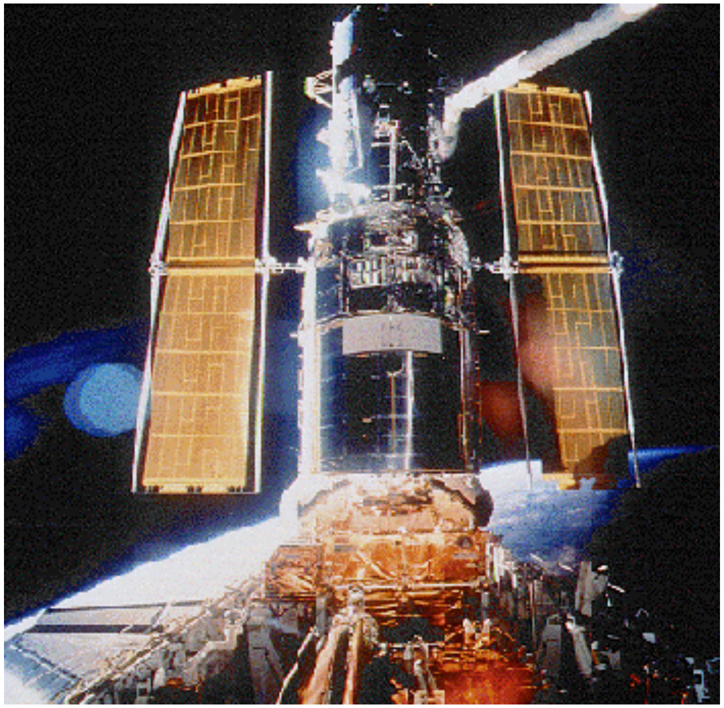
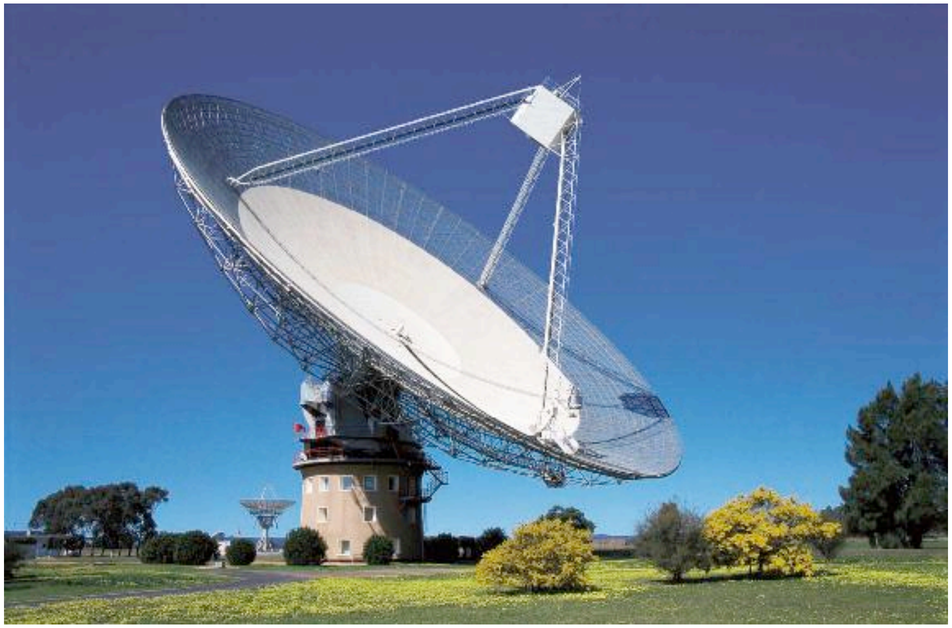


Telescopes (Part 2)



Donna Kubik PHYS162 Fall, 2006

Types of EM radiation

Low frequency/long wavelength *LOW ENERGY*

Radio

Millimeter

Sub-millimeter

Mid frequency/mid wavelength *MID ENERGY*

Infrared

Optical

High frequency/short wavelength *HIGH ENERGY*

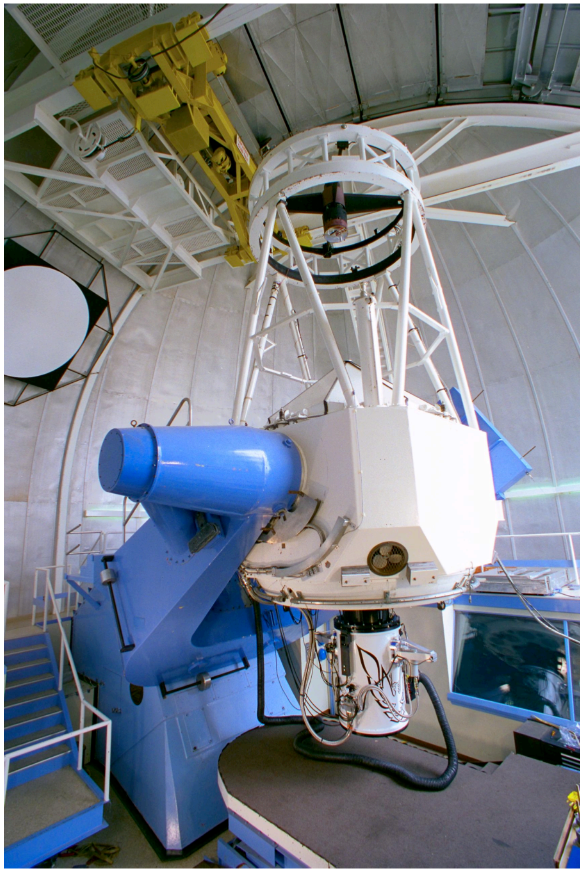
Ultraviolet

X-ray

Gamma ray

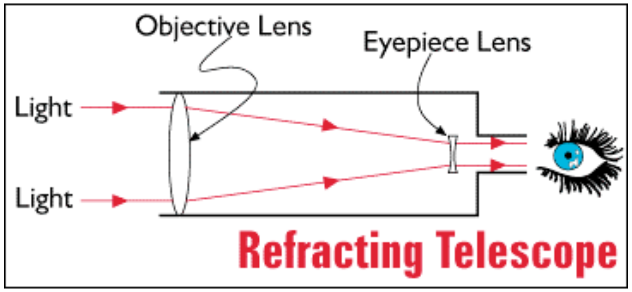
Two classes of optical telescopes: Refracting and Reflecting

