's rotation. The rotation is slowed by about 0.0015 seconds every century. Eventually, the Moon and the Earth will become "tidally locked," so that the same face of the Earth always faces the same face of the Moon. An Earth day will slow to be about 47 of our current days long.

As the Earth is slowing down, its angular momentum decreases. Conservation of angular momentum requires that the Moon's angular momentum should increase. Indeed, the Moon increases its angular momentum by receding from the Earth (about 3 cm per year). As it gets further away, its angular size decreases, and it looks smaller relative to the Sun. It will take several centuries for this to add up to a noticeable effect.

THE MOON ORBITS THE EARTH

The Moon goes through one cycle of phases in about 29 days. This is not the same as the length of a calendar month. This is why the moon is not always new on the first day of the calendar month.

The Moon is in "synchronous rotation." The length of time that it takes to rotate on its axis is equal to the length of time it takes to revolve around the Earth. As a result, the same side of the Moon always faces the Earth.

As the moon orbits, it exhibits phases. Figure 2-2 shows the Moon at various points in its orbit around the Earth. The lighter shading indicates the illuminated portion of the Moon. This diagram is drawn from the point of view of looking down from north.

THE EARTH ORBITS THE SUN

A year is defined as the amount of time that it takes for the Earth to complete a full orbit around the Sun. A year is about 365.25 days long. This has many visible consequences.

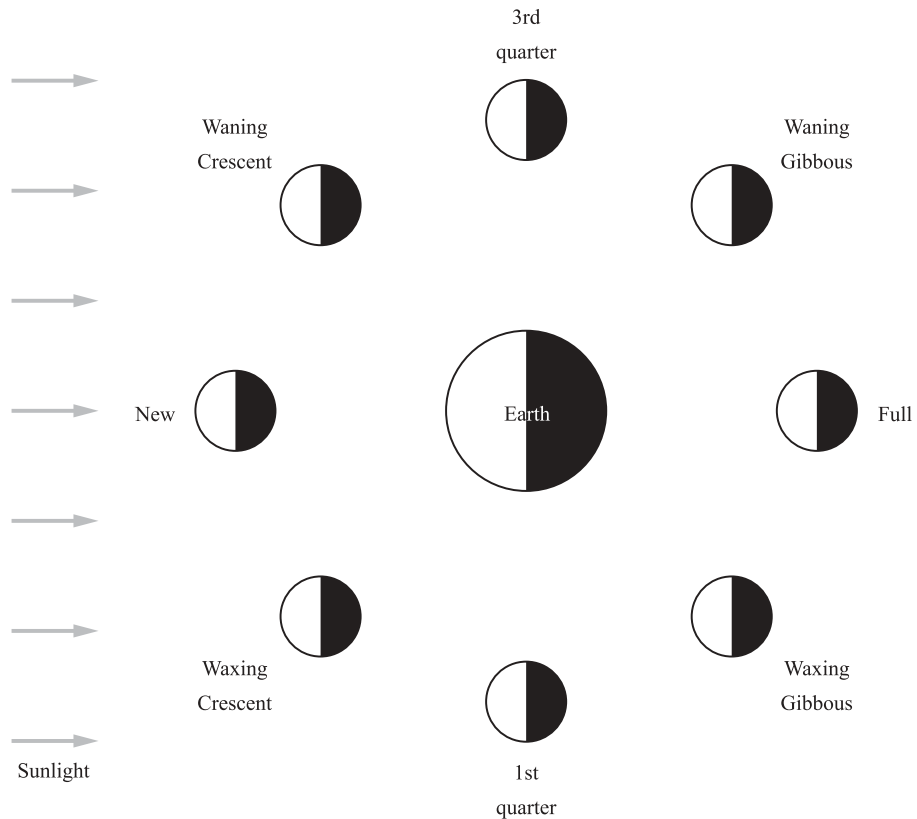


Fig. 2-2. The phases of the Moon. Depending on the relative orientation of the Earth, the Sun, and the Moon, different parts of the Moon appear lit.

