III. ASTRONOMY TOOLS:

A. Since light is so important to astronomers, they want to collect as much of it as possible from a given object, and quantitatively study it in great detail.
   1. Astronomers use telescopes to gather light and provide greater clarity.
   2. Light is recorded with electronic detectors, which are more sensitive than eges and provide more quantitative measurements than eyes.
   3. Long exposures make it possible to see fainter stars; the eye/brain combination distinguishes a new image about 30 times per second.
   4. Spectrographs and other devices are used to analyze the light in greater detail.
   5. A variety of telescopes on Earth and in space are used to collect light throughout the electromagnetic spectrum, not just visible light.
   6. Computers are essential for thorough quantitative analysis of light.

B. Advances in observational astronomy have been driven by detector technology as much as by increases in telescope size.
   1. At visual wavelengths, for example, the use of photographic emulsions provided a great improvement over the human eye.
      a. Long exposures are possible, making faint objects visible.
      b. Many stars over a wide field of view can be recorded simultaneously.
      c. The data are stored for subsequent analysis, and archiving is easy.
      d. Quantitative measurements can be made.
   2. Various electronic devices were gradually developed and now supersede plates for most purposes.
      a. By far the most frequently used detectors are CCDs (charge-couple-devices, like those used in video camera recorders).
      b. These consist of a semi-conductor "chip" with a very large number of "pixels" (picture elements). Typical sizes of CCDs in the late 1990s are 2048 x 2048 pixels.
      c. Each pixel develops an electric charge as light hits it, and the amount of charge per pixel is measured at the end of the exposure.
      d. CCDs have the following advantages over photographic plates.
         i) The response of a CCD is linear—that is, if you double the exposure time, or look
         ii) CCDs are extremely sensitive--- up to 80% of the incoming photons are detected, as compared with 1-2% for photographic plates or human eye.
         iii) CCDs have a wide dynamic range –very faint and bright stars can be measured in a given image.
         iv) The output of CCDs is digital, and hence is immediately suitable for computer analysis.

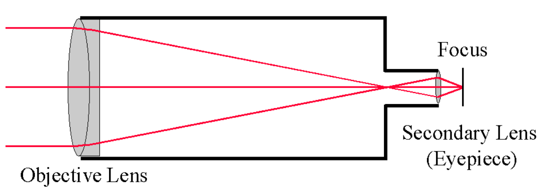
C. Telescopes serve at least two useful purposes.
   1. Their main purpose is to collect light quickly and in large quantities.

a. Light rays from a distant object are essentially parallel and hit all parts of the exposed face of the Earth.
b. The primary mirror or lens of a telescope acts as a gigantic eye pupil that intercepts the light rays.
c. The larger it's area, the more light it will collect in a given time, allowing fainter objects to be seen. (The length of the telescope tube is irrelevant to the light-gathering power).
d. The area of a circle is proportional to the square of it's radius r (or diameter D =2r): $A = \pi r^2 = \pi(D/2)^2 = \pi D^2/4$.
e. Therefore, the ratio of the areas of two telescopes with circular mirrors of diameter D_1 and D_2 is given by $A_2/A_1 = D_2^2/D_1^2 = (D_2/D_1)^2$.
f. Suppose D_2 = 4 m (a typical size for a large telescope), and D_1 = 4 mm = 0.004m (as for the pupil opening of a typical dilated human eye). The ratio of areas is $(D_2/D_1)^2 = (4m/0.004m)^2 = 1000^2 = 10^6$. This, looking through the eyepiece of such a telescope, one could see stars a million times fainter than with the unaided eye.
g. By attaching a detector to the telescope, the exposure time can be made very long, making even fainter stars visible.
h. Some detectors, such as CCDs, are far more sensitive than eyes, and detect most of the photons that hit them.
i. With large telescopes, long exposures, and high-quality CCDs, objects over 10^9 (a billion) times fainter than the limit of the unaided eye have been detected.

