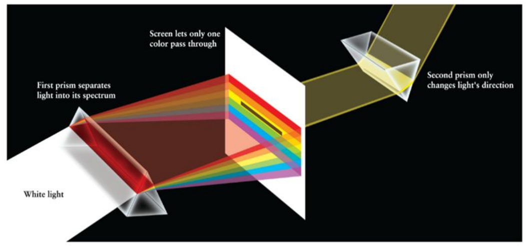
Chapter 3- Light and telescopes

Newton’s light experiments

- Glass does not add colour



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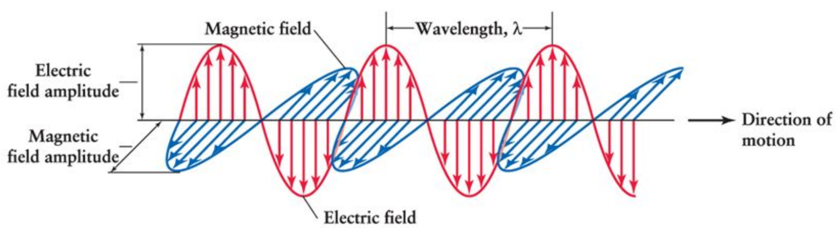
Electromagnetic radiation

•EM radiation travels as coupled oscillating electric and magnetic fields **perpendicular** to each other. The direction of travel of this wave is **perpendicular** to the two fields: g, X, UV, Vis, IR, MW, Radio.

•Wavelength (l) is the distance between two wave crests. The period *P* is the time between crests, and the frequency ‘nu’ n = 1/*P* determines the **colour**.

•EM waves travel at 299 792 458 m/s » 3 x 10^8 km/s in vacuum, *v* (not n here) **slower** in materials: **index of refraction** $n = c/v > 1$ and wavelength l in materials is shorter than wavelength l_0 in vacuum (value quoted): $l = l_0/n$.



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Wave travel, interference, diffraction

Water waves do not affect each others as they pass through but can add momentarily **constructively** or **destructively**: **interference**. Same with EM waves.
Double slit experiment can be realized with both kinds of waves. This is demonstration of wave nature of light. EM radiation also behaves like particles: dual nature!

The nature of light (EM radiation)

•Despite the name, neither visible light nor any other type of EM is electrically charged.

