Chapter 6
Light and Telescopes

Guidepost
Chapter 2 described the sky as it appears to our unaided eyes, but modern astronomers turn powerful telescopes on the sky. This chapter introduces us to the modern astronomical telescope and its delicate instruments. The study of the universe is so challenging that astronomers cannot ignore any source of information, and so they use the entire spectrum, from gamma rays to radio waves. This chapter shows how critical it is for astronomers to understand the nature of light.

Guidepost (2)
On our journey to understand the planets, we first need to answer the following questions:
1. What is light?
2. How do telescopes work?
3. What are the powers and limitations of telescopes?
4. What kinds of instruments do astronomers use to record and analyze the light gathered by their telescopes?
5. Why must some telescopes be located in space?

The science of astronomy is based on remote observations. Most of our information on stars and the planets comes from telescopes of various sorts.

Light and Other Forms of Radiation

• The Electromagnetic Spectrum
In astronomy, we cannot perform experiments with our objects (stars, galaxies, …). The only way to investigate them is by analyzing the light (and other radiation) which we observe from them.

Light as a Wave (1)
• Wavelengths of light are measured in units of nanometers (nm) or angstroms (Å):
  1 nm = 10⁻⁹ m
  1 Å = 10⁻¹⁰ m = 0.1 nm
Visible light has wavelengths between 4000 Å and 7000 Å (= 400 – 700 nm).

Light as a Wave (2)
• Wavelengths of light are measured in units of nanometers (nm) or angstroms (Å):
  1 nm = 10⁻⁹ m
  1 Å = 10⁻¹⁰ m = 0.1 nm
**Light as a Wave (3)**

- Wavelength and Frequency are related:

  \[ f \lambda = c \]

  - \( f \) = frequency
  - \( \lambda \) = wavelength
  - \( c \) = the speed of light

**Light as Particles**

- Light can also appear as particles, called photons (explains, e.g., photoelectric effect).
- A photon has a specific energy \( E \), proportional to the frequency \( f \):

  \[ E = hf = hc/\lambda \]

  - \( h = 6.626 \times 10^{-34} \text{ J} \cdot \text{s} \) is the Planck constant.
  - \( c \) = the speed of light

  The energy of a photon does not depend on the intensity of the light, but on its frequency!

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**The Electromagnetic Spectrum**

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Low</td>
<td>Low</td>
</tr>
</tbody>
</table>

Astronomers use telescopes to gather more light from astronomical objects.

The larger the telescope, the more light it gathers.

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**Telescopes**

- Refracting telescopes use a pair of lenses to focus an image of distant objects.
- Galileo's homemade telescopes were refracting telescopes. This image shows two of the telescopes he used to make the amazing discoveries discussed earlier.

**Refracting Telescopes**

- Chromatic aberration: Different wavelengths are focused at different focal lengths (prism effect).
- Difficult and expensive to produce: All surfaces must be perfectly shaped, flawless glass and correctly supported.

**Disadvantages of Refracting Telescopes**

- Can be corrected, but not eliminated by second lens out of different material.
Reflecting Telescopes

Isaac Newton invented the reflecting telescope. His original telescope had a spherical primary mirror; newer telescopes have a parabolic mirror.


Almost all modern telescopes are reflecting telescopes.

Secondary Optics

In reflecting telescopes:
- Secondary mirror, to redirect light path towards back or side of incoming light path.
- Eyepiece: To view and enlarge the small image produced in the focal plane of the primary optics.

The Powers of a Telescope: Size Does Matter!

1. Light-gathering power: Depends on the surface area $A$ of the primary lens/mirror, proportional to diameter squared:
$$A = \pi \left(\frac{D}{2}\right)^2$$

The Powers of a Telescope (2)

2. Resolving power: Wave nature of light means the telescope aperture produces fringe rings that set a limit to the resolution of the telescope.
Resolving power $= \min$ angular distance $\alpha_{\text{res}}$ between two objects that can be separated.
$$\alpha_{\text{res}} = 1.22 \left(\frac{\lambda}{D}\right)$$
For optical wavelengths, this gives
$$\alpha_{\text{res}} = 11.6 \text{ arcsec} / D[\text{cm}]$$

The Powers of a Telescope (3)

3. Magnifying Power = ability of the telescope to make the image appear bigger.

The magnification depends on the ratio of focal lengths of the primary mirror/lens ($F_o$) and the eyepiece ($F_e$):
$$M = \frac{F_o}{F_e}$$
A larger magnification does not improve the resolving power of the telescope!
Seeing

Weather conditions and turbulence in the atmosphere set further limits to the quality of astronomical images.

Bad seeing  Good seeing

The Best Location for a Telescope

Far away from civilization – to avoid light pollution

The Best Location for a Telescope (2)

On high mountain-tops – to avoid atmospheric turbulence (→ seeing) and other weather effects

Paranal Observatory (ESO), Chile

Traditional Telescopes (1)

Traditional primary mirror: sturdy, heavy to avoid distortions.

Secondary mirror

Traditional Telescopes (2)

The 4-m Mayall Telescope at Kitt Peak National Observatory (Arizona)

Examples of Modern Telescope Design (1)

Design of the Large Binocular Telescope (LBT), which has two 8.4 m mirrors.

The Keck I telescope mirror has 36 individually controlled mirrors.
Examples of Modern Telescope Design (2)

The Very Large Telescope (VLT) has 4 computer-controlled 8.2 m mirrored telescopes.