Refractor

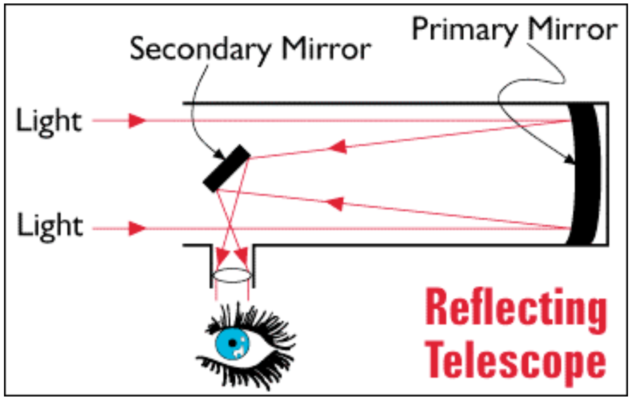


Reflector

Two classes of optical telescopes: Refracting and Reflecting



Uses lenses



Uses mirrors

Three functions of refracting and reflecting telescopes

Magnification

To collect light

Angular resolution

Magnification

$$\text{Magnification} = \frac{\text{focal length of primary lens (mirror)}}{\text{focal length of eyepiece}}$$

Orion Nebula at magnifications of approximately 50x, 80x, and 120x.

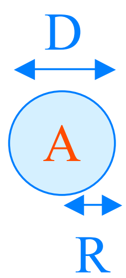
Notice that as the magnification increases the field of view shrinks and the image gets dimmer.

Telescope aperture

The diameter (D) of the primary lens (mirror) is called the *aperture*.

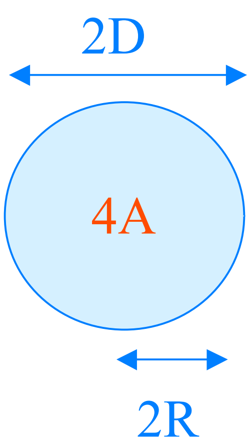
With larger apertures, a telescope can collect more light and therefore see fainter objects.

Light collection



The amount of light gathered is proportional to the area (A) of the lens (mirror):

$$A = \pi R^2$$



If the diameter is doubled, the collecting area is quadrupled:

$$\pi(2R)^2 = \pi 4R^2 = 4(\pi R^2) = 4A$$

Angular Resolution

Distant objects are separated by an angle.

Angular resolution refers to the ability to see objects that are close together.

The larger the aperture (D), the better the resolution:

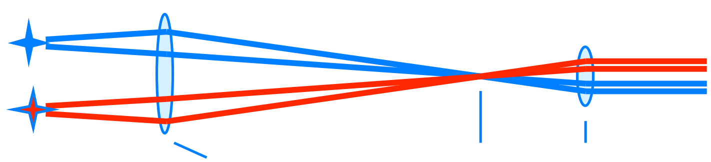
$$resolution = \frac{\lambda}{D},$$

$$\lambda = wavelength$$

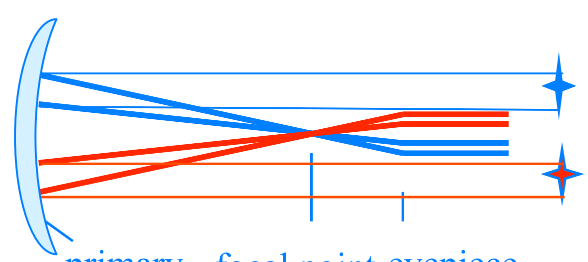
$$D = diameter$$

If the diameter is doubled, the detail that can be seen is doubled

refractor



reflector

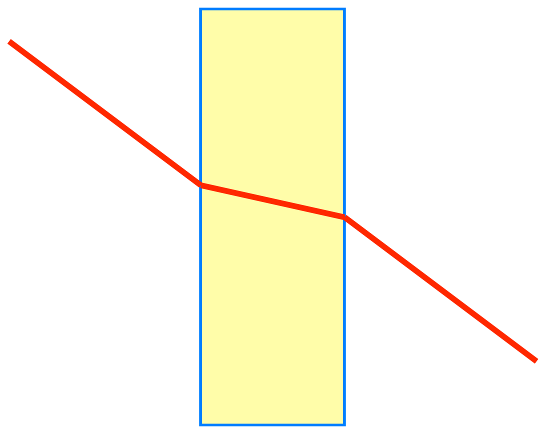


Refracting Telescopes

Refraction

Light is bent at the surface between two media.

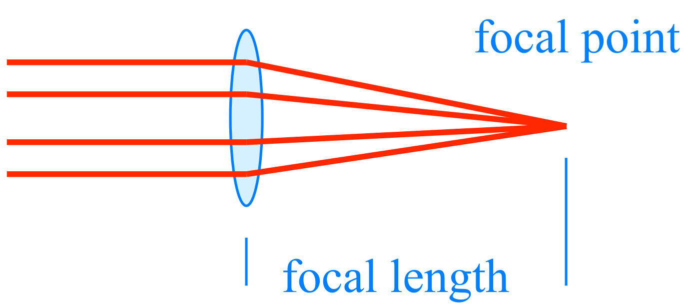
This bending is called refraction.



Lenses

When the surfaces are curved, light can be focused

Lenses have a *focal length* and a *focal point*.



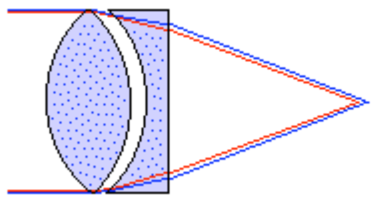
Problems with refractors

1) Chromatic aberration
2) Spherical aberration
3) Sagging (gravity)
4) Unwanted refraction in glass (bubbles,etc)
5) Opaque to some frequencies and attenuates light

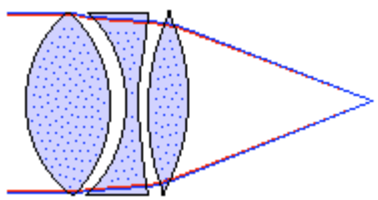
Chromatic aberration

Chromatic aberration is an optical effect which causes differing wavelengths of light to focus at different points

Achromatic refractors use two lens elements to help minimize *chromatic aberration*,



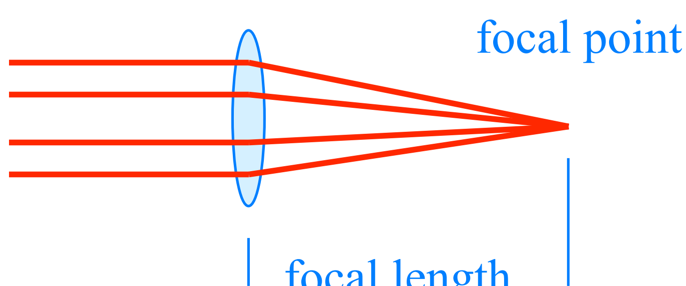
Apochromatic refractors (often called "apos") use three or more lens elements, one or more having special properties, to eliminate chromatic aberration entirely