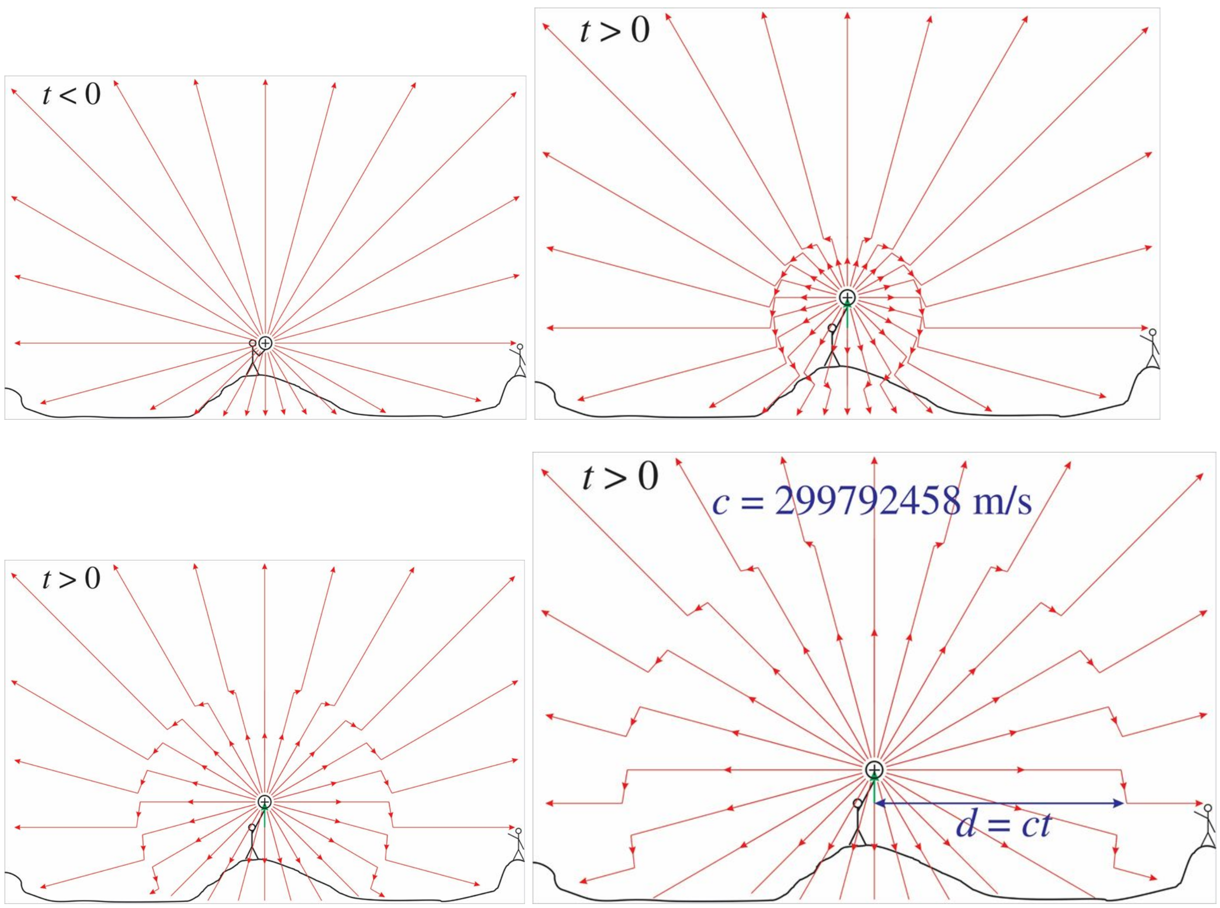
•Refraction (bending of light) is dependent on speed of light in material, and so is wavelength: $l = l_0/n$. Shorter wavelengths are more refracted (usually). So blue more than red.

•Constant universal speed of light in vacuum is 299 792 458 m/s. But really this is the **speed of information** in our universe!

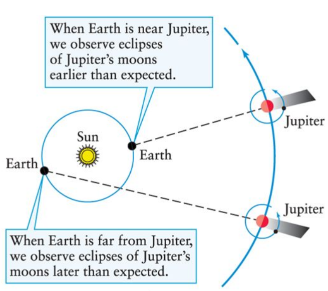
•Einstein proposed that light travels as waves enclosed in discrete **wave packets** later called **photons.** Photons with different frequencies n (thus different wavelengths) have different amounts of energy. Thus blue has more energy than red, UV more than blue, MW and radio are least energetic: $E = h n$, $h = 6.626 \times 10^{-34}$ J s (Planck's constant).

•Chemical bonds can be broken by UV, X and g rays (cancer etc.). IR, MW and radio can only **heat** materials (despite lunatic fringe). Visible is in between: red dye degraded by visible light etc.

C is speed of info?



Evidence that light travels at c



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•In 1675, Ole Rømer used two eclipses of one of Jupiter's moons to first show that light does not travel infinitely fast. He used these observations to measure its speed. His measurement was close: 220 000 000 m/s.

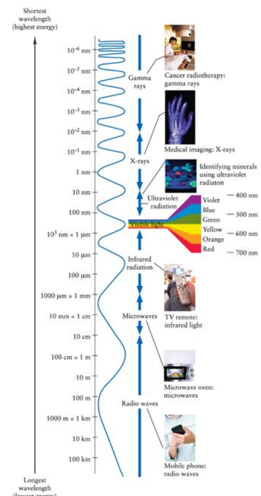
•One can also use Maxwell's equations to calculate the speed of light from constants e_0 and m_0. Get same value 299 792 458 m/s.

