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.

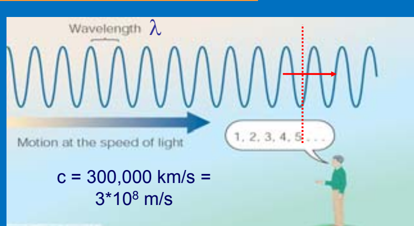
Light and Other Forms of Radiation

- 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)



- Light waves are characterized by a wavelength λ and a frequency f.
- f and λ are related through $f = c/\lambda$

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

Visible light has wavelengths between 4000 Å and 7000 Å (= 400 – 700 nm).

Light as a Wave (3)

- Wavelength and Frequency are related:

$$f\lambda = c$$

f = frequency

λ = 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:

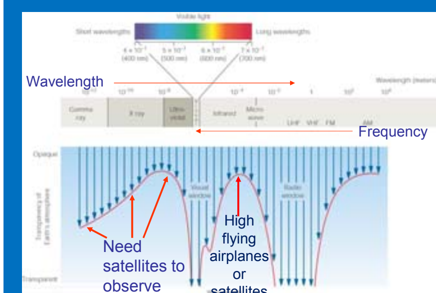
$$E = hf = hc/\lambda$$

$h = 6.626 \times 10^{-34}$ J*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***!

The Electromagnetic Spectrum

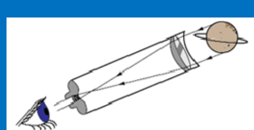


Telescopes

Astronomers use telescopes to gather more light from astronomical objects.

The larger the telescope, the more light it gathers.

Refracting Telescopes



Refracting telescopes use a pair of lenses to focus an image of distant objects.

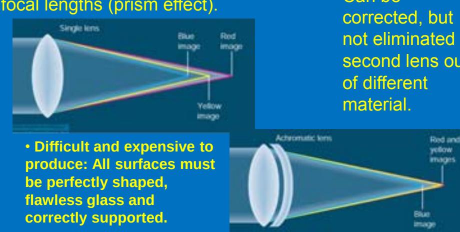
Galileo's homemade telescopes were refracting telescopes. This image shows two of the telescopes he used to make the amazing discoveries discussed earlier.

http://www.scitechantiques.com/galileo-telerscope-lenght-measurement/
http://www.nasa.gov/audience/foreducators/informal/features/F_Build_a_Telescope.html

Disadvantages of Refracting Telescopes

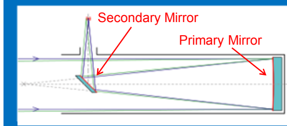
- **Chromatic aberration:** Different wavelengths are focused at different focal lengths (prism effect).

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



- **Difficult and expensive to produce: All surfaces must be perfectly shaped, flawless glass and correctly supported.**

Reflecting Telescopes



Reflecting telescopes use mirrors to focus an image of distant objects.

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

http://en.wikipedia.org/wiki/Newtonian_telescope

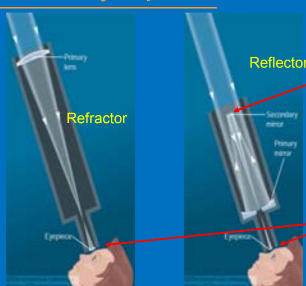
Refracting/Reflecting Telescopes

Refracting telescope: *Lens* focuses light onto the focal plane

Reflecting telescope: Concave *mirror* focuses light onto the focal plane

Almost all modern telescopes are reflecting telescopes.

Secondary Optics



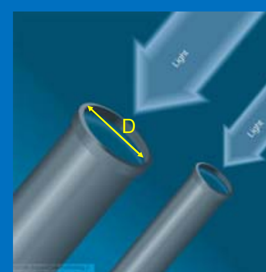
In reflecting telescopes: **Secondary mirror**, to re-direct light path towards back or side of incoming light path.

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:

$$A = \pi\,(D/2)^2$$



The Powers of a Telescope (2)

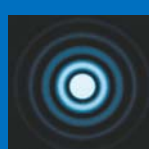
2. **Resolving power**: Wave nature of light => The telescope aperture produces fringe rings that set a limit to the resolution of the telescope.

