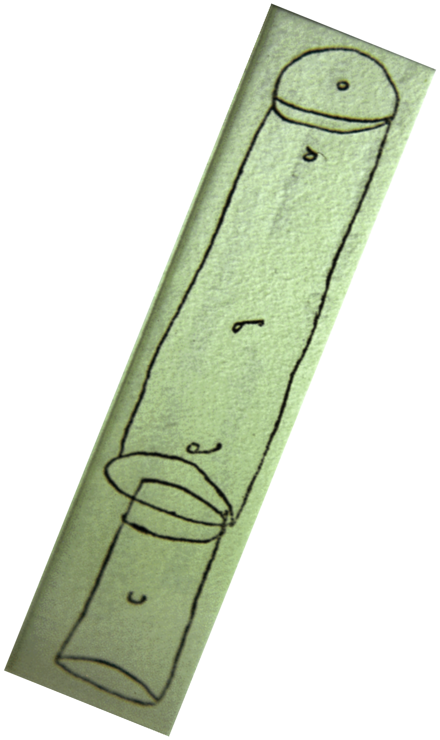
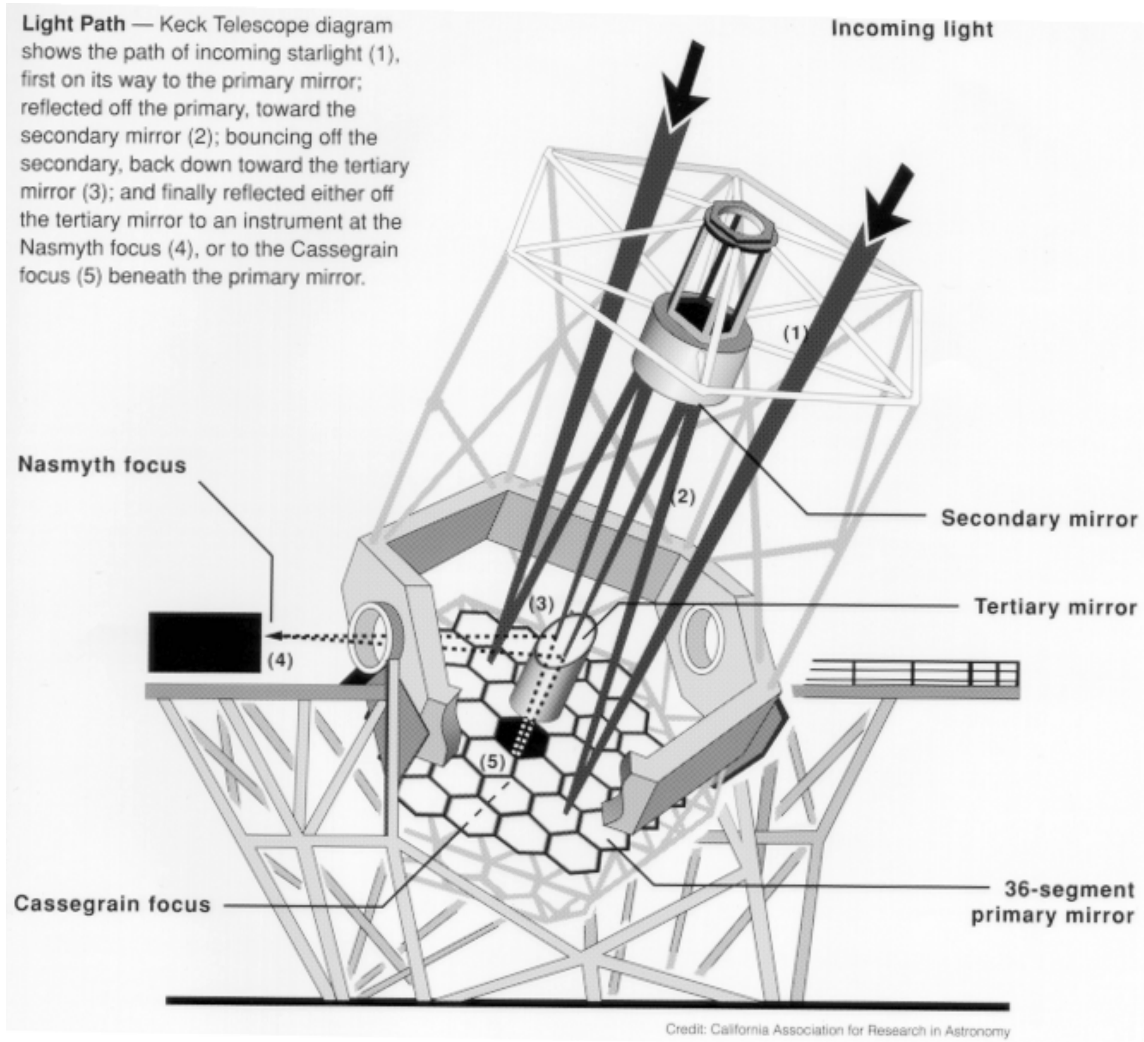
Optics and Telescopes





Optics and Telescopes

A telescopes main purpose is to :
-**gather more light** than can be collected by the unaided eye.
-provide high resolution **images and spectra** of objects.

How well we can **resolve an object** in the sky will depend on:
-the telescope's **angular resolution**
-the conditions of the atmosphere (**seeing**)

Multi-wavelength Astronomy
Telescopes are used to observe the sky in the radio, microwave, infrared, visible, ultra-violet, X-ray, gamma ray, and TeV bands.

High Energy Particle Observatories:
Several observatories are designed to detect high energy particles (ie electron, positrons, muons, neutrinos) from space.

Telescopes

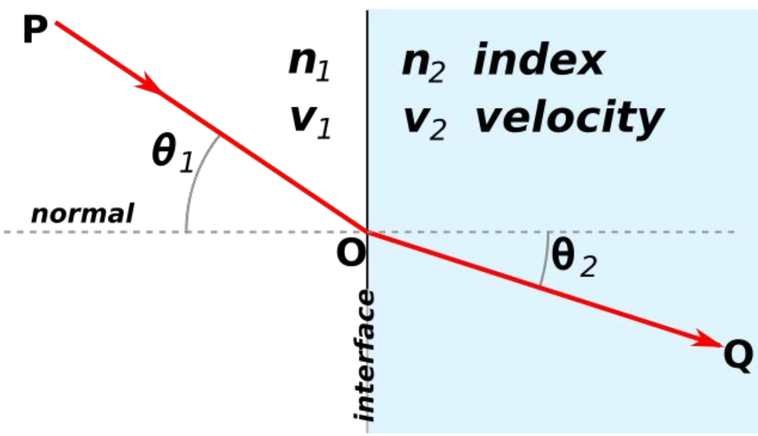
To understand telescopes we need to discuss **refraction.**

Refraction is the change in direction of light due to a change in its speed. This usually happens when light goes from one type of medium to another.

Refraction is described by **Snell's law**, which states that the angle of incidence θ_1 is related to the angle of refraction θ_2 by:

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{v_1}{v_2} = \frac{n_2}{n_1}$$

where n_1 and n_2 are the indices of refraction of the two media. $n = \frac{c}{v}$

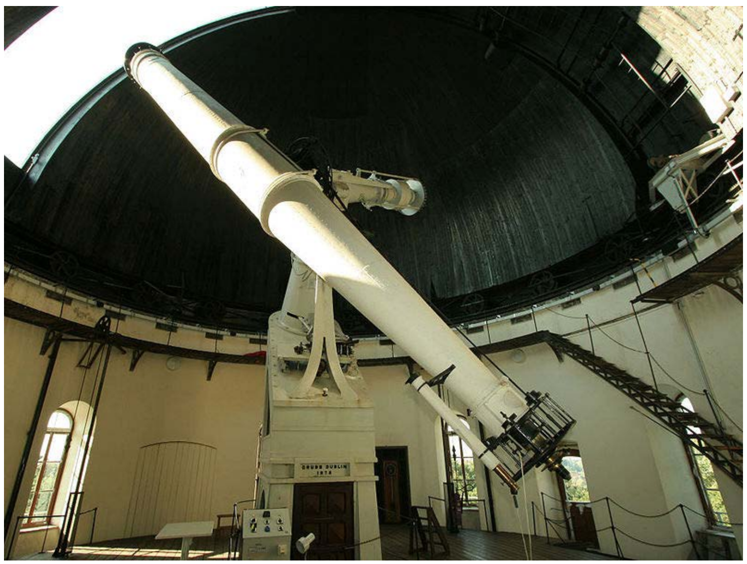


Telescopes

We will discuss two main types of optical telescopes:

(1) Refracting Telescopes

(2) Reflecting Telescopes



The 68 cm refractor at the Vienna University Observatory.

The 8 in reflecting telescope MEADE LX 200.