1. **Visible constellations cycle.** Because the Earth is traveling around the Sun, the constellations (made up of stars that are much further away than the Sun) that are visible at night vary during the course of the year. That is, the direction that you are looking into the night sky changes. The stars rise 4 minutes earlier each night (a total of about 2 hours per month). For example, if a star rises at 6 p.m. on January 1, it will rise at 4 p.m. on February 1.
2. **Seasons.** The Earth's equator is tilted by 23.5 degrees to the plane of the Earth's orbit (the ecliptic). Because of this, the Earth has four seasons each year. When the North Pole is tipped in the direction of the Sun, it is summertime in the Northern Hemisphere, but wintertime in the Southern Hemisphere. Conversely, when the South Pole is tilted towards the Sun, it is summer in the Southern Hemisphere, and winter in the North.

The ecliptic and the celestial equator intersect at two points, called the **equinoxes**. When the Sun has reached those points on the ecliptic, it is directly over the Earth's equator, and the whole planet gets 12 hours of sunlight and 12 hours of darkness. This happens once in the spring (vernal equinox, March 21), and once in the fall (autumnal equinox, September 21). **Solstices** occur when the Earth's North Pole is tilted farthest towards

or away from the Sun. Summer solstice (June 21) is the longest day of the year in the Northern Hemisphere, and winter solstice (December 21) is the shortest day of the year in the Northern Hemisphere.

3. **Relative motion of planets.** The Earth and the other planets change their relative positions, so that the planets appear to move generally eastward with respect to the stars and constellations over the course of the year. The Earth completes an orbit considerably faster than most of the outer planets, so that they tend to be visible at nearly the same time of year for many years in a row.

ECLIPSES

In a **solar eclipse**, the Moon comes between the Earth and the Sun, and casts its shadow on the Earth. In a **lunar eclipse**, the Earth comes between the Sun and the Moon, and the Earth's shadow is cast on the Moon. Lunar eclipses are quite common, but solar eclipses are relatively rare at any given location. A given eclipse is visible from particular geographic locations, and may not produce any effect elsewhere. Eclipses do not occur every month because the Moon's orbit around the Earth is not aligned with the Earth's orbit around the Sun (the ecliptic). The two orbits are inclined about 5 degrees with respect to each other.

PRECESSION

Precession is the change in the direction of the Earth's spin axis. Precession is easily observed in tops. A spinning top not only rotates around on its own axis, but also the axis wobbles, and points in different directions due to gravity. The axis of the Earth behaves in a similar manner due to the Sun's gravitational force, so that the North Pole points at different stars at different times. Therefore, Polaris has not always been the North Star. About 3,000 years ago, Thuban (a star in the constellation Draco) was the North Star; about 12,000 years from now, Vega (a star in the constellation Lyra) will be the North Star. It takes 26,000 years for the pole to completely precess.

As the axis points in different directions, the plane of the celestial equator moves, so that the equinoxes also move. This is often called "precession of the equinoxes." Every 50 years or so, astronomers have to recalculate the positions of all of the stars in the sky, since the origin of the declination–right ascension coordinate system (the vernal equinox) moves.



Solved Problems

- 2.2. If the Earth rotated in the opposite sense (clockwise rather than counterclockwise), how long would the solar day be?

- 2.3. If you look overhead at 6 p.m. and notice that the moon is directly overhead, what phase is it in?



- 2.4. Which declinations can be observed from the North Pole? the South Pole? the equator? Which right ascensions can be seen from the above locations each day?



- 2.5. What is the latitude of the North Pole? Why is it impossible to give the longitude? What are the coordinates (in RA and dec) of the north celestial pole?



- 2.6. Suppose that the Earth's pole was perpendicular to its orbit. How would the azimuth of sunrise vary throughout the year? How would the length of day and night vary throughout the year at the equator? at the North and South Poles? where you live?



