Chapter 5 - Astronomical Instruments

5.1-5.3 Telescopes

Galileo first used a telescope for astronomical observations in 1610. He used it to study craters on the Moon, first observed the phases of Venus, and discovered the four brightest moons orbiting Jupiter. These are now called the "Galilean" satellites.

The first telescope was a refractor with a simple lens.

The distance between the lens and the image, formed at a point called the focus, when the object is "infinitely" far away is called the focal length of the lens.
A telescope has two main functions:

a) collect light
b) form a sharp, magnified, image.

To collect more light the aperture must increase. The sharpness and ability to distinguish between closely spaced details of an object is called the resolution of the telescope. The theoretical resolution of a telescope also increases with increasing aperture (as long as the lens is accurately made), but the Earth's atmosphere limits the resolution of ground based telescopes to ~1 arc second (1/3600 of a degree).

<table>
<thead>
<tr>
<th>Aperture</th>
<th>Limiting Mag</th>
<th>Theoretical Resolution (5' arc)</th>
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</thead>
<tbody>
<tr>
<td>Naked Eye 6-7 mm</td>
<td>6th mag</td>
<td>21 seconds</td>
</tr>
<tr>
<td>1&quot; = 25.4 mm</td>
<td>9th mag</td>
<td>5.4 sec</td>
</tr>
<tr>
<td>2.5&quot; = 63.5 mm</td>
<td>11th mag</td>
<td>2.2 sec</td>
</tr>
<tr>
<td>4.0&quot; = 101.6 mm</td>
<td>12th mag</td>
<td>1.4 sec</td>
</tr>
<tr>
<td>10.0&quot; = 254 mm</td>
<td>14th mag</td>
<td>0.5 sec</td>
</tr>
<tr>
<td>16.0&quot; = 406 mm</td>
<td>15th mag</td>
<td>0.3 sec</td>
</tr>
</tbody>
</table>

The magnitude increases as the star's brightness decreases. A smaller number means a brighter star. Each increase in the magnitude is a factor of \( \sqrt{2.5} \) in brightness, i.e. mag 1 is 2.5 times brighter than mag 2, etc.
Refractors suffer from two problems

a) chromatic aberration — the lens acts like a prism and different colors come to focus at different focal lengths.

![Diagram of white light, blue focus, red focus]

Thus the image is blurry and shows colored fringes for simple lenses. This gets worse the shorter the focal length and the larger the lens.

b) support + optical quality of glass — it is hard to make good optical glass in large sizes. The light must pass through the glass so it must be free of bubbles and striations. The lens must be supported by its edges, so large lenses tend to sag under their own weight and are hard to support.

The first problem was partially solved in 1785 by using a compound lens or achromat. The second problem limits the size of the lens to less than 1 meter apertures. The largest refractor has an aperture of 40 inches.
Achromatic lens:

The "f-ratio" is the ratio of focal length to aperture. A good achromat is limited to f 1:10 or f 1:15

An f 15 lens has a focal length 15 times its aperture

e.g. 4" f 15 refractor has a 60" f.l.

The reflector or reflecting telescope uses a mirror instead of a lens to gather light.

Two advantages of a reflector

a) No chromatic aberration — all wave lengths focus at the same point. No prism effect.

b) Glass can be of lower quality since light does not have to pass through the glass. Also mirrors can be made bigger since they can be supported from the back.
Problems with Reflectors:

a) The image is formed at the focus at a point in the light path, so it is hard to reach without blocking the incoming light.

b) Reflecting coating on mirrors took a long time to perfect.

18th century - metal mirrors
mid 19th century - silver on glass (transmitting)
early 20th century - aluminum on glass (standard today)

A Newtonian reflector solves the first problem by introducing a diagonal mirror to reflect the image to the side.

A Cassegrain telescope solves the problem by drilling a hole in the main mirror.
If the mirror is large enough photographic plates or detectors can be placed at the "Prime" focus.

The largest Telescopes (by date):

<table>
<thead>
<tr>
<th>Name of telescope</th>
<th>Date</th>
<th>Size of Primary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mt. Wilson</td>
<td>1917</td>
<td>100 in = 2.5 meters</td>
</tr>
<tr>
<td>Mt. Palomar, Hale</td>
<td>1946</td>
<td>200 in = 5 meters</td>
</tr>
<tr>
<td>Large Alt-Azimuth</td>
<td>1976</td>
<td>6 meters</td>
</tr>
<tr>
<td>Keck I</td>
<td>1993</td>
<td>10 meters</td>
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</table>

Most telescopes were in the 3 to 4 meter range until recently. The Keck achieves its impressive light gathering ability by combining the light from 36 1.8 meter mirrors under computer control.
Astronomers rarely look through telescopes with the naked eye anymore. The eye has been replaced by photographic plates or charge-coupled devices (CCD's) like those found in video and digital cameras.