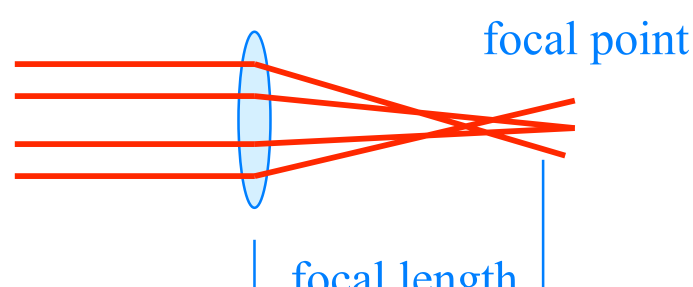
Spherical aberration

When a lens has a spherical surface, light rays entering the lens at different distances from the lens' center come into focus at different focal points

Spherical aberration results in a blurry image



No aberration



Spherical aberration

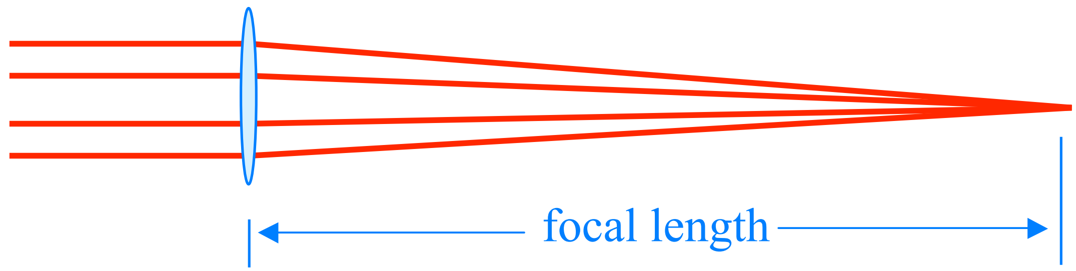
Spherical aberration

Could get rid of spherical aberration by grinding a parabolic surface

Spherical shaped lenses are much easier to make

Try to make spherical lens very thin so its spherical surface approximates a parabola, but this results in *long focal lengths*

Note how long refracting telescopes are….(see next few slides)



Yerkes Refractor

World's largest refractor is in Williams Bay, Wisconsin

102-cm aperture

1936-cm tube (length)

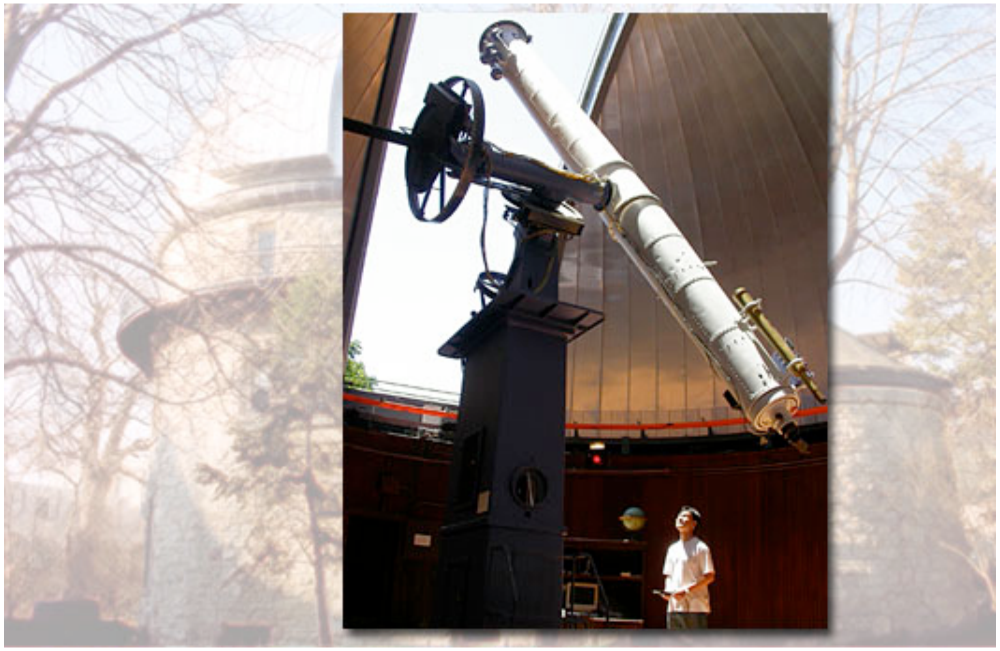
Dearborn Observatory

A large refractor is at
Dearborn Observatory

at Northwestern University,
Evanston IL

18.5 inch (~47 cm)

22 feet long (~670 cm)



ROG 28-inch refractor

With its 28-inch (70-cm) diameter lens, this is the largest telescope at the Royal Observatory Greenwich (ROG).

It was first used in 1893, but has recently been upgraded to include a computer control system and CCD camera

Sagging of large lenses

Glass can flow over time

The glass distorts under the pull of gravity

This is especially a problem because a lens can only be supported around the edge

As the telescope tracks (follows an object as the Earth rotates) the orientation of the telescope changes, and, along with it, the amount of distortion.

There is no way to know the exact distortion that is occurring

This limits the size of refractors

Unwanted refractions

Lenses are ground from large, thick disks of glass that are formed by pouring molten glass into a mould

As the liquid cools, gas in it becomes trapped, creating air bubbles in the solidified disk

Air bubbles inside will create unwanted and unpredictable extra refractions that blur the image

Opacity to some wavelengths

Glass is opaque to certain rages of wavelengths

Even visible light is dimmed when it passes through the glass lens, and ultraviolet light is largely absorbed by the glass

Refractors vs. reflectors

Newton replaced the objective lens with a mirror to eliminate chromatic aberration of lenses