- 2.7. You are an astronaut on the moon. You look up, and see the Earth in its full phase and on the meridian. What lunar phase do people on Earth observe? What if you saw a first quarter Earth? new Earth? third quarter Earth? Draw a picture showing the geometry.



Fig. 2-5. The phases of the Earth as seen from the Moon.

2.8. Explain why some stars in your sky never rise, while others never set—assume that you live in a northern latitude (between 0° and 90° north).

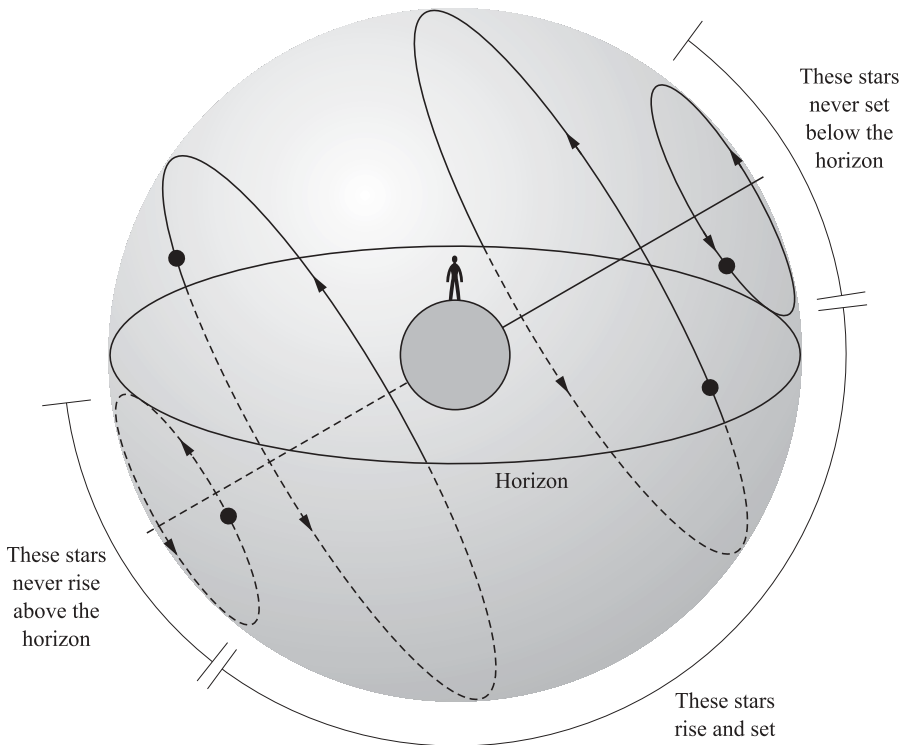


Fig. 2-6. Position of horizon and fraction of circumpolar stars.

2.9. (a) How does the declination of the Sun vary over the year? (b) Does its right ascension increase or decrease from day to day?

2.10. If a planet always keeps the same side towards the Sun, how many sidereal days are in a year on that planet?

- 2.11. If the lunar day were 12 hours long, what would be the approximate time interval between high and low tide?

- 2.12. If on a given day, the night is 24 hours long at the North Pole, how long is the night at the South Pole?

- 2.13. On what day of the year are the nights longest at the equator?

- 2.14. How many degrees ($^{\circ}$), arc minutes ($'$), and arcseconds ($''$) does the Moon move across the sky in 1 hour? How long does it take the Moon to move across the sky a distance equal to its own diameter?

- 2.15. From the fact that the Moon takes 29.5 days to complete a full cycle of phases, show that it rises an average of 48 minutes later each night.