CCD's are more sensitive than the eye and electronic detectors also work at infrared wavelengths. A photographic plate can be exposed for hours to build up an image of faint objects invisible to the eye. This is the main advantage of photography.

Spectrographs can also be attached to telescopes so spectra of faint objects can be taken.

Requirements for a good observatory site:

1. weather — little clouds, wind, or rain
2. dry high altitude sites — especially important for infrared, water vapor blocks IR
3. dark sky — away from city lights and skylow
4. good seeing — atmosphere should be steady to allow sharp image.
Radio Astronomy

The first radio observation of astronomical objects were just before WWII.

Radio telescopes work at longer wavelengths so they must be large to get resolution comparable to optical telescopes. The accuracy of the surface of a radio telescope though can be much lower. Sizes of 300 feet to 100 meters are possible for a steerable dish.

![Diagram of a radio telescope]

Interferometry is easier at longer wavelengths.

In interferometry the signal from two or more telescopes is combined to get resolution equivalent to one large telescope with a size equivalent to the distance between the telescopes.
**Signal from object**

**T #1**

**Signal from object**

**T #2**

\[ \text{baseline} = \text{distance between telescopes. (Resolution can be calculated by replacing the aperture in the DO equation by the length of the baseline!)} \]

This is a two element **interferometric array**

Very long baseline interferometry use telescopes separated on the scale of continents (1000's of miles) to achieve resolution on the order of \(10^{-4}\) arc seconds at radio wavelengths.
Mathematical Aside on resolution:

\[ \Delta \theta = 1.22 \frac{\lambda}{a} = \text{minimum resolvable angular separation in radians} \]

\( \lambda = \text{wavelength (m)} \)
\( a = \text{aperture (m)} \)

To convert to seconds of arc

\[ \Delta \theta_{\text{sec}} = 1.22 \frac{\lambda}{a} \frac{180}{\pi} \text{rad} \frac{3600 \text{ seconds}}{1 \text{ degree}} \]

\[ \Delta \theta_{\text{sec}} = 2.52 \times 10^5 \text{ seconds} \left( \frac{\lambda}{a} \right) \]

Optical:
1. Japanese refractor 60mm objective; \( \lambda = 5500 \text{ Å} \)
\[ \Delta \theta_{\text{sec}} = 2.52 \times 10^5 \left( \frac{550 \times 10^{-9} \text{ m}}{0.060 \text{ m}} \right) \approx 2.3 \text{ seconds} ! \]

Radio:
2. Arecibo 305 meter fixed dish; \( \lambda = 10 \text{ meter to 1 meter} \)
\[ \Delta \theta_{\text{sec}} = 2.52 \times 10^5 \left( \frac{10 \text{ m}}{305 \text{ m}} \right) = 8262.3 \text{ seconds} \left( \frac{1 \text{ degree}}{3600 \text{ sec}} \right) = 2.3 \text{ degrees} ! \]
The Hubble avoids problems with atmospheric seeing by orbiting above the atmosphere.

The 2.4 m mirror can resolve (wow!) down to the theoretical limit of 0.06 arcseconds.

<table>
<thead>
<tr>
<th>Name of Satellite</th>
<th>Spacecraft</th>
</tr>
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<tbody>
<tr>
<td>X-Ray astronomy</td>
<td>AXAF</td>
</tr>
<tr>
<td>Gamma Ray astronomy</td>
<td>GRO</td>
</tr>
<tr>
<td>Infrared astronomy</td>
<td>IRAS</td>
</tr>
</tbody>
</table>

(show slide show with pictures of telescopes and satellites)
Chapter 5 - Review

Terms to know:
- Aperture
- Focus
- Focal length
- Refraction
- Reflection
- Dispersion (see chapter 4 + notes)
- Achromat (see notes)
- Resolution
- Arc-second
- Newtonian
- Cassegrain
- Charge-coupled devices (CCDs)
- "Seeing", good and bad
- Interferometry
- Interferometric Array