2. Telescopes also improve the clarity with which objects are seen: they have higher *angular resolution* (the ability to see fine detail) than the human eye.
   a. Angular measure is important in astronomy.
      i) The full circle is divided into 360°. The Moon and the Sun each subtend (cover) about ½°.
      ii) Each degree consists of 60 arc minutes (60').
      iii) Each minute of arc consists of 60 arc seconds (60").
      iv) A second of arc is very small –approximately the angle subtended by a dime viewed from a distance of 3.7 km.
      v) One can also use radians for angular measure. There are 2π radians in 360°, So 1" = 1/206265 radian.
      vi) If the angular size (Θ) of an object is measured in radians, and if the object appears small in the sky, then the physical size (s) = distance (d) X Θ.
   b. If two point-like objects are closer together than 1-2 arc minutes, the unaided eye will perceive them as only one object because their individual "blur circles" merge together.
   c. With a telescope, the size of the individual blur circles decreases, and the objects become resolved.
   d. The angular size of the blur circle is proportional to λ/D, where λ is the observation wavelength and D is the diameter of the lens or mirror. Hence, in principle, large telescopes are able to resolve finer details than small telescopes (at a given wavelengths).

e. In practice, Earth's atmosphere blurs starlight: layers of air with different densities move in a turbulent way relative to each other, and the rays of light bend in different directions. This is related to the twinkling of light.
f. The angular resolution of telescopes larger than 20-30 cm is limited by the blurring effects of the atmosphere (typically 1 arc second, and rarely smaller than 1/3 arc second), not by the size of the mirror or lens; thus, even bigger ground-based telescopes do not give clearer images.
g. There are exceptions to this limitation.
   i) Images of bright objects can be taken with very short exposures in quick succession, and computer processing can remove much of the blurring because the instantaneous images have high resolution. This technique is called "speckle interferometry".
   ii) If there is a bright star next to the object of interest, light from this star can be monitored, and rapid changes can be made to a deformable mirror in the telescope so as to produce a very sharp image of the star. The object next to the star will then also appear sharp. This technique is called "adaptive optics."
   iii) If there is no bright star next to the object of interest, and artificial star can be produced by shining a green laser beam up and exciting a layer of sodium atoms in the upper atmosphere. Light form this artificial star is monitored.

D. Telescopes come in two main types and several different subtypes.
   1. Refracting telescopes use a lens to collect light, bend (refract) it, and bring it to a focus.
      a. They were invented in Holland around the year 1600.
      b. Galileo Galilei heard of the idea and built his own refractor in 1609. He was the first to make and interpret systematic astronomical observations with a telescope.
      c. The focal length is the distance between the lens and the focus, for parallel incident light rays. The light rays reaching us from a distant star are essentially parallel. Consider light rays diverging spherically from an object. The great the object's distance, the more it will seem like the rays reaching our telescope are parallel, since the telescope diameter subtends a very small angle as viewed from the object.



      d. A CCD or other detector can be placed at the focus to record the light.
      e. An eyepiece is used to magnify the image when looking with the eye.
      f. Each "monocular" in a pair of binoculars is a refracting telescope.
      g. Refractors have a number of undesirable characteristics.
         i) They suffer from chromatic aberration: light of different wavelengths is brought to different foci. (The focus is closest to the lens for short wavelengths.) This

focus is closest to the lens for short wavelengths.) This produces a fuzzy image unless a filter is used to transmit only one color .

ii) An additional lens must be installed to partially correct for chromatic aberration. Thus, there are many surfaces to grind, increasing the cost.

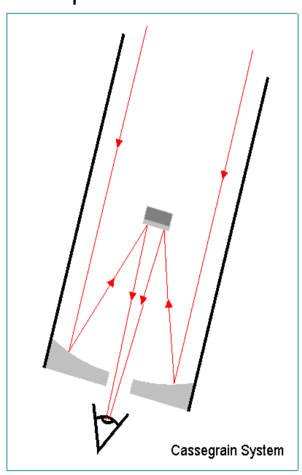
iii) Some of the light gets absorbed when passing through the lenses. Also, bubbles in the lenses can affect the image.

iv) The lenses must be supported by their edges, and they tend to sag in the middle, creating distortions in the final image.

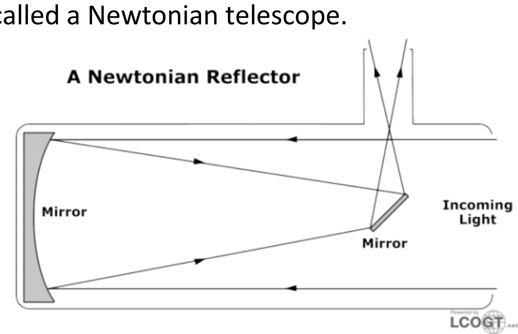
v) The focal length is very large, so the telescope tube is long and heavy.

h. Because of these difficulties, large refractors are no longer being built. The two biggest dating from about a century ago, are the Lick Observatory 36-inch refractor and the Yerkes Observatory 40-inch refractor.