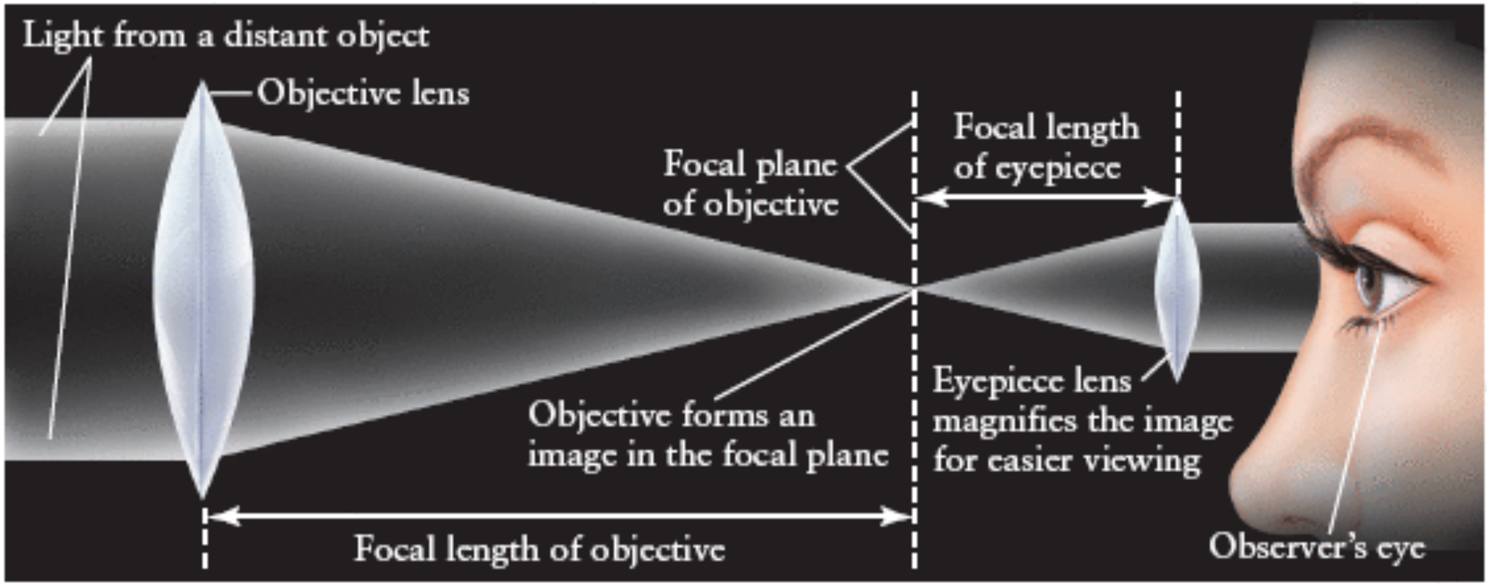
Properties of Telescopes

The two most important properties of a Telescope are:

(1) Collecting Area: Telescopes with larger collecting areas can gather more light in a shorter amount of time.

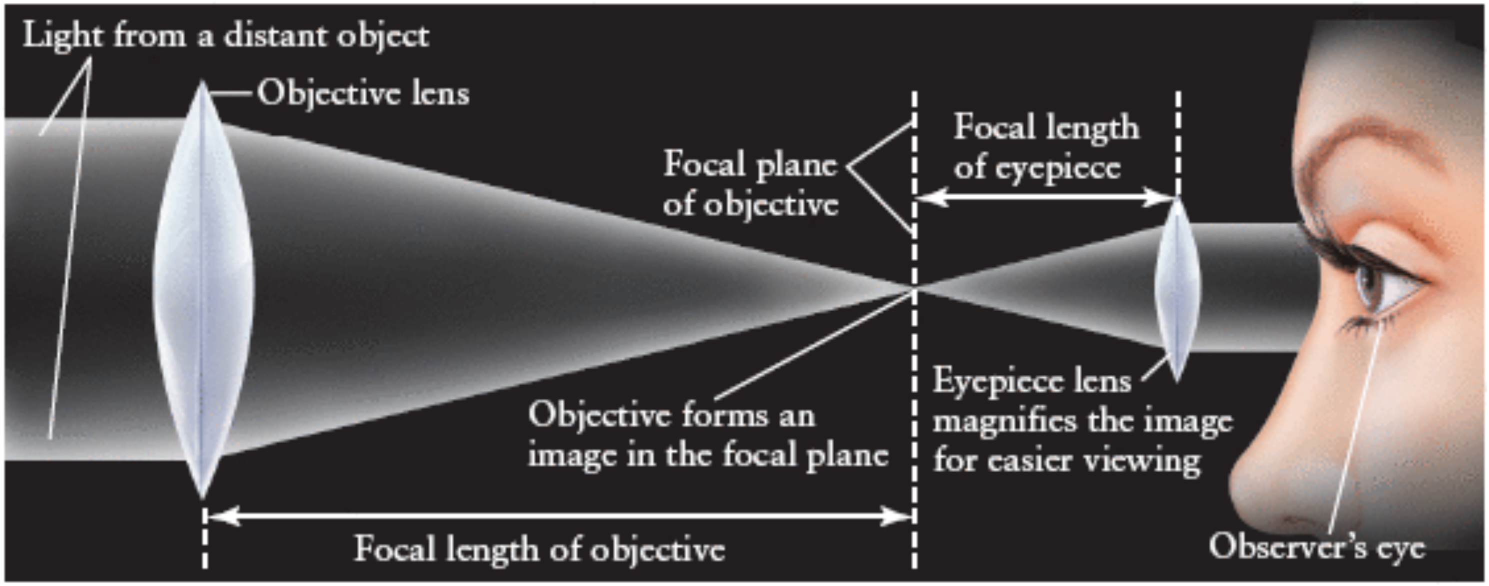
(2) Angular Resolution:
Angular Resolution is the angular size of the smallest feature that can be distinguished.

Refracting Telescopes



A **refracting telescope** consists of a large-diameter **objective lens** (convex lens) with a long focal length and a small eyepiece lens of short focal length. The **eyepiece lens** magnifies the image formed by the objective lens in its focal plane (shown as a dashed line).

Refracting Telescopes



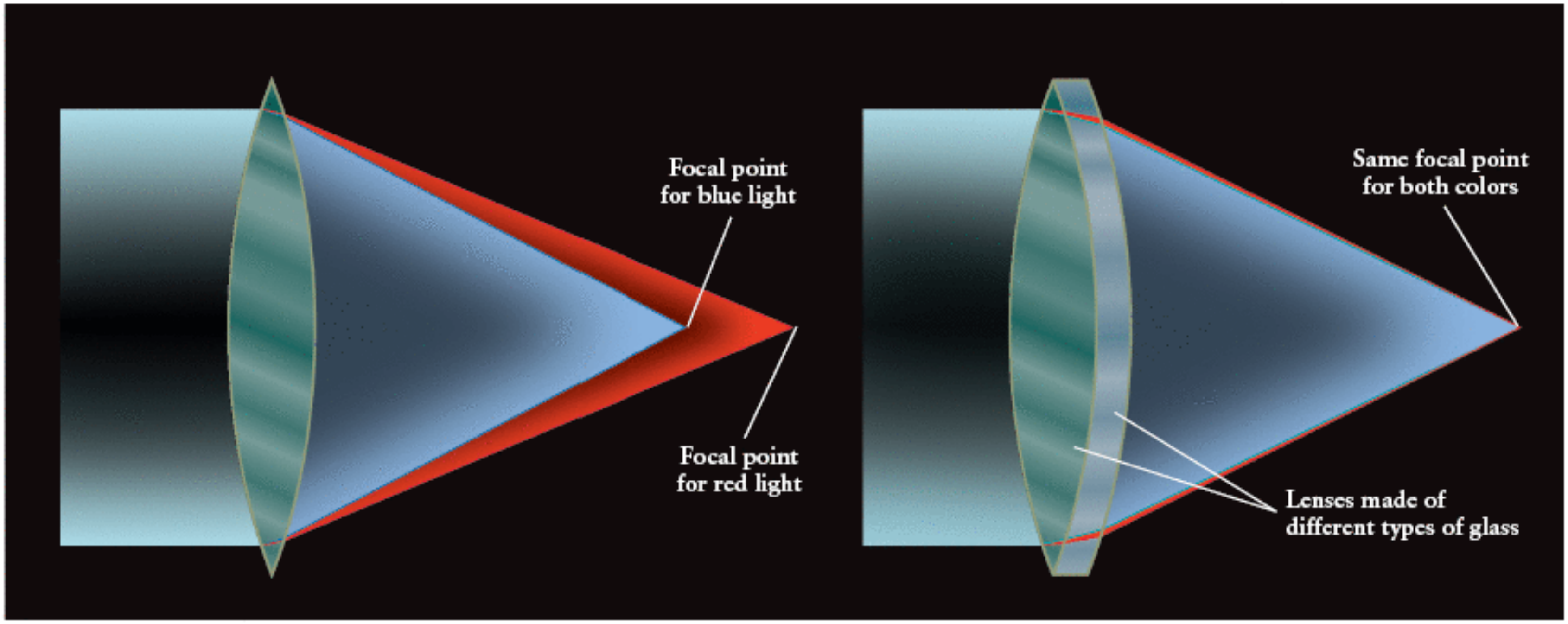
The **magnification** (M) provided by a **refracting telescope** is the ratio of the focal length of the objective (f_1) to the focal length of the eyepiece (f_2). $M = f_1/f_2$

Assume a crater on the moon has an angular size of about 0.01°. A telescope with a magnification of 20× will make it appear to have an angular size of 20×0.01° = 0.2°

Refracting Telescopes

Example: A small refracting telescope has an objective of focal length 1 m. If the eyepiece has a focal length of 4.0 cm, what is the magnification of the telescope?

Chromatic Aberration of Refractors



(a) The problem: chromatic aberration

(b) The solution: use two lenses

(a) A single lens suffers from a defect called chromatic aberration, in which different colors of light are brought to a focus at different distances from the lens. (b) This problem can be corrected by adding a second lens made from a different kind of glass.