2.16. What is the altitude of Polaris (Fig. 2-7) as seen from 90, 60, 30, and 0 degrees latitude?

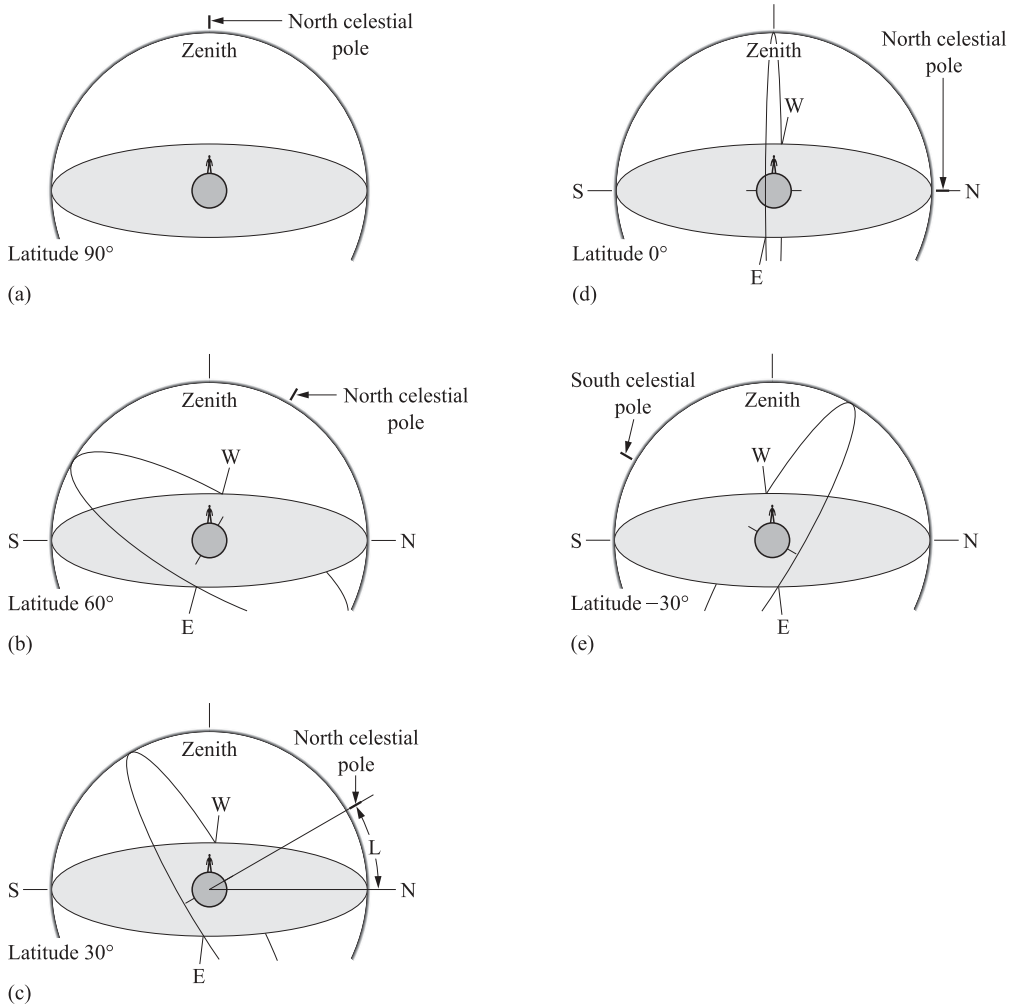


Fig. 2-7. The altitude of Polaris.

90° latitude is the North Pole. By definition, the North Star is at the zenith, or at 90° altitude.

0° latitude is the equator. At the equator, the North Star is at 0° altitude.

At 60° latitude, the altitude = 60°.

At 30° latitude, the altitude = 30°.