2. Reflecting telescopes use a mirror to collect light, reflect it, and bring it to a focus.
   a. Isaac Newton invented the reflecting telescope around the year 1670.
   b. Since the angle of reflection is independent of wavelength, there is no chromatic aberration.
   c. A detector can be placed at the prime focus of the telescope, within the tube.
   d. More commonly, a curved secondary mirror is placed in the tube, and light is reflected back through a central hole in the primary mirror to a mounted instrument. This is called a Cassegrain telescope.



   e. Another configuration, often used in amateur telescopes, is to place a flat secondary mirror in the tube, reflecting light in a perpendicular direction through a hole in the tube. This is called a Newtonian telescope.



f. Note that the secondary mirror blocks some of the incoming light from an object, making the object look somewhat fainter than in the unblocked case, but it doesn't produce a "hole" in the image. Each little part of the primary mirror produces a complete (but faint) image of the object.
g. The simplest curved mirror to construct is a section of a sphere, but it suffers from spherical aberration: Parallel rays of light are reflected to different foci, depending on their distance from the center of the mirror. This produces a fuzzy image.
h. One solution is to make the mirror parabolic, to get a single focus.

3. Schmidt telescopes combine features of reflectors and refactors.
   a. They have a Spherical primary mirror, and a corrector lens near the top of the tube.
   b. Photographic plates are placed at the prime focus.
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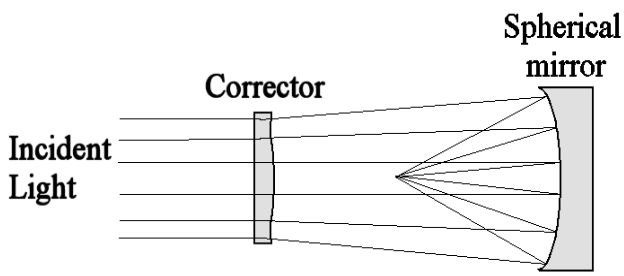
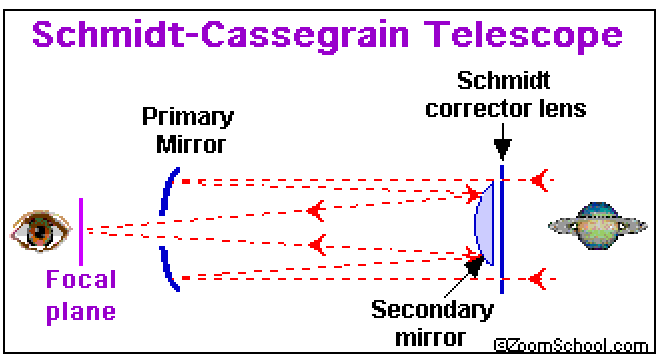
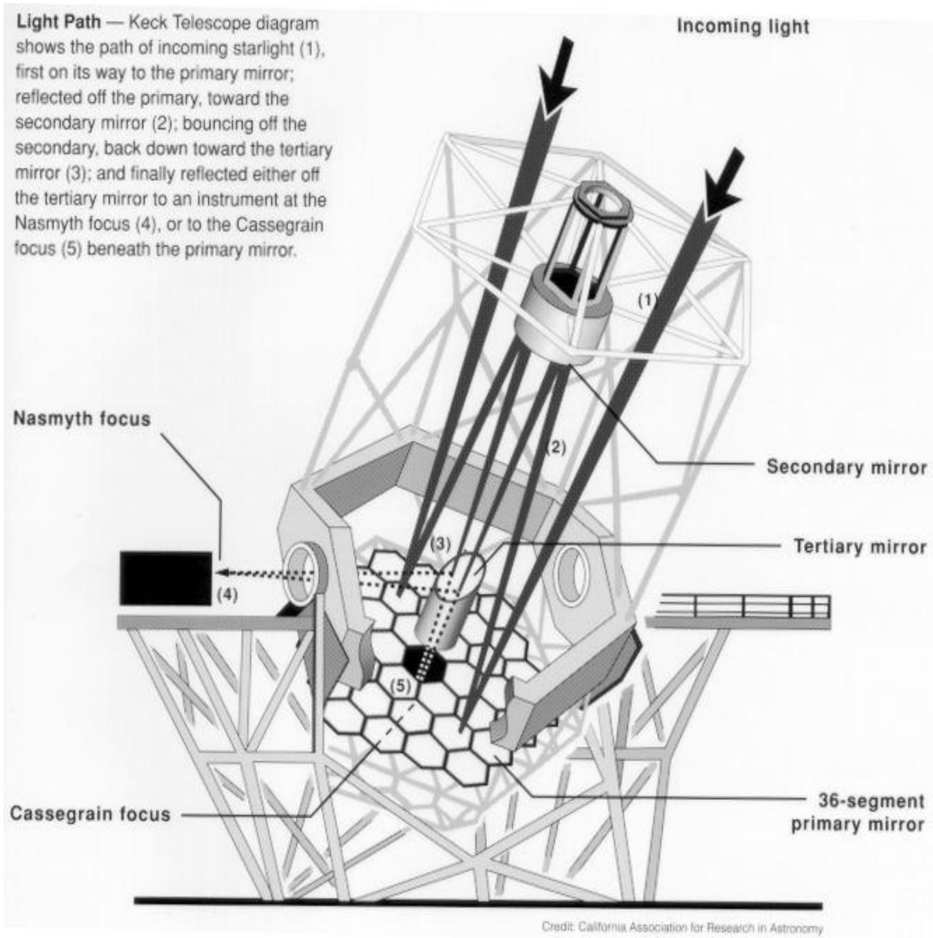