Why you should not get a refractor

(a) Light has to travel through an objective lens. In reality objective lenses contain **defects** such as bubbles that can **distort the image**.

(b) Some of the **light gets absorbed** by the objective lens.

(c) Chromatic aberration is difficult and expensive to correct especially for very large lenses.

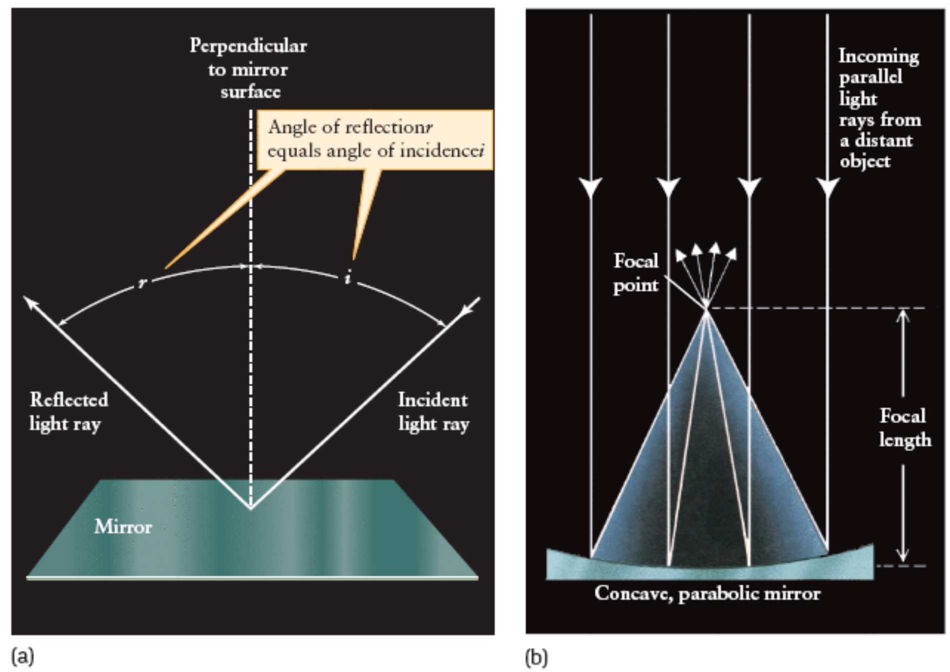
(d) Large objective lenses suffer from sag because of their weight. This **sag results in distortion** of the image.

Reflecting Telescopes

Almost all modern day telescopes are reflecting telescopes. The understand reflecting telescopes we first need to discuss reflection.

(a) The **angle of incidence** (i), is always equal to the angle the angle of **reflection** (r).

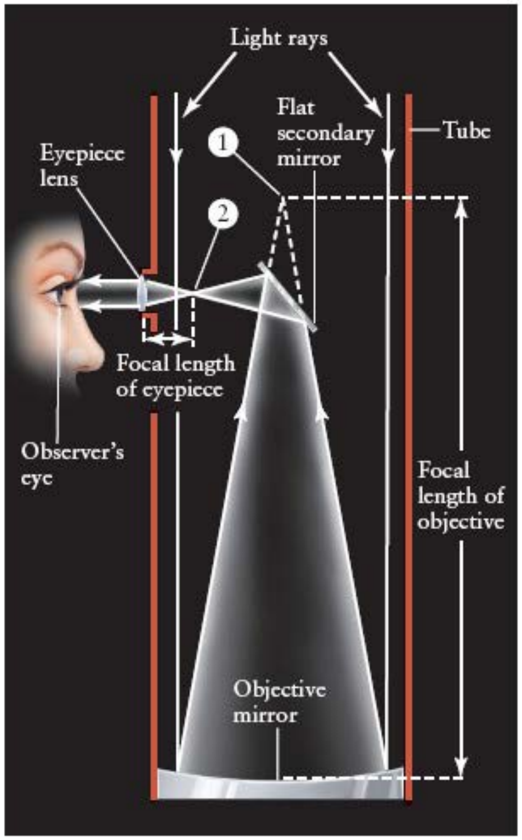
(b) A concave mirror causes parallel light rays to converge to a focus at the **focal point**. The distance between the mirror and the focal point is the **focal length** of the mirror.



Types of Reflecting Telescopes

1. In a **Newtonian telescope**, the image made by the objective is moved from point 1 to point 2 by means of a flat mirror called the secondary. An eyepiece magnifies this image, just as for a refracting telescope.

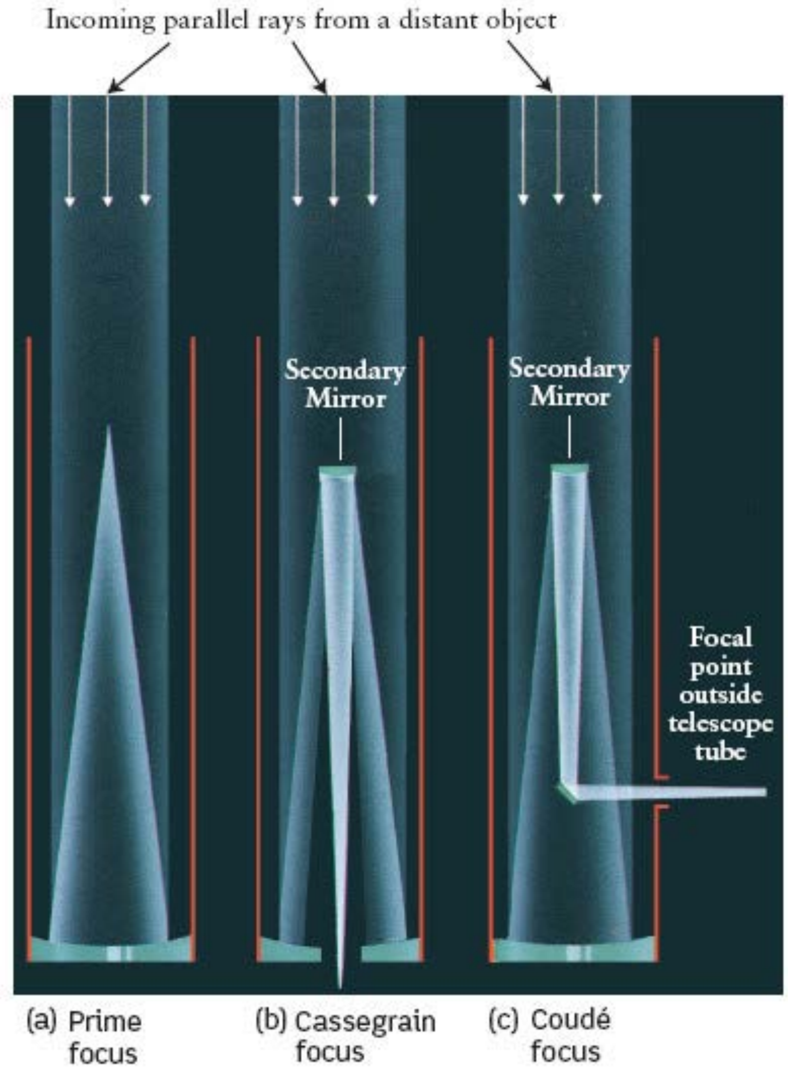
The magnification of a Newtonian is the ratio of the focal length of the objective to the focal length of the eyepiece: M = f1/f2



Types of Reflecting Telescopes

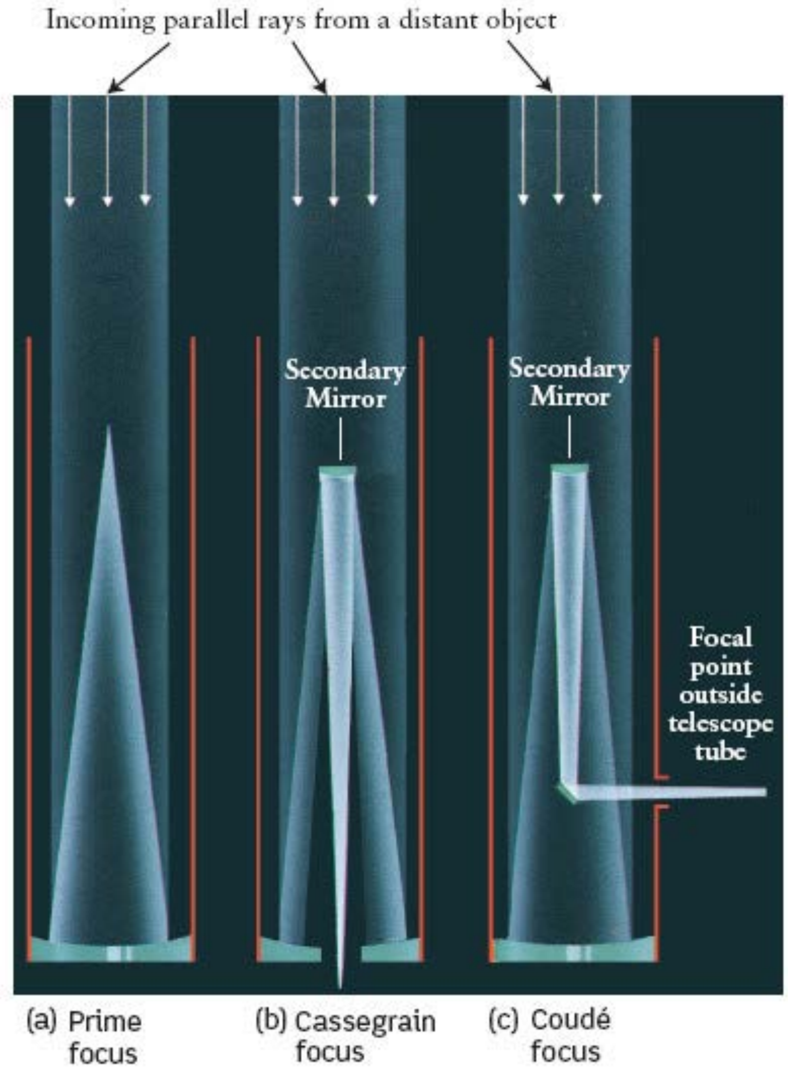
2 **Prime Focus**: The focal point is in front of the mirror. It has been used in some large telescopes and it usually provides the highest-quality image, because there is no need for a secondary mirror.