Instrumentation

TELESCOPES

The primary function of a telescope is to gather *more* light than the unaided human eye can gather. The amount of light that can be collected by a telescope is determined by the collecting area (the area of the telescope's lens or mirror that is open to the sky),

$$F = \text{constant} \cdot A$$

Alternatively, the amount of time it takes to collect a certain amount of light scales like the inverse of the area—the bigger the telescope, the less time it takes to collect a certain amount of light,

$$t = \frac{\text{constant}}{A}$$

In theory, this means that more astronomers can use a larger telescope, since it takes less time to accomplish a task. Of course, this is not true in practice. Astronomers observe fainter, more distant objects with larger telescopes, and so take about the same amount of time as on a smaller telescope, where they would restrict themselves to brighter objects.

There are two kinds of optical telescopes: refractors and reflectors. Refracting telescopes use lenses to bend the light to a focus. Reflectors use curved mirrors that reflect the light to the focus (Fig. 2-8).

Reflecting telescopes are preferred over refracting telescopes for several reasons:

1. A large mirror can be as thin as a small mirror, but a large lens must be thicker (thus heavier). For large diameters, lenses get much heavier than mirrors.
2. A lens has two surfaces that must be polished and cleaned; a mirror has only one.
3. Glass absorbs light. The thicker the glass, the more light gets absorbed.
4. Lenses can be supported only around the outside, but mirrors need supporting all across the back.
5. For large lenses, the glass deforms under its own weight and the image slides out of focus.
6. In a lens, different colors are refracted by different amounts. The blue light gets bent further than the red light. This phenomenon is called **chromatic aberration**, and in some cases is a positive quality: prisms can spread out

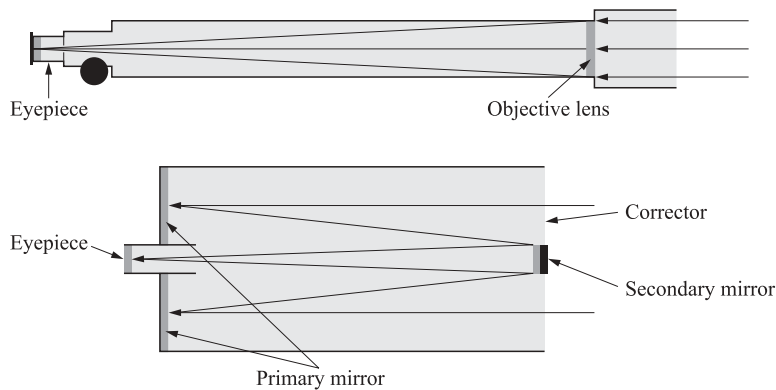


Fig. 2-8. The two types of optical telescopes: refractors and reflectors.

light into a rainbow. However, in the case of a telescope, the light coming through a lens will be focused at different locations, depending on the color. Only one color will be focused, and the others will be out of focus. This can be fixed by combining lenses made out of a number of different materials, which compensate each other. These combination lenses are heavier and prohibitively expensive, especially in larger sizes.

Of course, reflectors are not perfect either. The worst problem is that the outer edges of the image are blurred. This effect is called **coma**. Some of the incoming light rays enter the telescope at an angle, rather than parallel to the axis, and so are imperfectly focused by the mirror. This problem can be fixed with a special lens, but then a special camera with curved photographic plates is necessary to “see” the picture. You can’t just look through the telescope with your eye.

The angular resolution of a telescope indicates how close together two points can be before they can’t be distinguished. This number should be as small as possible. The angular resolution is measured in arcseconds (an arcsecond is $1/3,600^\circ$). The angular resolution is given by

$$\text{AR} = 250,000 \cdot \frac{\lambda}{d}$$

where λ is the wavelength at which you are observing and d is the diameter of your telescope (these must be in the same units). If the diameter of the telescope is large, the angular resolution is small. If the wavelength is large, the angular resolution is large. Fortunately, it is easy to build large telescopes for observing at large wavelengths. Unfortunately, at small wavelengths, such as ultraviolet, X-ray, or gamma ray, it is very difficult to build telescopes with even modest diameters. The atmosphere is opaque at these wavelengths, so telescopes must be placed in orbit to be useful. This places strong constraints on the possible size of these telescopes.