Romer’s notes rediscovered in 1913

Evidence for invisible infrared radiation

Visible colours separated by a prism. Thermometers in region illuminated by visible light show *T* lower than the thermometer to the right of red. Therefore, there must be some (more in fact) radiation heating the warmest thermometer. This energy is what we call infrared radiation—invisible to the human eye but detectable as heat. Pit vipers can ‘see’ IR.

Electromagnetic spectrum



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From top: Will & Deni McIntyre/Science Source; Ted Kinsman/Science Source; Chris Martin-Bahr/Science Source; Bart Broek/Getty Images; Michael Haegele/Corbis/Getty Images; franckreporter/E+/Getty Images

•There are a wide range of wavelengths of electromagnetic waves. We classify these waves depending on their source, use, or interactions with matter.

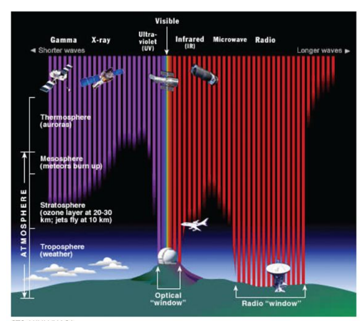
•Only a very small range of wavelengths, 380 nm to 740 nm (1 nm = 10^{-9} m), is visible to humans. This corresponds to range 430 to 770 THz (1 THz = 10^{+12} Hz).

•Other wavelengths are classified as gamma rays, X-rays, ultraviolet radiation, infrared radiation, microwaves, or radio waves.

•Visible light correspond to atmosphere’s transparency: no coincidence…

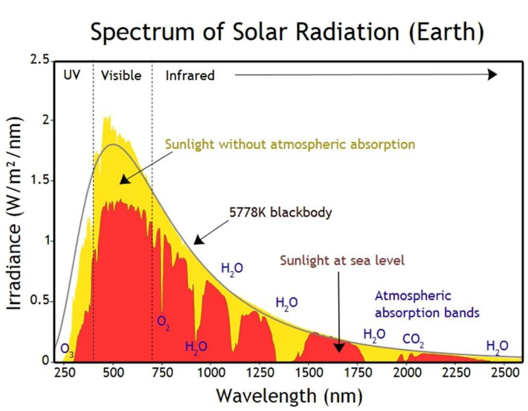
Windows through the atmosphere

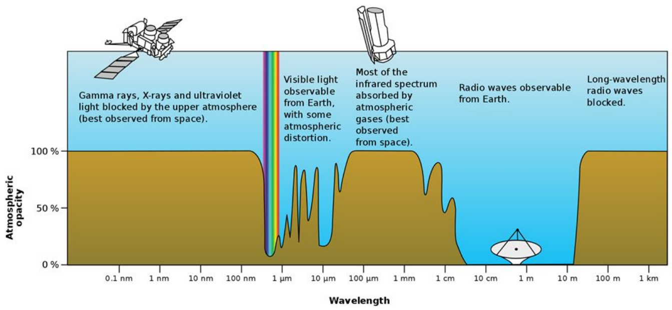
- Different types of EM radiation penetrate Earth’s atmosphere in varying amounts. Some reach Earth’s surface
- Other types are absorbed or scattered by gases in air at different characteristic altitudes (indicated by heights of windows)
- Atmosphere does not have actual windows
- Researchers use the term to characterize the passage of radiation through it



STScI/JHU/NASA

Spectrum of solar radiation (earth)





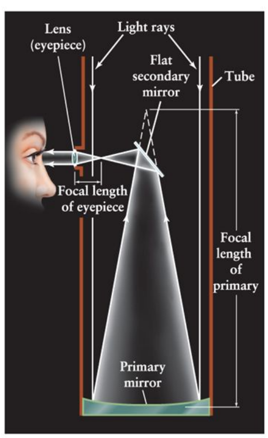
Newton’s refelcting telescope (replica)

This is a replica of Newton’s reflecting telescope that was built in 1672. This reflecting telescope had a spherical primary mirror 30 mm in diameter.