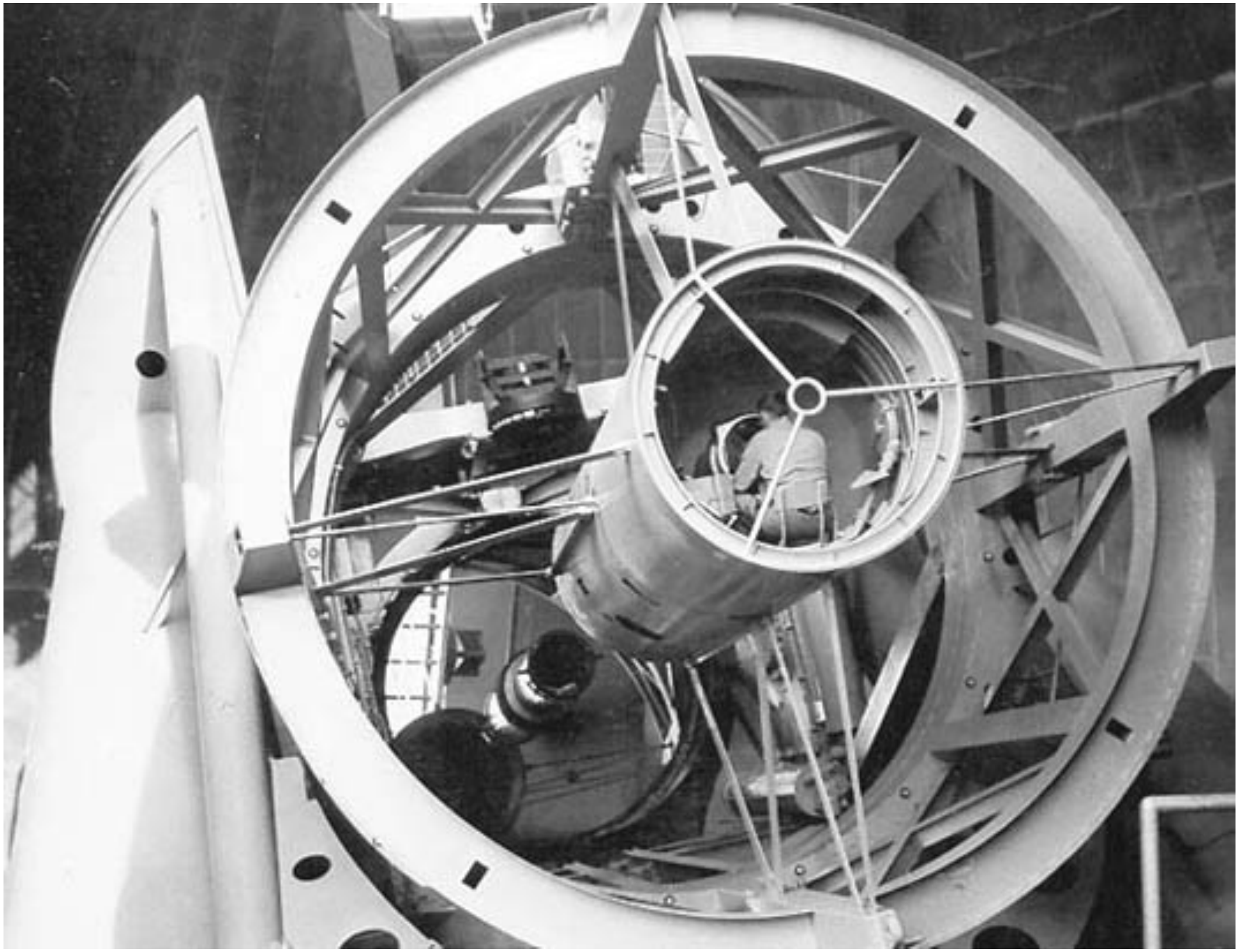
3. **Cassegrain Focus**: A hole is drilled directly through the center of the primary mirror, and a convex secondary mirror placed in front of the original focal point reflects the light rays back through the hole.



Types of Reflecting Telescopes

4 **Coude Focus**: a series of mirrors channels the light rays away from the telescope to a remote focal point where the equipment is located.





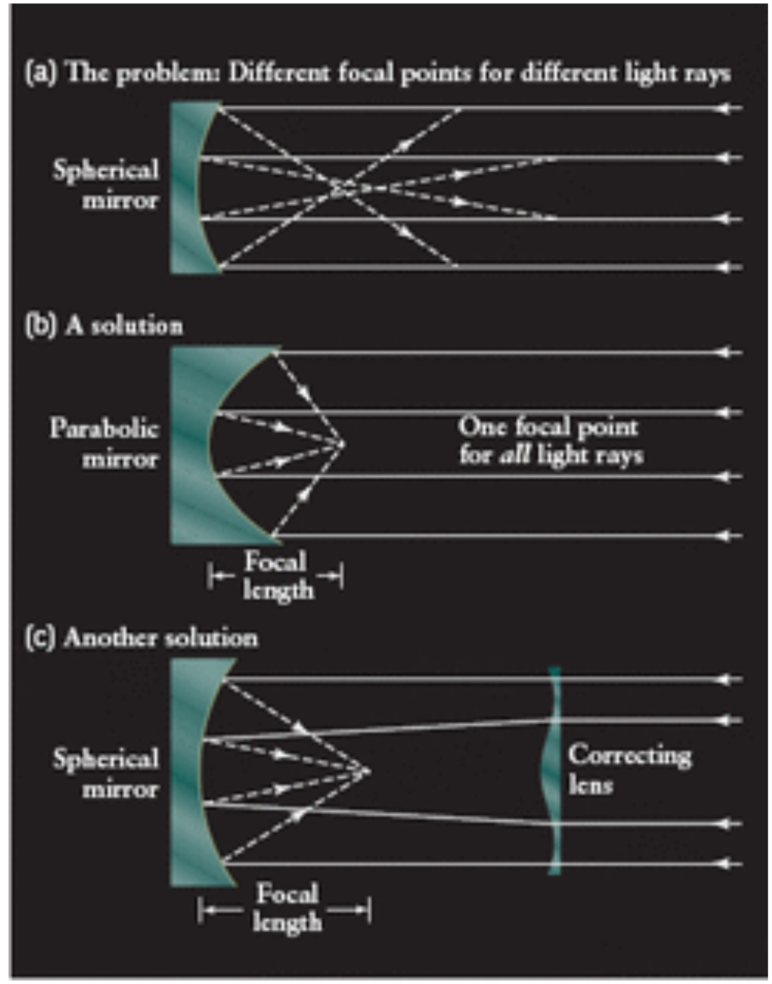
Spherical Aberration of Reflectors

Different parts of a spherically concave mirror reflect light to slightly different focal points. This effect, called **spherical aberration**, causes image blurring.

Spherical aberration can be corrected by using :

- a parabolic objective mirror

- or using a correcting mirror



Ritchey-Chretien Reflectors

The Ritchey-Chretien telescope is a Cassegrain reflector that is specialized to eliminate coma. Coma makes off axis sources appear as tear drops.

A Ritchey-Chretien telescope has a hyperbolic primary and a hyperbolic secondary mirror.

The twin Keck telescopes on Mauna Kea are among the largest optical/ near-infrared instruments currently in use around the world.

Light-gathering power of a telescope

The **light-gathering power of a telescope** is measure of the amount of light brought to a focus.

A telescopes light-gathering power (P_T) is therefore directly **proportional to the area of the objective lens**, which in turn is proportional to the square of the lens diameter (D). $P_T \propto D^2$

Example: Each of the two Keck telescopes on Mauna Kea in Hawaii uses a concave mirror 10 m in diameter to bring starlight to a focus.
Question: How many times greater is the light-gathering power of either Keck telescope compared to that of the human eye? Assume a human eye has a pupil diameter of about 5 mm.

Angular Resolution of a Telescope

An important property of a telescope is its **angular resolution**.