Resolving power = minimum angular distance α_{min} between two objects that can be separated.

$$\alpha_{min} = 1.22\,(\lambda/D)$$

For optical wavelengths, this gives

$$\alpha_{min} = 11.6 \text{ arcsec} / D[\text{cm}]$$



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):

$$M = F_o/F_e$$

A larger magnification does <u>not</u> 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

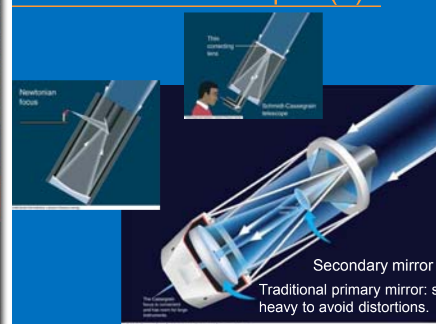
Far away from civilization – to avoid light pollution

The Best Location for a Telescope (2)

Paranal Observatory (ESO), Chile

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

Traditional Telescopes (1)



Traditional Telescopes (2)

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

Examples of Modern Telescope Design (1)

The Keck I telescope mirror has 36 individually controlled mirrors.

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

Examples of Modern Telescope Design (2)

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

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

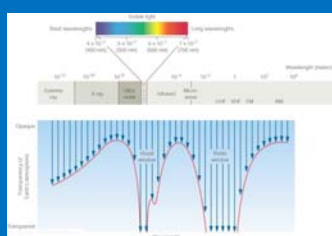
Examples of Modern Telescope Design (3)

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

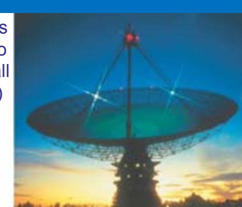
Radio Astronomy

Recall: ***Radio waves*** of λ ~ 1 cm – 1 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 100-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 ~ 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 2000's

- 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 λ < 290 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

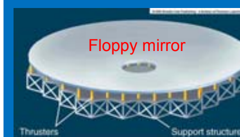
Gamma-rays: most energetic electromagnetic radiation; traces the most violent processes in the universe

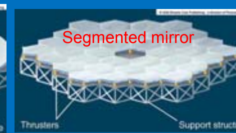
The Compton Gamma-Ray Observatory

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

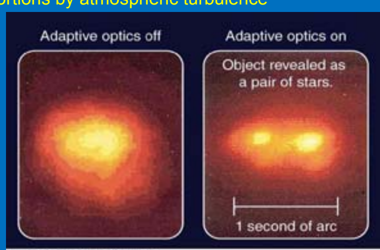




2. Simpler, stronger mountings ("Alt-azimuth mountings") to be controlled by computers

Adaptive Optics

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



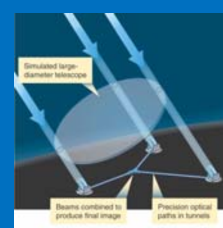
Interferometry

Recall: Resolving power of a telescope depends on diameter D:

$$\alpha_{min} = 1.22\ \lambda/D.$$

This holds true even if the entire surface is not filled out.

• Combine the signals from several smaller telescopes to simulate one big mirror → **interferometry**



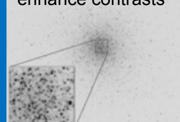
CCD Imaging

CCD = Charge-coupled device

• More sensitive than photographic plates

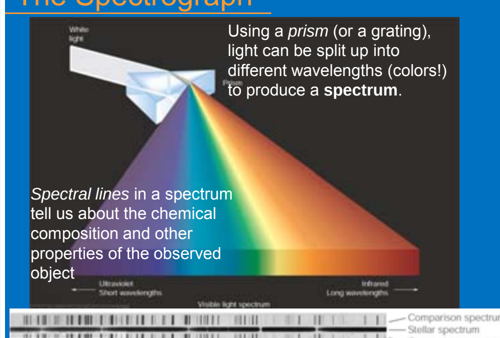
• Data can be read directly into computer memory, allowing easy electronic manipulations

Negative image to enhance contrasts



False-color image to visualize brightness contours

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 $\alpha_{min} = 1.22\ \lambda/D$.

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.

http://physics.ua.edu/astroparticle/

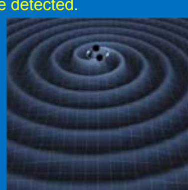
Particle Astronomy

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.

http://physics.ua.edu/astroparticle/

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.



http://www.space.com/20939-gravitational-wave-detector-search.html

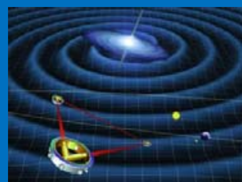
Gravity Waves

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.

http://www.ligo-la.caltech.edu/LLO/overviewsci.htm

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 <u>not</u> 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/