Its magnification was 40x, meaning that as seen through the telescope, the images were 40 times larger in angle than they appeared to the naked eye.

Incidentally, 40x is close to maximum theoretical magnification for 30 mm objective mirror, so Newton must have tried many configurations before this.

Newtonian telescope



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•Large mirror used to gather and focus light is called **primary mirror**.

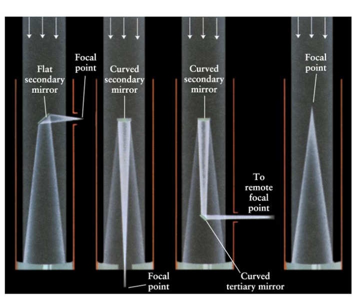
•The surface is concave. Parallel light rays from distant objects converge to a focal point.

•The distance between the mirror and its focal point is called the focal length.

•Newtonian telescope uses flat secondary mirror to redirect focused light to the side for viewing. The image is viewed through a small focal length lens called an eyepiece which determines **magnification** value.

•Best ‘bang for the buck’ but needs collimation (open design). **Dobsonian** refers to AltAz mount, otherwise same.

Other reflecting telescopes



a Newtonian focus b Cassegrain focus c Nasmyth focus and coudé focus d Prime focus

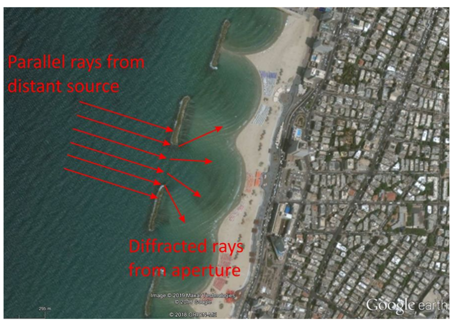
Purposes of a telescope

•**Light Collection**: a telescope most important function is to provide observers with as **bright** an image as possible. **Aperture** is objective diameter. Geometry, goes as **square of aperture**. Human eye is about 7 mm max. A 70 mm aperture telescope gather 100x light than human eye! This is fixed for a given telescope.

•**Higher Resolution**: Another vital function of any telescope is to reveal details of objects. Due to diffraction, goes as **aperture**. So a 70 mm aperture telescope shows 10x more detail than human eye! This is fixed for a given telescope.

•Magnification:The final function of a telescope is to make objects appear larger, up to a point: because of diffraction and wavelength of light, theoretical maximum is 1x to 2x per every mm of aperture. So max magnification for 70 mm telescope is between 70x and 140x.

Water travel, interference aka diffraction



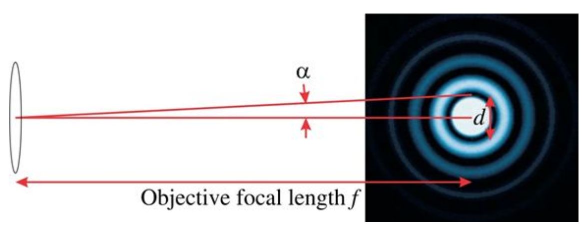
Resolution of telescope

Angular resolution (often just called *resolution)* measures the clarity of images.
A **circular aperture** will turn a point source into an **Airy pattern** due to diffraction. Resulting image is thus 'painted' with that brush.
Angular width of that brush in **radians** is given by

$a = 2.44\ l / D$

where l is light wavelength
and *D* is aperture diameter.

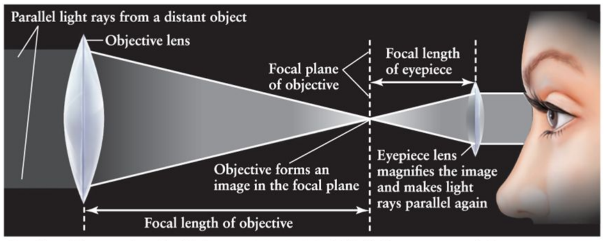
•**Rayleigh criterion** for resolving point sources is half that:



$a_{min} = 1.22\ l / D$

Essential of a telescope

A refracting telescope consists of a large long-focal-length f_o **objective** lens that collects and focuses light rays and a small short-focal-length f_e **eyepiece** lens that restraightens the light rays. The lenses work together to brighten, resolve, and magnify the image formed at the focal plane of the objective lens. Magnification is just ratio f_0/f_e and can be adjusted by selecting different eyepieces.