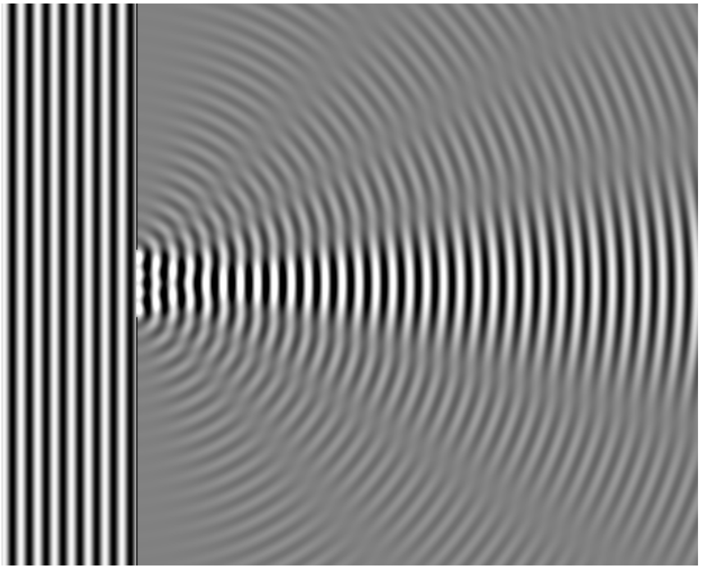
Angular resolution of a telescope is the **angular size of the smallest feature that can be distinguished**.

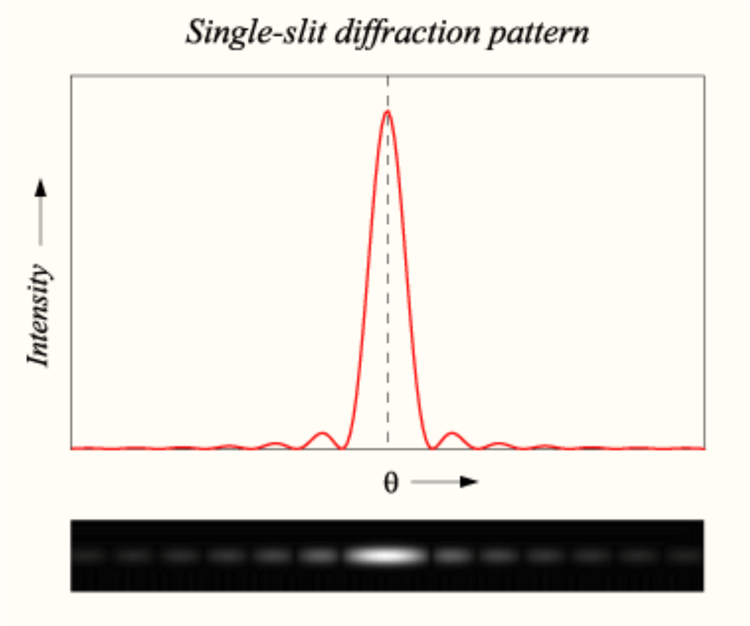
The angular resolution of your eye (for 20/20 vision) is about 1 arcmin. The planets have angular sizes of less than 1 arcmin and this is why they appear as points.

The angular resolution will depend on
- the quality of the mirrors, mirror design
- diffraction
- atmospheric turbulence (seeing)

Diffraction

Diffraction is the apparent bending of waves around small obstacles and the spreading out of waves past small openings.





Diffraction

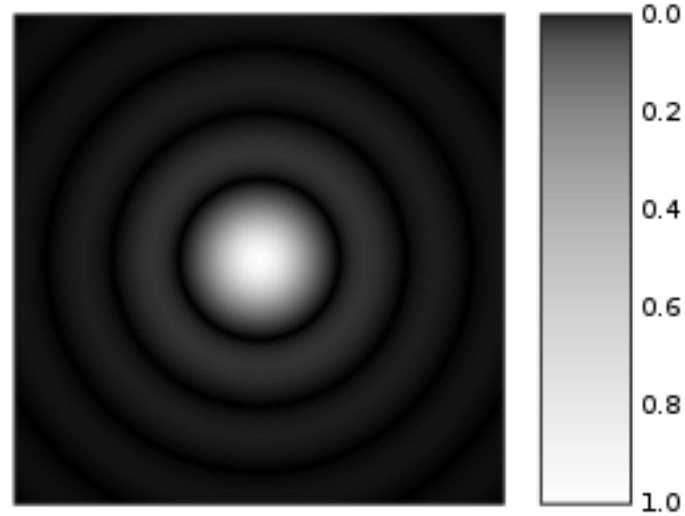
The light collected by a telescope at the focal point is not focused to a point but forms a **diffraction pattern** having a central peak with a angular size between the peak and the first null:

$$\theta(arc\sec) = 2.5 \times 10^5 \frac{\lambda}{D}$$

θ = diffraction-limited angular resolution of a telescope, in arcseconds

λ = wavelength of light, in meters

D = diameter of telescopes objective, in meters



Diffraction by a **circular aperture.** Notice the variation of intensity with angle.

Question: What is the diffraction limited angular resolution of

(a) the human eye (D = 5 mm)

(b) The Keck telescope (D = 10 m)

at H_α.

Seeing Disk

Turbulence in the atmosphere will blur an image. Even through the largest telescopes that are not limited by diffraction a point source looks like a blob.

The angular size by which a stars size is broadened due to the atmosphere is called the **seeing disk**.

The size of the seeing disk depends on the location of the observations. For example, on **Kitt Peak** in Arizona and **Cerro Tololo** in Chile, the seeing disk is typically around 1 arcsec.

Correcting for Turbulence: Adaptive Optics

The goal of **adaptive optics** is to compensate for atmospheric turbulence.

In an adaptive optics system, sensors monitor the dancing motion of a star due to turbulence 10 to 100 times per second, and a powerful computer rapidly calculates the mirror shape needed to compensate.

If a bright star is not near the field of view a laser beam is used. The beam strikes sodium atoms in the sky, causing them to glow and make an **artificial "star."** Tracking the twinkling of this "star" makes it possible to undo the effects of atmospheric turbulence on telescope images.

Astronomical Interferometry

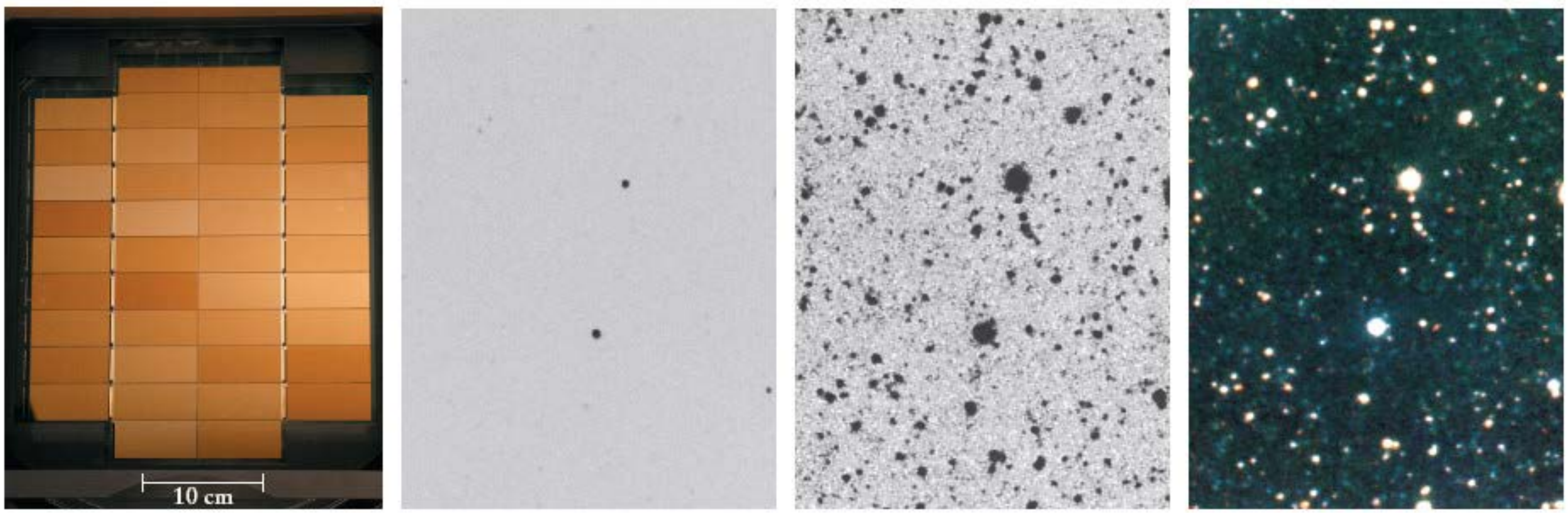
The ideal angular resolution that a telescope can achieve is determined by its diffraction limit (which is proportional to its diameter). The larger the telescope, the better its resolution.

The effective resolution of a combination of two telescopes is equivalent to that of one giant telescope with a diameter equal to the **baseline**, or distance between the two telescopes.

The twin Keck telescopes on Mauna Kea use **interferometry,** a technique of combining two or more telescopes to improve the angular resolution.