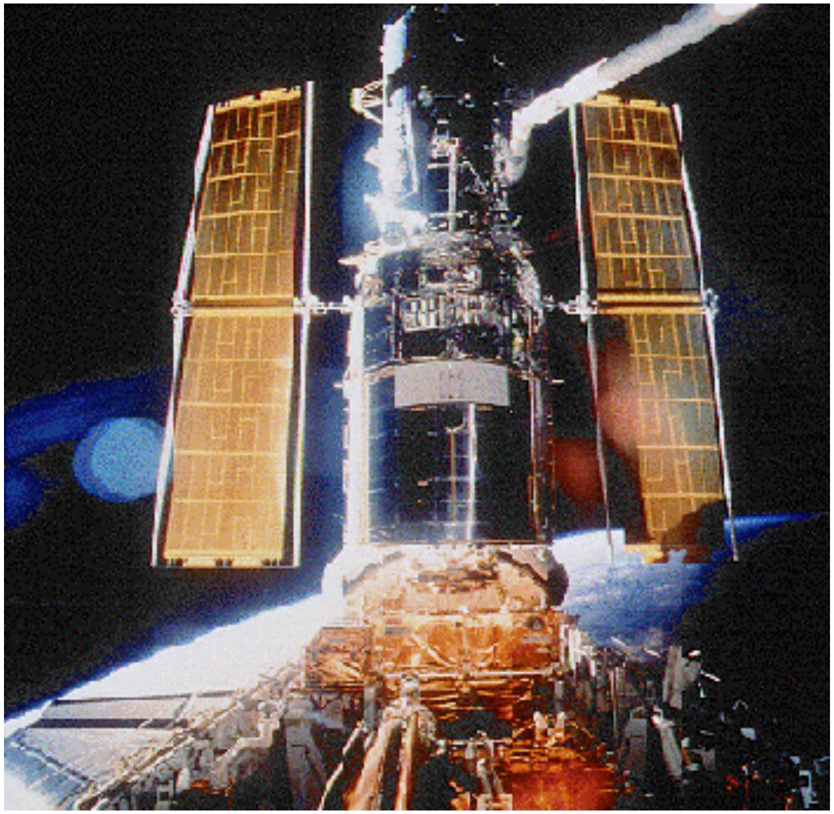
Mirrors also overcome some of the other problems associated with refractors

19th century telescope designers worked to overcome the problems associated with refractors

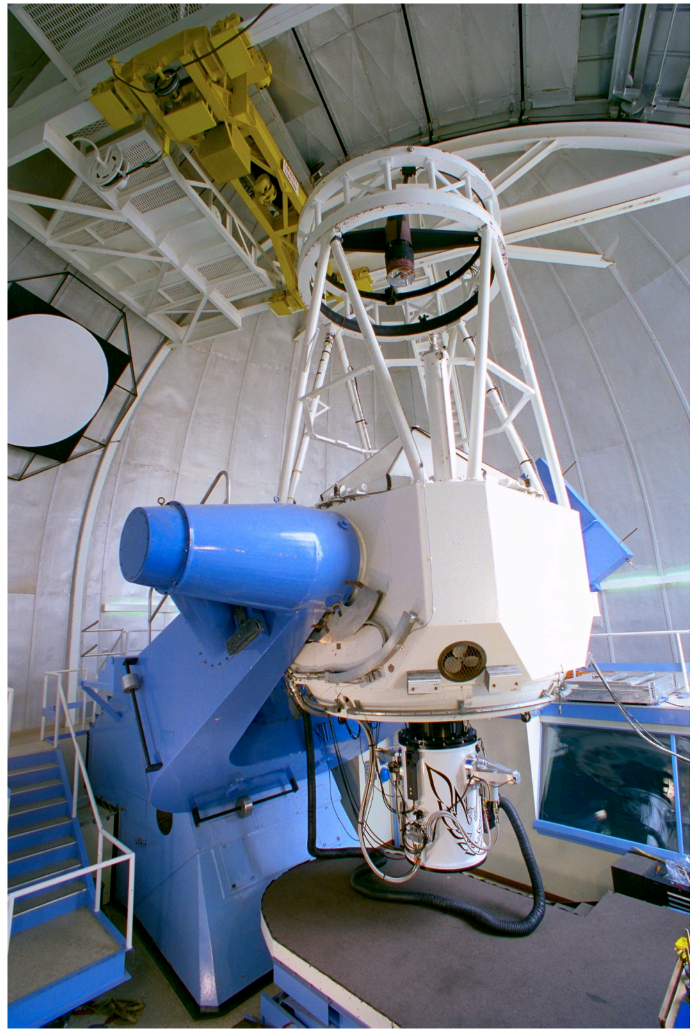
Yerkes was completed in 1897.