Even at relatively long wavelengths, such as in the visible or radio region of the spectrum, orbiting telescopes are preferable to ground-based telescopes. This is because the temperature of the atmosphere is not the same throughout, which causes changes in the density and flow of air. As light travels through air currents or pockets of high- and low-density air, it is refracted, or bent. As these patterns in

the atmosphere change, the light coming into your telescope will be observed in a slightly different place on your detector over time, spreading out the image. The phenomenon of the moving light paths is called atmospheric scintillation, and limits the angular resolution of even large telescopes.

Relatively recent developments in telescope technology, such as interferometry or adaptive optics, are able to produce images with angular resolutions comparable to those that could be achieved with space-based telescopes. Interferometry has been used primarily in the radio and millimeter wavelengths, and links many smaller telescopes together to simulate a much larger telescope. Optical interferometers have been built but, because of the higher frequencies, are much more difficult to construct on the same scale as radio and millimeter interferometers. New projects are under way to build optical interferometers in space, which may be able to detect Earth-sized planets around other stars. These projects are still very much in the early planning stages, and rely on unproven technologies, but over the next decade or so the feasibility of such telescopes should be determined. Adaptive optics is used in the optical and infrared to correct for the motion of the atmosphere while the observation is taking place. The correction makes use of a bright star close to the target as a reference. The Gemini North telescope in Mauna Kea, Hawaii (a large telescope with an adaptive optics imaging system) has produced images with less than one-tenth of 1 arcsecond angular resolution. (Recall that 1 arcsecond is the angular diameter of a tennis ball 8 miles away.)

MAGNIFICATION

Telescopes gather more light, and this is the primary reason that they are useful. They can also be used to magnify an image. This is done in practice by changing the eyepiece. However, because the same amount of light is used to make a magnified image as was used to make the original image, the magnified image is fainter. Also, the field of view (the area of sky that can be seen through the telescope) is reduced as the image is magnified. In practice, astronomers rarely magnify an image using their telescope. Instead, they take a picture, using either photographic film or a digital camera, and then use an image-processing program to make the image larger. As a practical rule, the useful magnification of an amateur telescope does not exceed 10 times the diameter of the objective in centimeters. For example, a 4-inch reflector (diameter ~ 10 cm) will magnify $10 \times 10 = 100$ at most. At larger magnifications, the image deteriorates.

DETECTORS

The human eye is unparalleled in its range of color sensitivity, sensitivity to dim light, and adaptability. We can't manufacture anything that comes close to the human eye in overall usefulness. When used in connection with the brain, the eye is far and away the most sophisticated imaging system around. Observation of faint objects, which requires collection of light over extended periods of time, as well as image storage, can be achieved by various devices:

1. **Analog camera.** A 35-mm camera on the end of a telescope can take great pictures of the night sky. The shutter can be left open for a long time to image faint objects. The disadvantage of an analog camera is that it is awkward to get the pictures into a computer for analysis. Analog cameras have the advantage of being able to take “true-color” pictures.
2. **Digital cameras.** In astronomy, these are usually called CCDs (short for charge-coupled devices). These cameras provide the best link between a computer and the light coming from the sky. The information is digitized while it is taken, so that developing film or scanning photographs is not necessary. In general, digital cameras do not record in color, so that special filters are required to record only one color at a time. These filtered images can be recombined to form color images.
3. **Photometer.** A photometer adds up the light in an area of an image. All of the spatial information is lost. This is useful when observing objects which change in brightness over time, or when looking at sources whose light cannot be turned into an image (gamma-ray sources, for example).
4. **Spectrometer.** A spectrometer works like a prism, and records a spectrum of an object, in a particular set of wavelengths, with a particular frequency resolution. You will see why this detector is so important if you recall from Chapter 1 all the things we can find out from a spectrum.