Q. What is is diffraction limited angular resolution of Keck I+II? Hint : d = 85 m

Instruments for Telescopes: CCDs



(a) A mosaic of 40 charge-coupled devices (CCDs)

(b) An image made with photographic film

(c) An image of the same region of the sky made with a CCD

(d) Combining several CCD images made with different color filters

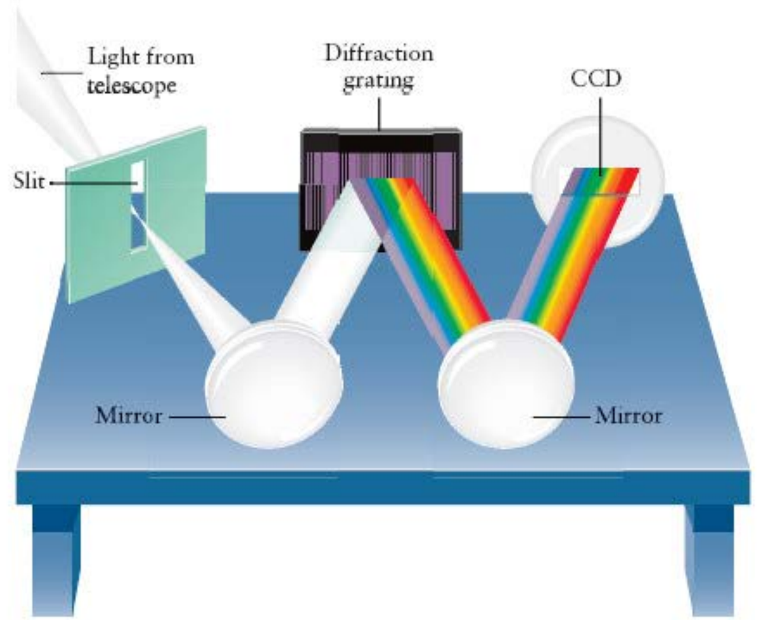
Telescopes can provide detailed pictures of distant objects. These images are usually recorded on charge-coupled devices (CCDs). Each one of the 40 CCDs used on the Canada-France-Hawaii Telescope (panel a) has 9.4 million pixels arranged in 2048 rows by 4608 columns.

Instruments for Telescopes: Spectrographs

A device that records spectra is called a **spectrograph**.

The main element on many spectrographs is a **diffraction grating**.

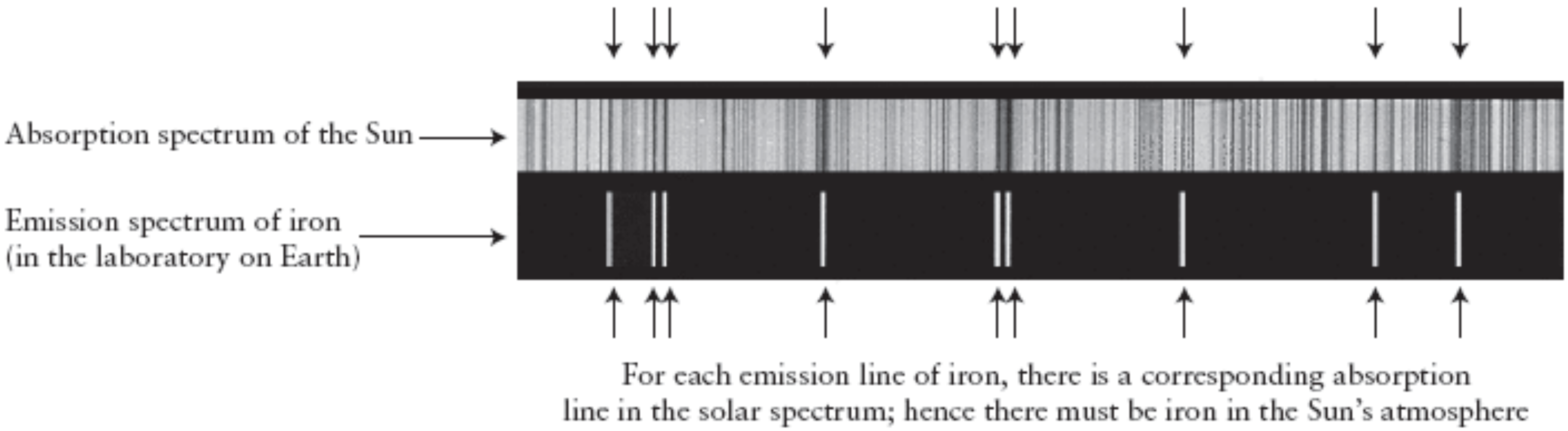
A **diffraction grating** consists of a slab of glass or metal that has thousands of closely spaced lines etched on it.



(a)

The light waves that come off from different parts of the diffraction grating interfere to produce a spectrum of the source.
The spectrum is sent onto a CCD where it is recorded.

Instruments for Telescopes: Spectrographs



After the spectrum of the source is recorded light from hot gasses are also passed through the slit, reflected off the grating and recorded on the CCD.

The emission lines from the hot gases serve as **reference lines** since the energies and elements that produce these lines are known from laboratory measurements.

Radio Astronomy

The first radio waves of an astronomical origin were discovered by **Karl Jansky** in the early 1930s.

Jansky was trying to figure out what was causing interference at 20 MHz with a trans-atlantic radio link. He built a steerable **radio antenna** to search for the source of the noise.

He concluded that an astronomical object in the direction of the constellation Sagittarius must be causing the radio interference.

In 1936 **Grote Reber** built the first parabolic "dish" radio telescope and conducted the first sky survey in the radio frequencies.

Reber’s radio telescope

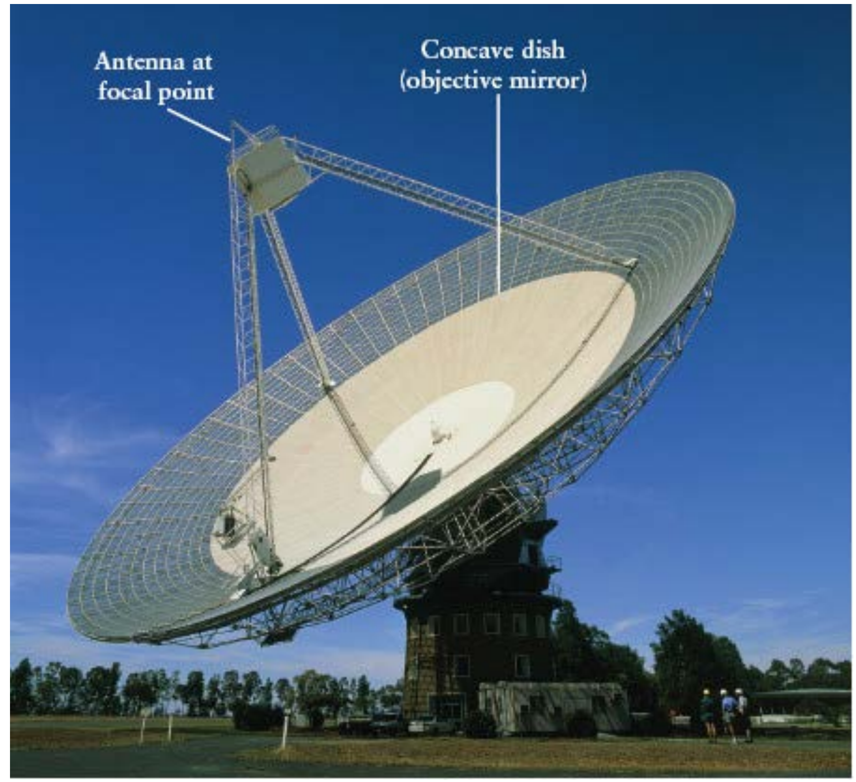
VLA in New Mexico

Radio Telescopes

A modern telescope consists of :

-a parabolic dish
- an antenna tuned to the desired frequency located at the focus.

The signal picked up by the antenna is relayed to an amplifier and recording instruments usually located at the base of the telescope pier.



PARKES, NSW, Australia
(64 m diameter)

Questions: 1) What frequency does 64 m correspond to?
2)Why can't microwaves at ν = 2.45 GHz leak through a microwave door?

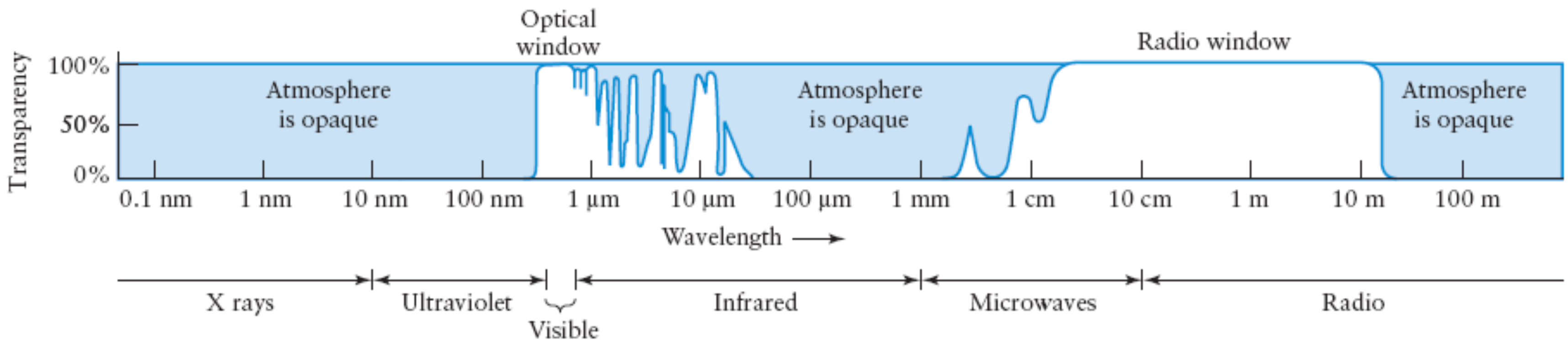
Radio Telescopes: Dealing with Diffraction

The diffraction limited angular resolution of a 10 m radio dish at λ = 21-cm is $\theta \sim 2.5\times10^5$ (21 cm /10 m) = 5250 arcsec

To improve the angular resolution of radio telescopes astronomers use the interferometry technique.