No major refractors were built in the 20th century

Reflecting Telescopes



HST

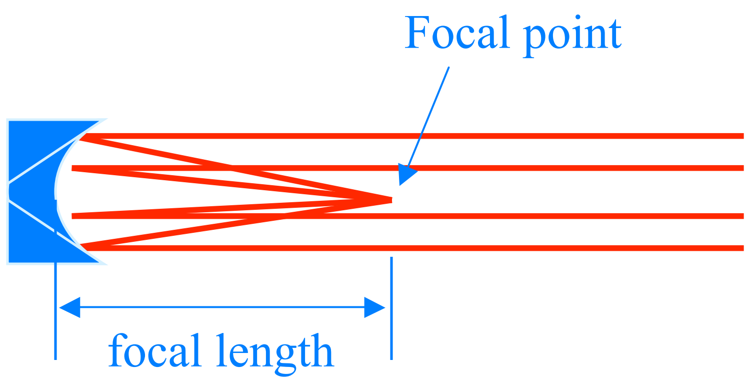


KPNO 2.1-meter

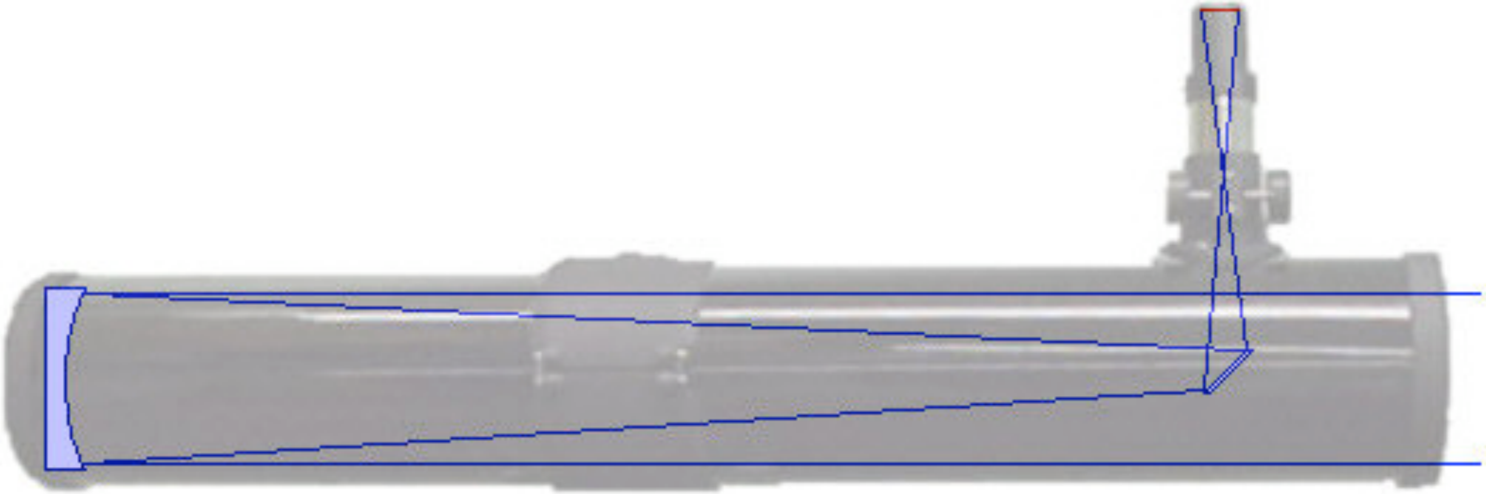
Mirrors

Flat mirrors just reflect light in parallel rays.

But a curved mirror can focus the light



Newtonian Reflector



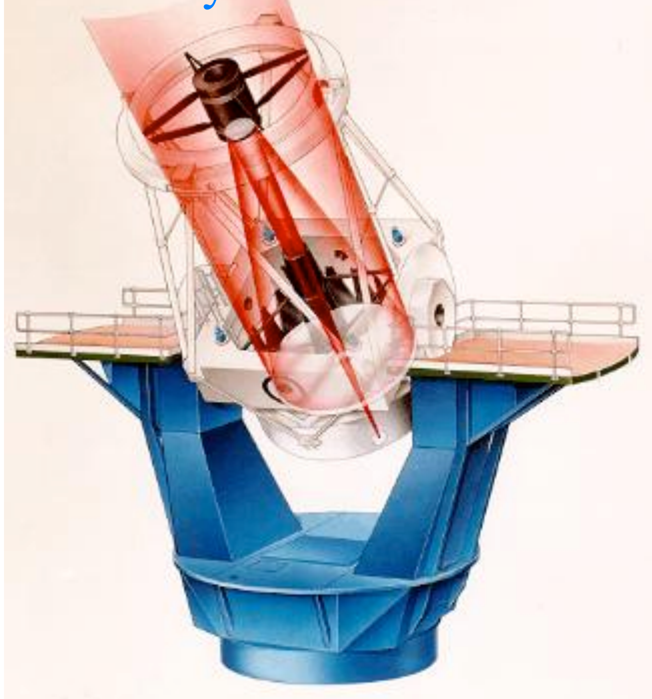
Cassegrain reflector

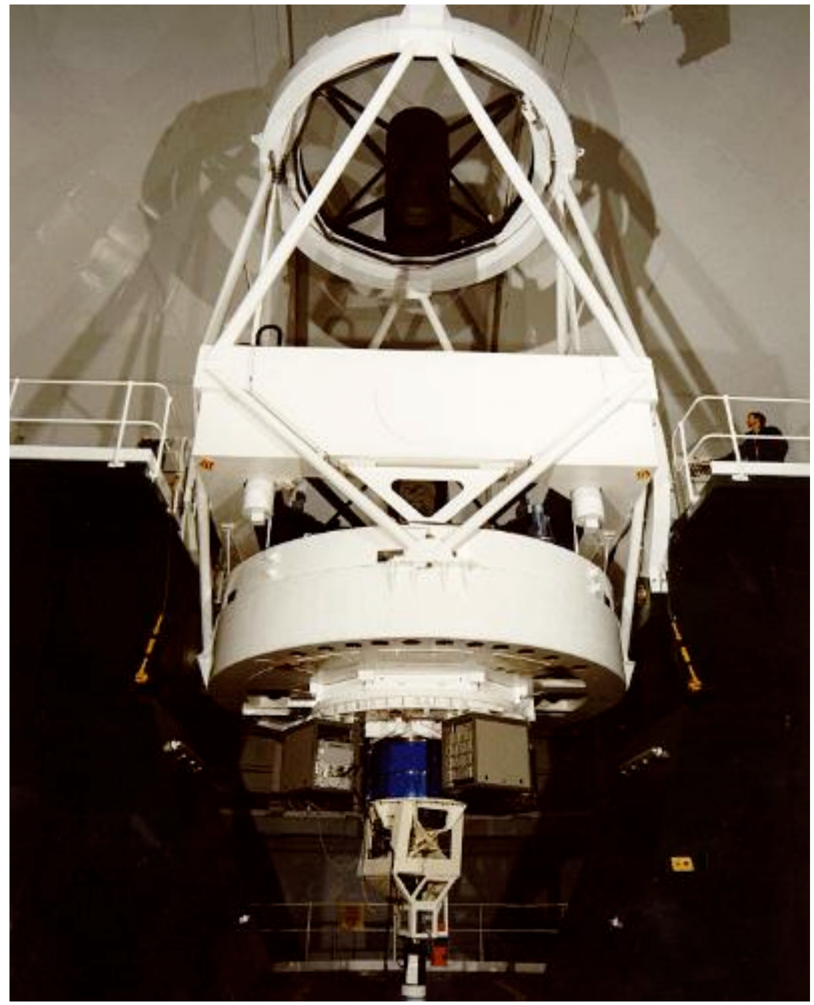
With a *Schmidt corrector plate*,
this optical design is called a *Schmidt-Cassegrain*

William Herschel Telescope

The WHT is a Cassegrain design with an alt-azimuth mount with a 4.2 meter diameter parabolic primary mirror

The telescope is located at La Palma, Canary Islands





Refractors vs. reflectors

Newton replaced the objective lens with a mirror to eliminate chromatic aberration of lenses

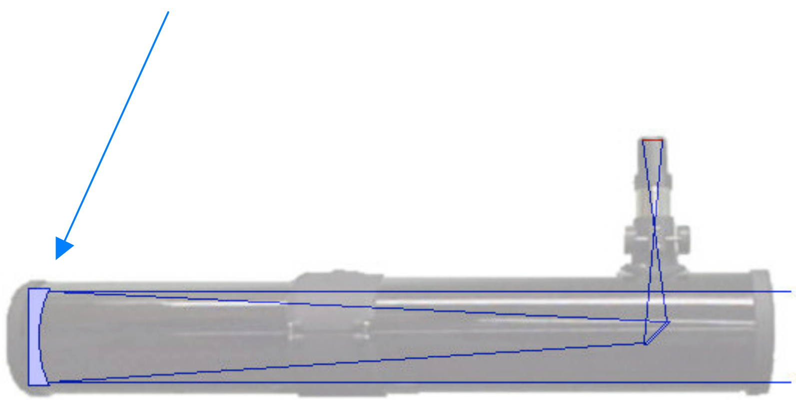
Mirrors overcome 4 of the 5 problems of refractors