9.1-m mirror of the Gemini Telescopes, one in Hawaii and one in Chile.

Examples of Modern Telescope Design (3)

9.2-m Hobby-Eberly telescope in West Texas. Has a segmented spherical mirror with correction for spherical aberration.

http://www.physics.uc.edu/~hanson/ASTRO/LECTURENOTES/F04/GRAVITYLIGHT/Page20.html

Radio Astronomy

Recall: Radio waves of \( \lambda \approx 1 \text{ cm} - 1 \text{ m} \) also penetrate Earth's atmosphere and can be observed from the ground.

Radio Telescopes

Large dish focuses the energy of radio waves onto a small receiver (antenna). Amplified signals are stored in computers and converted into images, spectra, etc.

The Largest Radio Telescopes

The 300-m telescope in Arecibo, Puerto Rico

The 150-m Green Bank Telescope in Green Bank, WV

Science of Radio Astronomy

Radio astronomy reveals several features, not visible at other wavelengths:

- Neutral hydrogen clouds (which don't emit any visible light), containing \( \approx 90\% \) of all the atoms in the universe.
- Molecules (often located in dense clouds, where visible light is completely absorbed).
- Radio waves penetrate gas and dust clouds, so we can observe regions from which visible light is heavily absorbed.
Infrared Astronomy
Most infrared radiation is absorbed in the lower atmosphere.
However, from high mountain tops or high-flying airplanes, some infrared radiation can still be observed.

NASA infrared telescope on Mauna Kea, Hawaii

Space Astronomy

The Hubble Space Telescope
- Launched in 1990; maintained and upgraded by several space shuttle service missions throughout the 1990s and early 2000s
- Avoids turbulence in Earth’s atmosphere
- Extends imaging and spectroscopy to (invisible) infrared and ultraviolet

NASA’s Space Infrared Telescope Facility (SIRTF)

Ultraviolet Astronomy
- Ultraviolet radiation with \( \lambda < 290 \text{ nm} \) is completely absorbed in the ozone layer of the atmosphere.
- Ultraviolet astronomy has to be done from satellites.
- Several successful ultraviolet astronomy satellites: IRAS, IUE, EUVE, FUSE
- Ultraviolet radiation traces hot (tens of thousands of degrees), moderately ionized gas in the universe.

X-Ray Astronomy
- X-rays are completely absorbed in the atmosphere.
- X-ray astronomy has to be done from satellites.

NASA’s Chandra X-ray Observatory
X-rays trace hot (million degrees), highly ionized gas in the universe.
Gamma-Ray Astronomy
Gamma-rays: most energetic electromagnetic radiation; traces the most violent processes in the universe.

The Compton Gamma-Ray Observatory

Advances in Modern Telescope Design
Modern computer technology has made possible significant advances in telescope design:
1. Lighter mirrors with lighter support structures, to be controlled dynamically by computers
2. Simpler, stronger mountings ("Alt-azimuth mountings") to be controlled by computers

Adaptive Optics
Computer-controlled mirror support adjusts the mirror surface (many times per second) to compensate for distortions by atmospheric turbulence.

Interferometry
Recall: Resolving power of a telescope depends on diameter D:
\[ \alpha_{\text{min}} = \frac{1.22}{\lambda/D} \]
This holds true even if the entire surface is not filled out.
- Combine the signals from several smaller telescopes to simulate one big mirror \( \rightarrow \) interferometry

CCD Imaging
CCD = Charge-coupled device
- More sensitive than photographic plates
- Data can be read directly into computer memory, allowing easy electronic manipulations

The Spectrograph
Using a prism (or a grating), light can be split up into different wavelengths (colors!) to produce a spectrum.

Spectral lines in a spectrum tell us about the chemical composition and other properties of the observed object.
Radio Interferometry

Just as for optical telescopes, the resolving power of a radio telescope is \( \alpha_{\text{min}} = \frac{1.22 \lambda}{D} \).

For radio telescopes, this is a big problem:
Radio waves are much longer than visible light

Use interferometry to improve resolution!

Radio Interferometry (2)

The Very Large Array (VLA): 27 dishes are combined to simulate a large dish of 36 km in diameter.

Even larger arrays consist of dishes spread out over the entire U.S. (VLBA = Very Long Baseline Array) or even the whole Earth (VLBI = Very Long Baseline Interferometry).

Particle Astronomy

Particle astronomy is the study of cosmic rays – high-energy particles from space that interact with Earth’s atmosphere. Some, like the neutrino, can only be found with large underground detectors.

The neutrino detector Ice Cube is located deep under the Antarctic ice and is designed to detect the interactions between the neutrinos and the hydrogen in the ice, producing gamma rays that can be detected.

Gravity Waves

Albert Einstein predicted the existence of gravitational waves in 1916 as part of the theory of general relativity. If two massive objects collide, or two massive objects orbit each other, they will send off ripples across space-time that can be detected.

The Laser Interferometry Gravity Wave Observatory (LIGO) is a device that uses laser light to detect any difference in two very long pathways for light in an L-shaped tunnel complex.
Gravity Waves

The Laser Interferometer Space Antenna (LISA) is a proposed interferometer that would detect gravity waves in space. The set of satellites would orbit the Earth as shown below.

The original mission is not going to happen (budget cuts), but the European Space Agency may try it alone.

http://applesandwormholes.wordpress.com/2011/07/09/gravitational-waves-for-dummies/