The **Very Large Array** (VLA) consists of 27 parabolic dishes, each 25 m in diameter. By pointing all 27 telescopes at the same object and combining the 27 radio signals, the VLA can produce radio views of the sky with an angular resolution as small as 0.05 arcsec.

The transparency of the Earth's Atmosphere



This graph shows the percentage of radiation that can penetrate the Earth's atmosphere at different wavelengths.

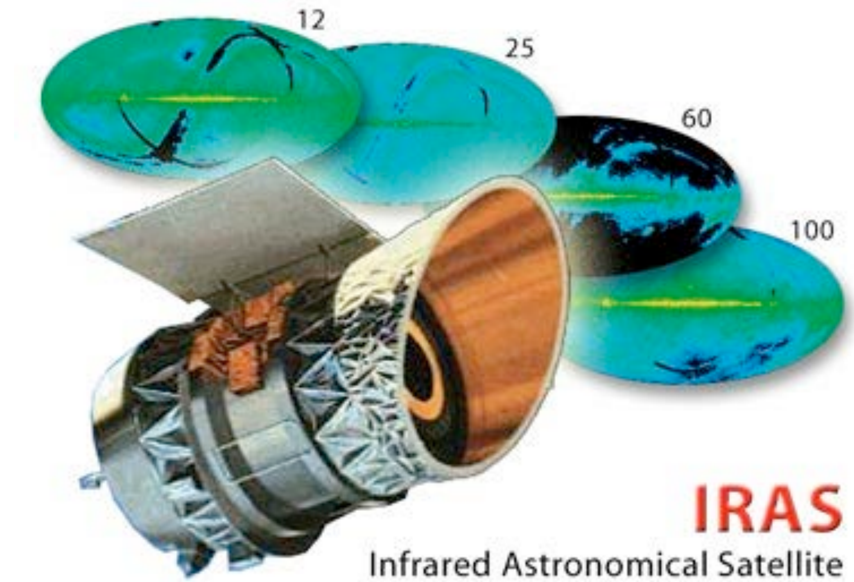
At wavelengths less than about 290 nm photons are absorbed by atmospheric **oxygen and nitrogen**.

Between the optical and radio windows photons are absorbed by **water vapor and carbon dioxide**.

At wavelengths longer than about 20 m, photons are **reflected** back into space by **ionized gases** in the upper atmosphere.

The Infrared Astronomy

The first orbiting infrared observatory, the Infrared Astronomical Satellite (IRAS), was launched in 1983. During its nine-month mission, IRAS used its 57-cm telescope to map almost the entire sky at wavelengths from 12 to 100 μm.



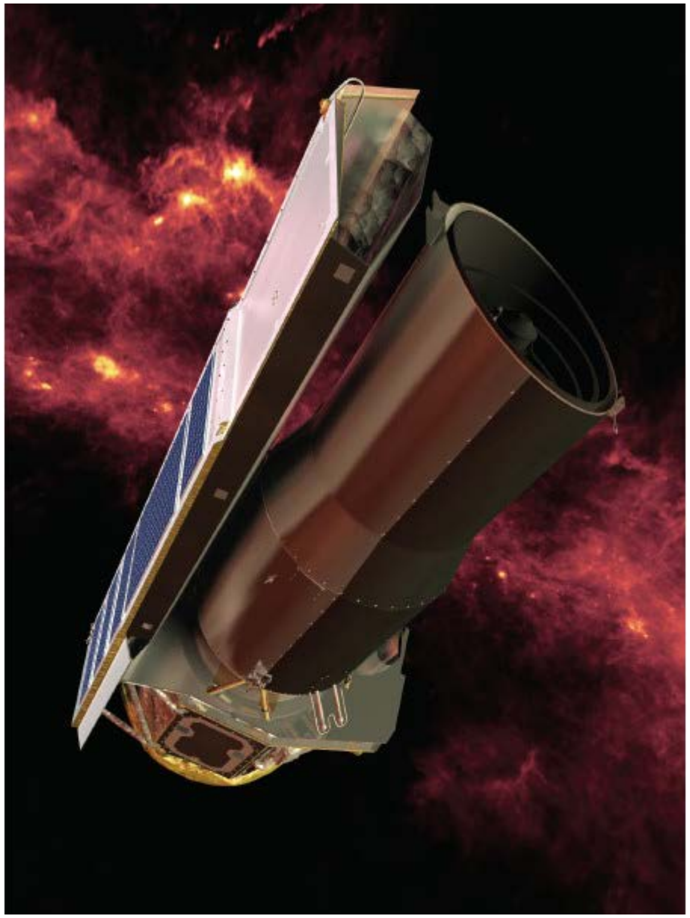
IRAS Discoveries:

-IR emission from **dust around stars**. Planets are thought to coalesce from disks of this kind.

-IR emission from **distant galaxies**. Many of these galaxies are heavily obscured by dust.

The Infrared Astronomy

In 2003 **the Spitzer Space Telescope,** an 85cm IR (3-180μm) telescope, was placed into orbit.



Discoveries:
• probed the inner structure of galaxies
• studied the **evolution of star formation** in galaxies
• detected the **first galaxies and stars** that formed after the big bang.
• SST became the first telescope to directly capture the light from an **extrasolar planet**, namely the "hot Jupiter" HD 209458b.

Ultraviolet Astronomy

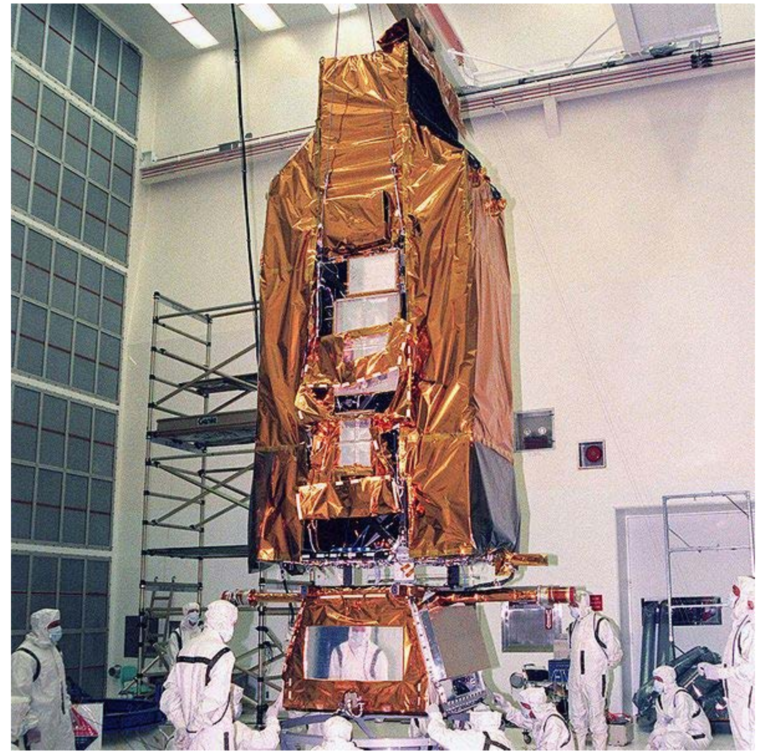
UV observations can reveal a great deal about :

- hot stars

- ionized clouds of high temperature gas between stars

-the Sun's high-temperature corona

- The composition of a planet's atmosphere (by studying the spectrum of ultraviolet sunlight reflected from the planet)



Far Ultraviolet Spectroscopic Explorer (FUSE) in pre-launch cleanroom. Confirmed that our Milky Way Galaxy is surrounded by an immense "halo" of gas at temperatures in excess of 200,000 K.

The Hubble Space Telescope

HST was placed in a 600-km-high orbit by the space shuttle Discovery in 1990.

HST has a **2.4-meter objective mirror** and was designed to observe at wavelengths from 115nm to 1μm. θ_{dif} at 1μm?

When launched in 1990, scientists found that the main mirror had been ground incorrectly, severely compromising the telescope's capabilities. However, after a servicing mission in 1993, the telescope was restored to its intended quality (~ 0.1 arcsec).