   d. Photographs can be obtained over a much wider field of view than with conventional reflectors.
   e. Schmidt-Cassegrain telescopes are a modification of this design; light passes through a hole in the primary mirror to the eyepiece. These are very compact, and popular among amateur astronomers.



4. From 1948 to the early 1990s, the world's largest telescope of superior quality was the 5 m Hale reflector at Palomar Observatory.
5. In the 1990s, new technology was developed that greatly reduced the cost of huge telescopes.
   a. The first major advance was the two Keck Observatory 10 m telescopes on Mauna Kea volcano in Hawaii.
   b. The primary mirror of each Keck telescope consists of 36 thin, lightweight, hexagonal segments arranged in a honeycomb pattern. The focal length is very short.

c. Devices behind the segments automatically and continually adjust their postions (in real time, while observing) to maintain the correct overall shape.



d. Another novel technique, developed at the U of Arizona, is to make a single thin mirror by spinning molten glass until it achieves the proper shape, and then allow it to cool.

e. Rigidity is provided by a honeycomb (mostly hollow, and therefore lightweight) structure behind the mirror.

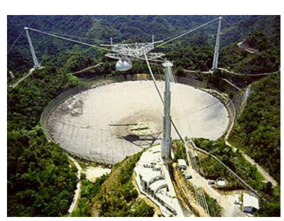
f. Each mirror is single and thin, and the proper overall shape is continually maintained (while observing) with a series of devices behind it.

E. Ground-based radio telescopes have also played an important role in astronomy.

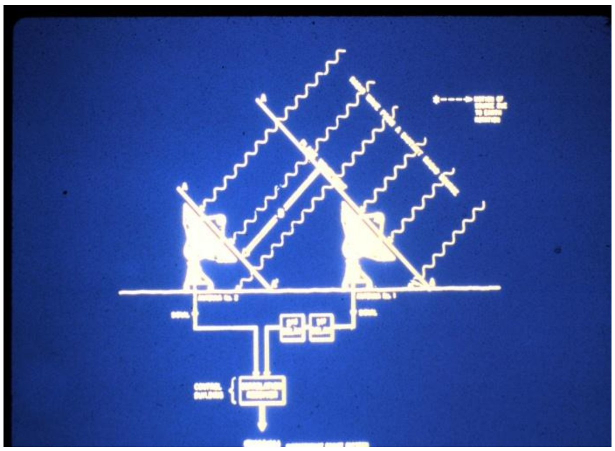
1. They must be made very large, to provide clear images.

   a. Recall that the angular size of an object's blue circle is proportional to λ/D. Since radio wavelengths are so large, D must be large to compensate.