Light refracting telescope

This giant refracting telescope, built in the late 1800s, is housed at Yerkes Observatory near Chicago. The objective lens is 102 cm in diameter, and the telescope tube is 19⅓ m long.

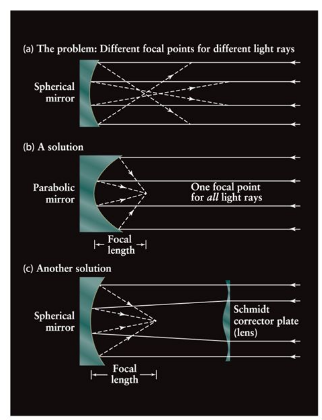
Size limited by glass flexibility since lenses are supported by edges. Mirrors can be supported from below.

Refractors suffer from chromatic aberration

Light of different **wavelengths** is refracted by **different amounts** when passing through glass. Therefore, single lenses have **different focal lengths** for light of different **colors** passing through them. Image showing chromatic aberration. Note the different colors on the edges of the petals (‘fringing’). Can be reduced using **achromatic doublets** and **triplets** made using at least 2 different kinds of glass

All suffer from spherical aberration

When a **spherically shaped** mirror or lens is used, the light rays hitting far from the center do not converge at the same point. One solution is to instead grind the mirror into a **parabolic** shape. Another solution is to use a **correcting lens** to make all the light rays converge at a single point.



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Mosaic of charge-coupled devices (CCD) camera

Multiple CCD devices have been combined into large CCD arrays such as this 40 CCD detector with 378 million light-sensitive pixels (370 MP).

●This image of the Rosette Nebula, a region of star formation 5000 ly away in the constellation Monoceros (the Unicorn), was taken with it. It shows the incredible detail that can be recorded by large telescopes and high-resolution CCDs.

Atmospheric turbulence (twinkling)

The same star field photographed with (a) a ground-based telescope, which is subject to poor **seeing** conditions that result in stars twinkling, and (b) the Hubble Space Telescope, which is free from the effects of twinkling.

Light pollution

Two images of New York City show the increase of light in the sky from 1955 to 2010. Compare the skies just above the buildings. This light prevents New Yorkers from seeing dimmer stars that are visible in darker locations. Since 1972, light pollution, a problem for many observatories around the world, has been **partially** controlled by local ordinances passed by cities if you're lucky.

Todd Carlson/ SkyNews Magazine

Hubble space telescope (HST)

NASA

This photograph of the Hubble Space Telescope (HST) hovering above the space shuttle's cargo bay was taken in 1993, at completion of the first servicing mission. HST has studied the heavens at infrared, visible light, and ultraviolet wavelengths. Note the Canadarm.

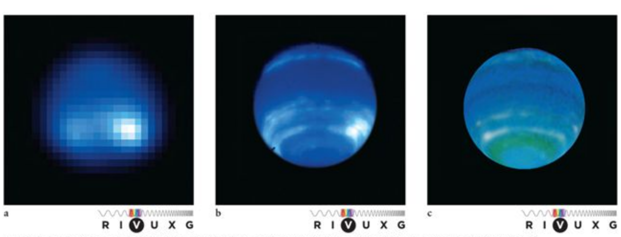
Images from Earth and space

Using adaptive optics, which calculate the amount of twinkling of our atmosphere and change the shape of the mirror accordingly, we can receive better images from ground-based telescopes.

a)Image of Neptune from an Earth-based telescope without adaptive optics.

b)Image of Neptune from the same Earth-based telescope with adaptive optics.

c)Image of Neptune from the Hubble Space Telescope, which does not incorporate adaptive optics technology.



a & b: Imke de Pater, UC Berkeley/W. M. Keck Observatory; c: NASA, L. Sromovksy, and P. Fry, University of Wisconsin-Madison

Orion in visible, UV and IR

•Optical photograph of the constellation Orion.