The Hubble Space Telescope

Important HST high-points:

-Accurate measurement of Hubble Constant → Age of Universe = 13.7 billion years

- Confirmed Accelerating Universe

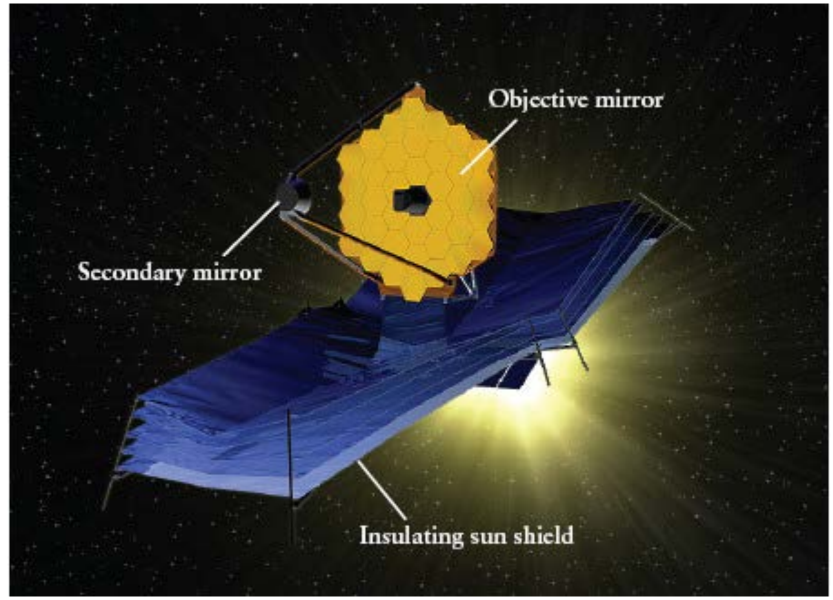
- discovery of proto-planetary disks (proplyds) in the Orion Nebula

- discovery of connection between galaxies and their central black holes

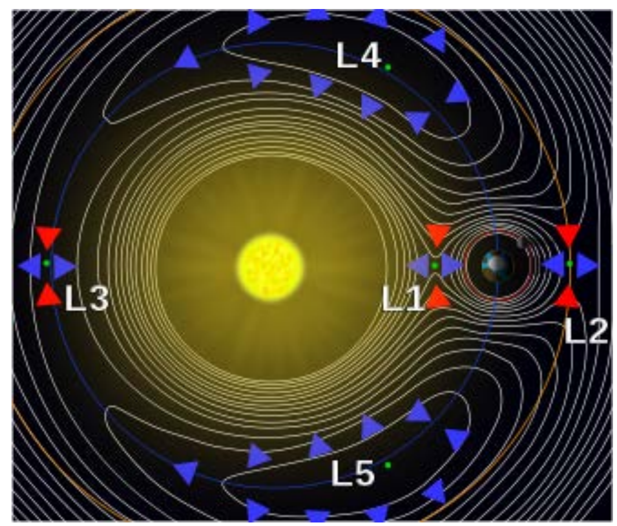
-Hubble Deep Field. The images revealed galaxies billions of light years away.

The James Webb Space Telescope

JWST will observe from the Lagrange L_2 point at visible and infrared wavelengths from 600 nm to 28 μm with a **6.5 m objective mirror.**



What is the enhancement over HST regarding light-gathering power?



JWST will study faint objects such as **planetary systems** forming around other stars and **galaxies** near the limit of the observable universe.

Wavelength of H_α emitted at $z = 10$?

X-ray Astronomy

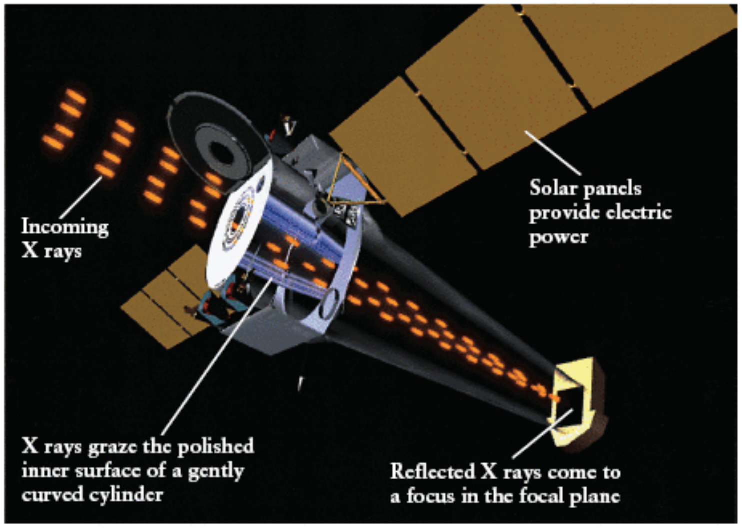
Chandra top Ten

Sources of X-rays:
Blackbodies with $10^6 < T < 10^8$ K

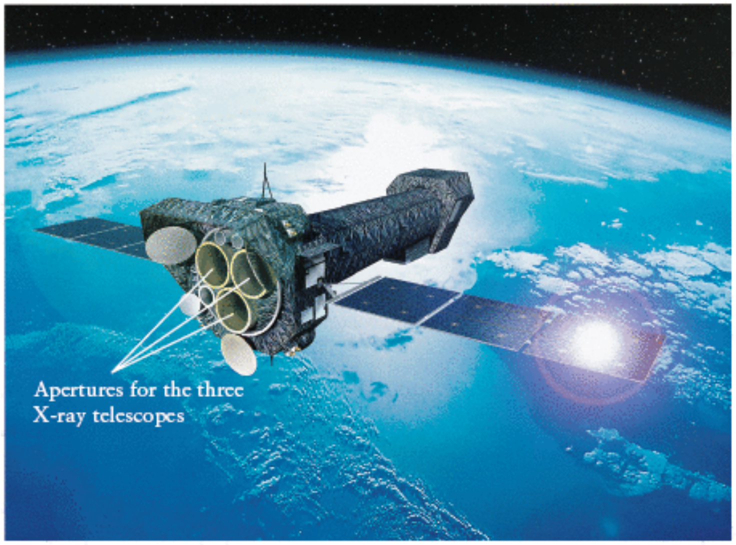
Synchrotron emission (charge particles accelerating in a magnetic field)

Very hot gas

Examples:
-Very young stars, Supernova Remnants, Black Hole Accretion disks, coronae and jets, Clusters of Galaxies



(a) Chandra X-ray Observatory



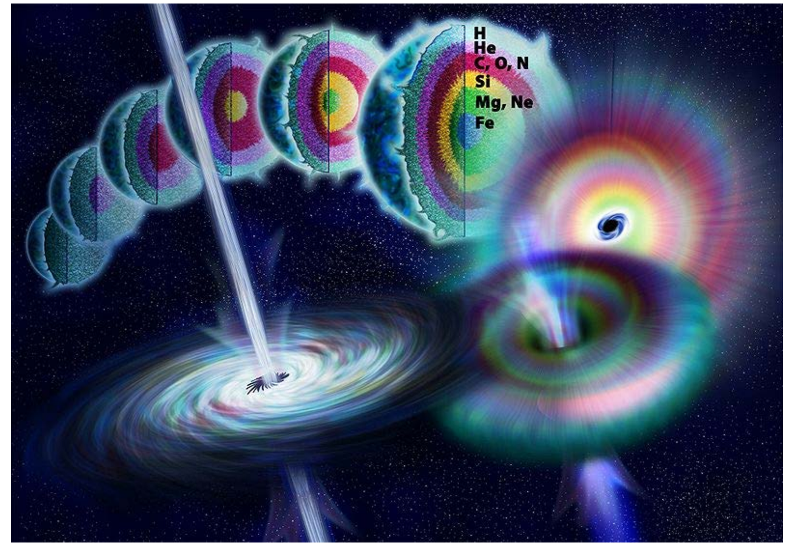
(b) XMM-Newton

Gamma-Ray Astronomy

Gamma rays are photons with energies > 100 keV and are produced by sub-atomic particle interactions. They are absorbed by our atmosphere making observations from satellites necessary.

Gamma-ray bursts (GRBs) are flashes of gamma rays associated with extremely energetic explosions in distant galaxies.

A typical GRB lasts a few seconds but can release more energy than what will be released in the lifetime of the Sun.



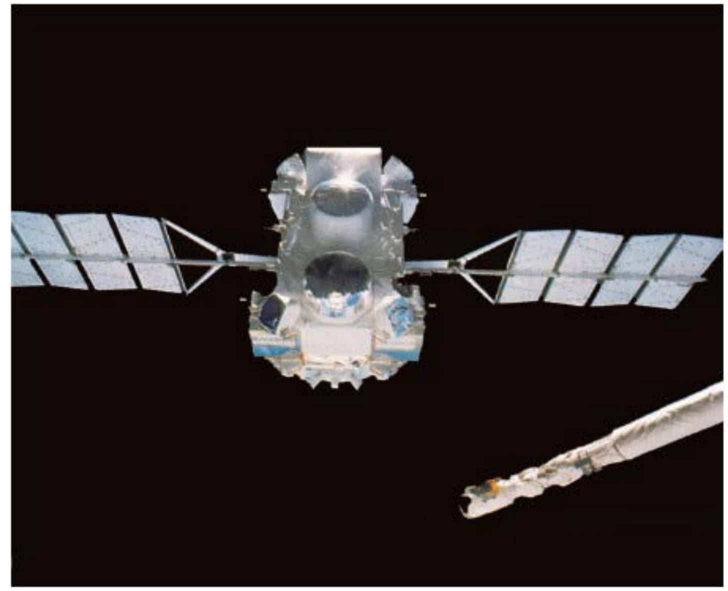
Most observed GRBs are believed to be a narrow beam of intense radiation released during a **supernova event**, as a rapidly rotating, high-mass star collapses to form a black hole.

Gamma-Ray Astronomy

The **EGRET** instrument conducted the first all sky survey above 100 MeV. Using four years of data it discovered 271 sources.

The **BATSE** instrument (20-600keV) made about 2700 GRB detections. It showed **(a)** that the majority of gamma-ray bursts must originate in distant galaxies, not nearby in our own Milky Way, and therefore must be very energetic.

(b) The separation of GRBs into two time profiles: **short duration** GRBs that last less than 2 seconds, and **long duration** GRBs that last longer than this.



One of the most important gamma ray telescopes placed in orbit in 1991 was the **Compton Gamma ray observatory** (**CGRO**). Instruments on CGRO were **EGRET, BATSE, OSSE, and COMPTEL.**
Energy range (20 keV - 30 GeV).