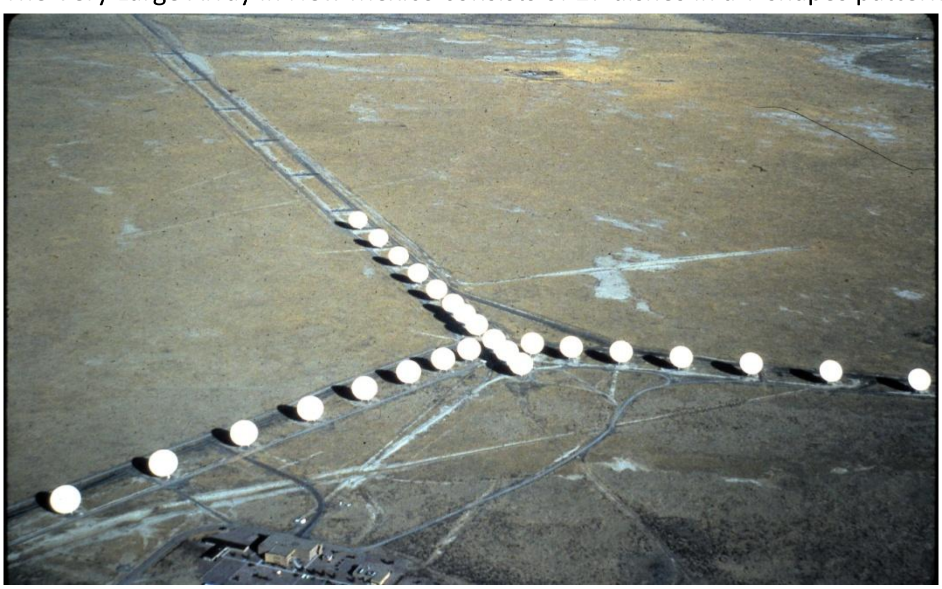
   b. The Arecibo radio telescope in Puerto Rico is the single largest radio telescope, 305 meters in diameter.



    c. Radio telescopes are always reflectors, and the detectors are at the prime focus.
    d. The reflecting dish can be a wire mesh; the long radio waves don’t notice the holes.
2. Signals from two or more separate telescopes can be combined to form a single image with very high resolution.
    a. This technique is known as interferometry; the wave collected by the different dishes interfere with each other, and the object’s structure can be deciphered form the pattern.
    b. The effective diameter of such a telescope is the largest spacing between the dishes. Thus, excellent clarity is achieved.



    c. However, the light-gathering power is still determined by the area of the dishes themselves.
    d. The Very Large Array in New Mexico consists of 27 dishes in a Y-shapes pattern.



    e. Signals detected from very widely spaced radio telescopes (i.g. on different continents) can be combined to produce astronomical images with extremely high angular resolution---better than 0.001 arc second. This is called Very Long Baseline Interferometry (VLBI).

F. Telescopes in space play a prominent role in astronomy.

1. Observations form the ground, especially at low altitudes, have some disadvantages.
    a. The Earth's atmosphere distorts (blurs) the images.
    b. Scattered light from cities and the Moon brightens the sky.
    c. The sky glows naturally; it is especially bright at infrared wavelengths.
    d. The atmosphere is opaque to many regions of the electromagnetic spectrum.
        i) Ozone (O_3) at altitudes of 20-40 km blocks UV radiation.
        ii) Water vapor (H_2O) at altitudes of 2-10 km blocks some infrared wavelengths.
        iii) Various atoms and molecules block X-Rays and gamma rays.
2. Telescopes on high, dry mountains far from city lights alleviate some of these problems. A good example is Mauna Kea volcano in Hawaii at an altitude of about 4 km.
    a. Atmospheric blurring is less, but still significant.
    b. The sky is darker, but there remains some scattered starlight and natural glow.
    c. Parts of the infrared spectrum are available, but most is not.
    d. X-rays, gamma rays, and the UV are still blocked.
3. Since space telescopes are expensive, they should be reserved only for those observations that cannot be obtained in other ways.
    a. Some parts of the infrared can be studied with telescopes in airplanes, but others require a space telescope.
    b. X-rays and gamma ray from bright objects can be studied with instruments carried by high-altitude balloons, or launched on short trips by rockets. Orbiting satellites provide more stability and longer duration for observations of faint objects.
    c. For UV wavelengths, orbiting space telescopes are used. A good example is the International Ultraviolet Explorer, which provided UV spectra of objects for nearly two decades before it was terminated in 1996.
4. NASA's Hubble Space Telescope (HST), with a 2.4 m primary mirror, has been enormously important: it provides very sharp images at UV, optical, and IR wavelengths, and it is also able to obtain spectra.