•Ultraviolet image of Orion.

•**False-color** view from the Infrared Astronomical Satellite of the entire Orion asterism. Colors indicate intensities of infrared radiation.

•Different wavelengths provide different information.

Radio telescope

The secondary mirror on most telescopes blocks some incoming light. This new radio telescope at the National Radio Astronomy Observatory in Green Bank, West Virginia, has its prime focus hardware located **off-center** from the telescope's 100-m x 110-m oval reflector.

Arecibo radio telescope

Karl G. Lansky Very Large Array

-27 telescopes of the Very Large Array (VLA) in central New Mexico. Besides being able to change the angles at which they observe the sky, these telescopes can be moved so that the array can detect either wide areas of the sky (telescopes close together, as here) or small areas with higher resolution (when they are farther apart)

- the inset shows the traditional secondary minor assembly in the center of each of these antennas

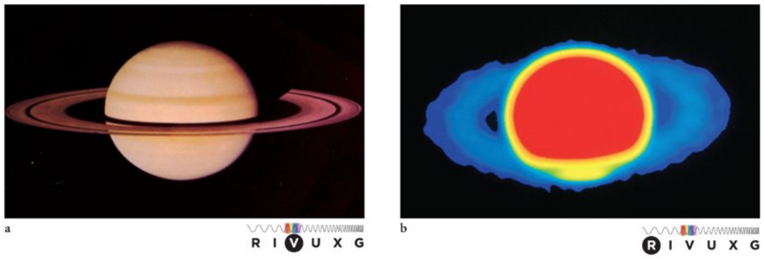
Very long baseline interferometry (VLBI)

Figure 4.7b The first successful long-distance interferometry experiment was conducted in 1967 in Canada, with the 25.6 m Dominion Radio Astrophysical Observatory telescope in Penticton, British Columbia (left), in conjunction with the 46 m telescope at the Algonquin Radio Observatory at Traverse Lake in Ontario (right) to simulate the resolution of a giant radio telescope measuring 3074 km, the physical distance between the two instruments.

Algonquin radio observatory (ARO)

Visible and radio views, Saturn

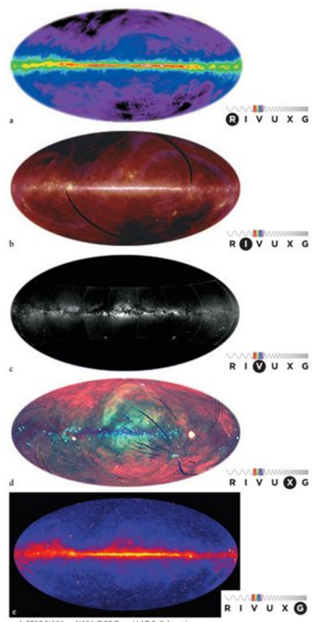
The visible light picture was taken by a camera on board a spacecraft as it approached Saturn. The view was produced by sunlight scattered from the planet's cloudtops and rings. The radio image is a false-color picture, taken by the VLA, and shows radio emission from Saturn at a wavelength of 2 cm.



a: NASA; b: Image courtesy of NRAO/AUI/NSF

Milky Way central region Universe, EM spectrum

NASA/JPL-Caltech; NASA Image Collection/Alamy stockphoto



a–d: GFSC/NASA; e: NASA/DOE/Fermi LAT Collaboration

Solar neutrino observatory (SudburyNO)

2073 m underground in the Creighton nickel mine in Sudbury. The Sudbury Neutrino Observatory is centered around a tank that contains 1000 tons of water. Occasionally, a neutrino entering the tank interacts with one or another of the particles already there, creating flashes of light called Cerenkov radiation. 9600 light detectors sense this light. The numerous silver protrusions are the back sides of the light detectors prior to their being wired and connected to electronics in the lab (seen at the bottom of the photograph).