1. Chromatic aberration
2. Sagging
3. Unwanted refractions
4. Opacity

Reflectors eliminate chromatic aberration

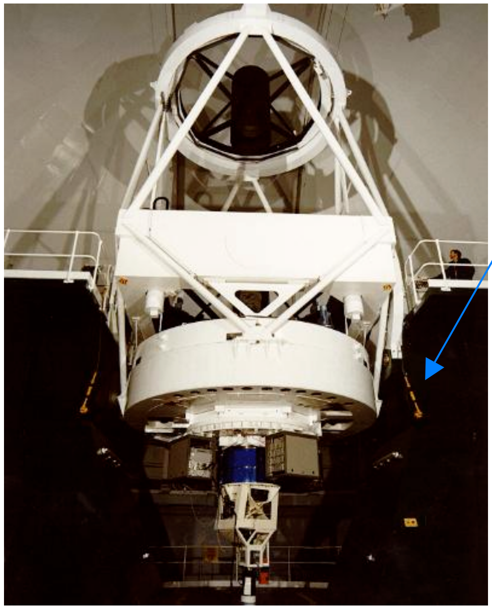
Reflectors avoid chromatic aberration because, unlike household mirrors, all telescope mirrors have coated top surfaces.

The light never enters the glass



Reflectors eliminate sagging

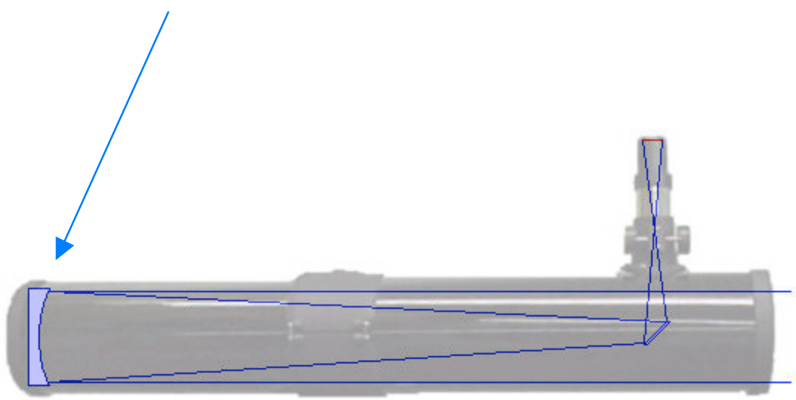
The mirrors, although they can weigh tons, do not warp because they can be rigidly supported from behind.



Reflectors eliminate unwanted refraction

A mirror maker needs only to find a surface, rather than an entire volume, that is free of bubbles that cause unwanted refraction

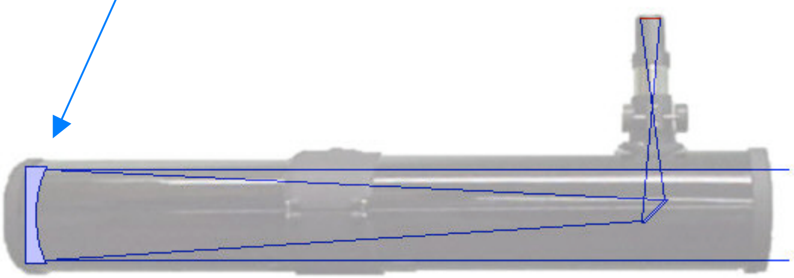
The light does not enter the glass



Reflectors eliminate attenuation

- The light never enters the glass, so the problem of a lens' opacity to different wavelengths never arises

The light never enters the glass



Refractors vs. reflectors

Newton replaced the objective lens with a mirror to eliminate chromatic aberration of lenses

But mirrors still have

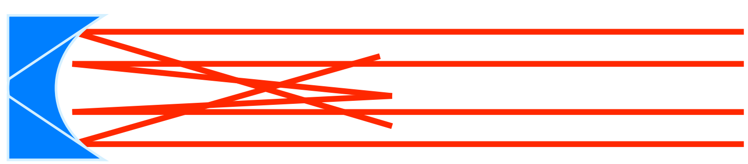
1. *Spherical aberration*

2. In addition, they have the problem of *blocked light*

Spherical aberration in reflecting telescopes

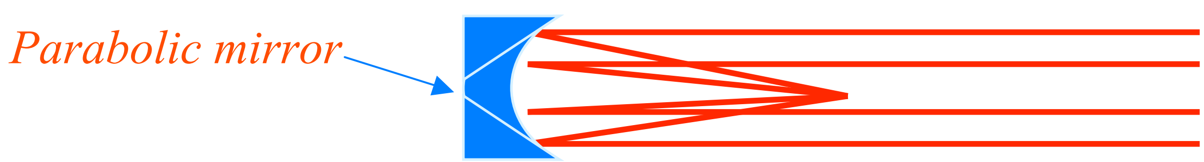
A *spherical* mirror (like a spherical lens) is easier to make but creates *spherical aberration*.

All rays are not focussed to the same point.



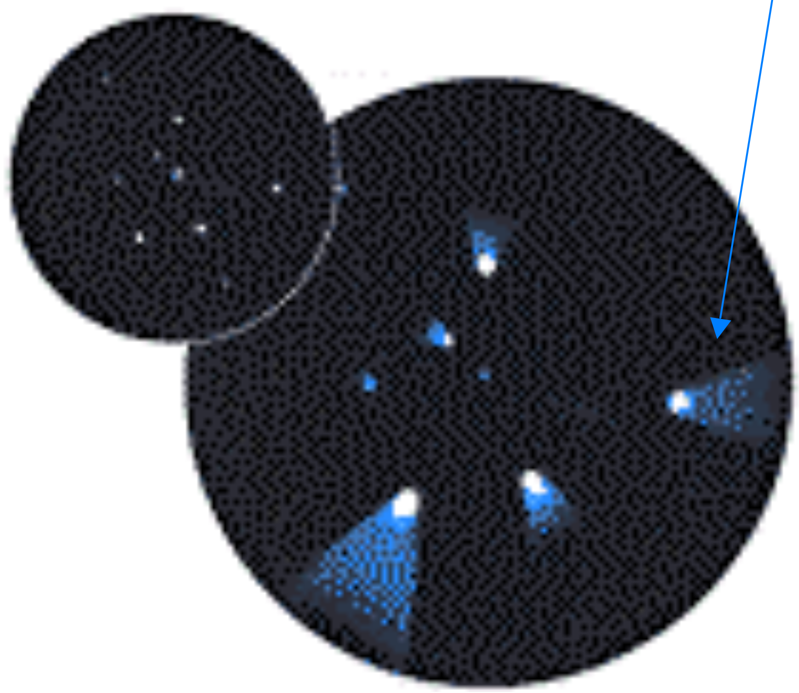
One solution

With a perfect *parabolic* mirror, all rays are focussed to the same point, so there is no spherical aberration.



Coma

However, a parabolic mirror creates *coma* (comet-like)

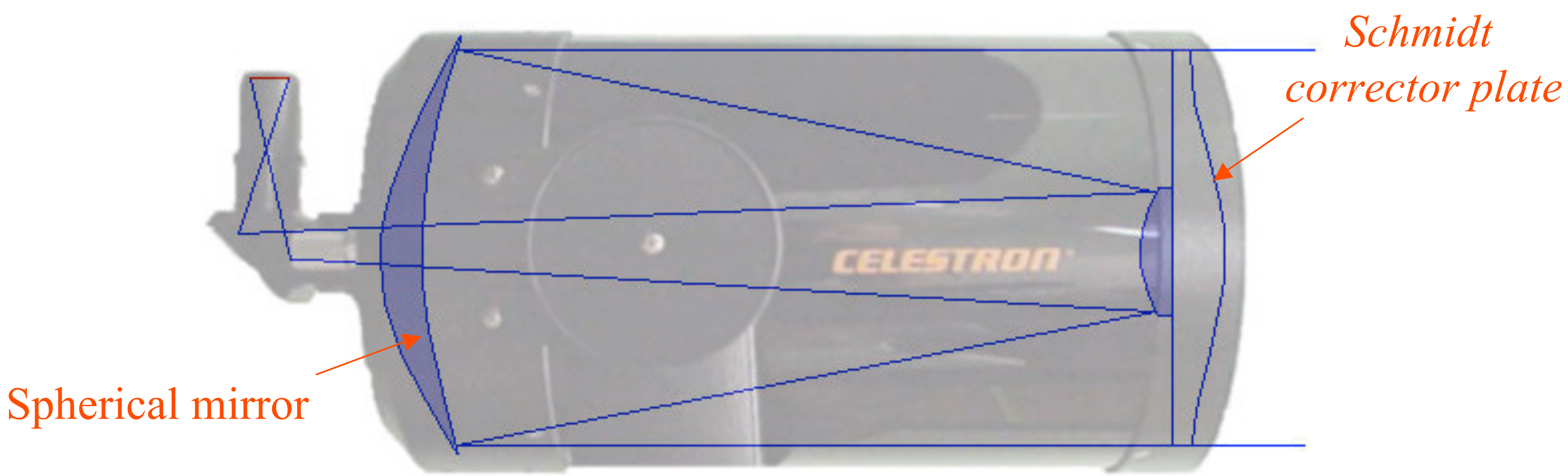


Another solution

Schmidt-Cassegrain design (*catadioptic* = uses lenses and mirrors)

Uses a *spherical* mirror (instead of parabolic) to minimize coma

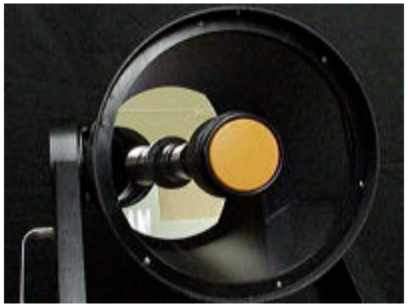
Uses *Schmidt corrector plate* to correct for spherical aberration.



Blocked apertures in reflecting telescopes

- The secondary mirror of a reflector blocks some incoming light

- Typically, prevents about 10% of light from reaching the primary



- This problem is addressed by constructing primary mirrors with sufficiently large area to compensate to the loss of light

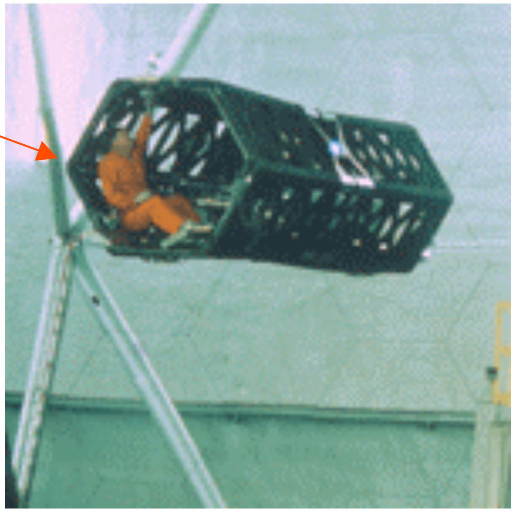
Keck Reflector

The twin Keck Telescopes, the world's largest optical and infrared telescopes.

Each stands eight stories tall and weighs 300 tons, yet operates with nanometer precision.

Ten meters in diameter, the mirror is composed of 36 hexagonal segments that work in concert as a single piece of reflective glass.

A person!



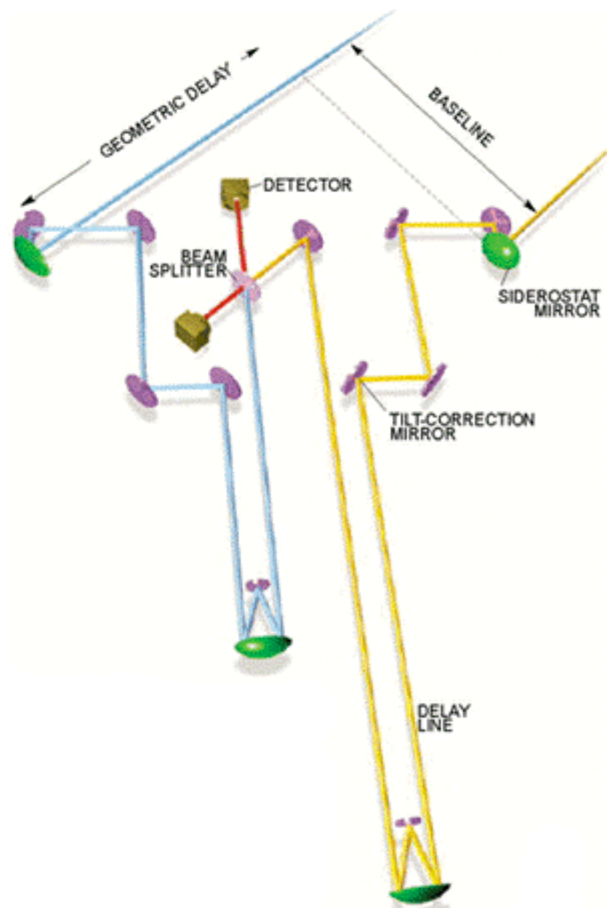
Keck's primary mirror

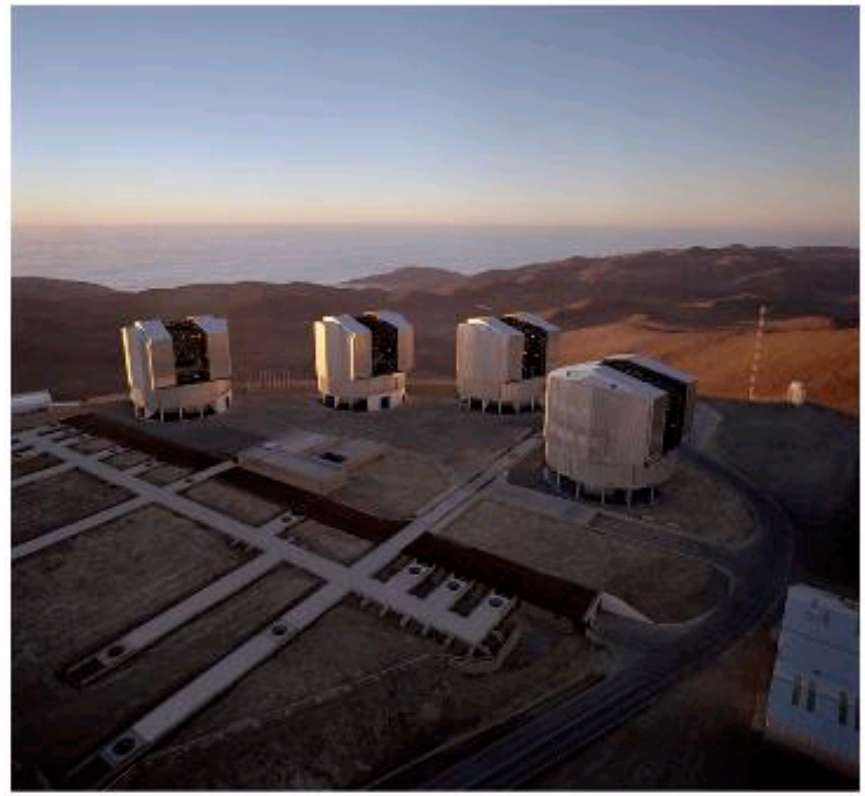
Optical Interferometry

A new generation of optical interferometers is letting astronomers study stars in 100 times finer detail than is possible with the Hubble Space Telescope

Optical interferometers

Increase angular resolution of optical images





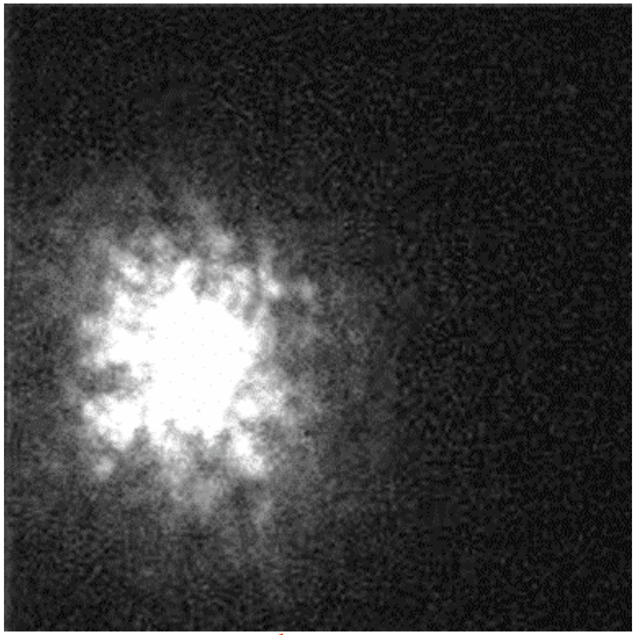
The VLT Array on the Paranal Mountain

ESO PR Photo 14a/00 (24 May 2000)

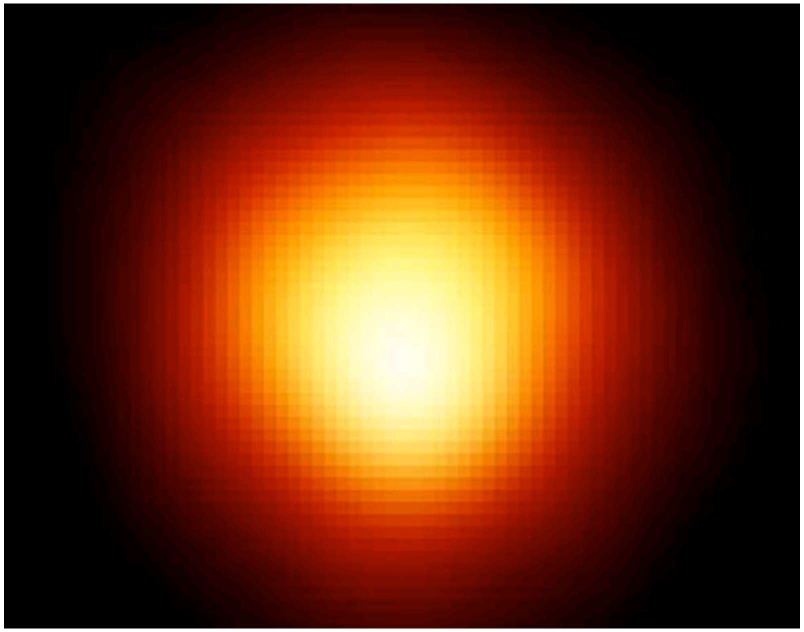
Atmospheric turbulence

Stars twinkle because of atmospheric turbulence

Without the effects of the Earth's atmosphere, stars do not twinkle. As a result, photographs taken from telescopes in space reveal stars as much finer points and reveal more detail for extended objects, as planets and galaxies.



Betelgeuse
twinkling as viewed through atmosphere



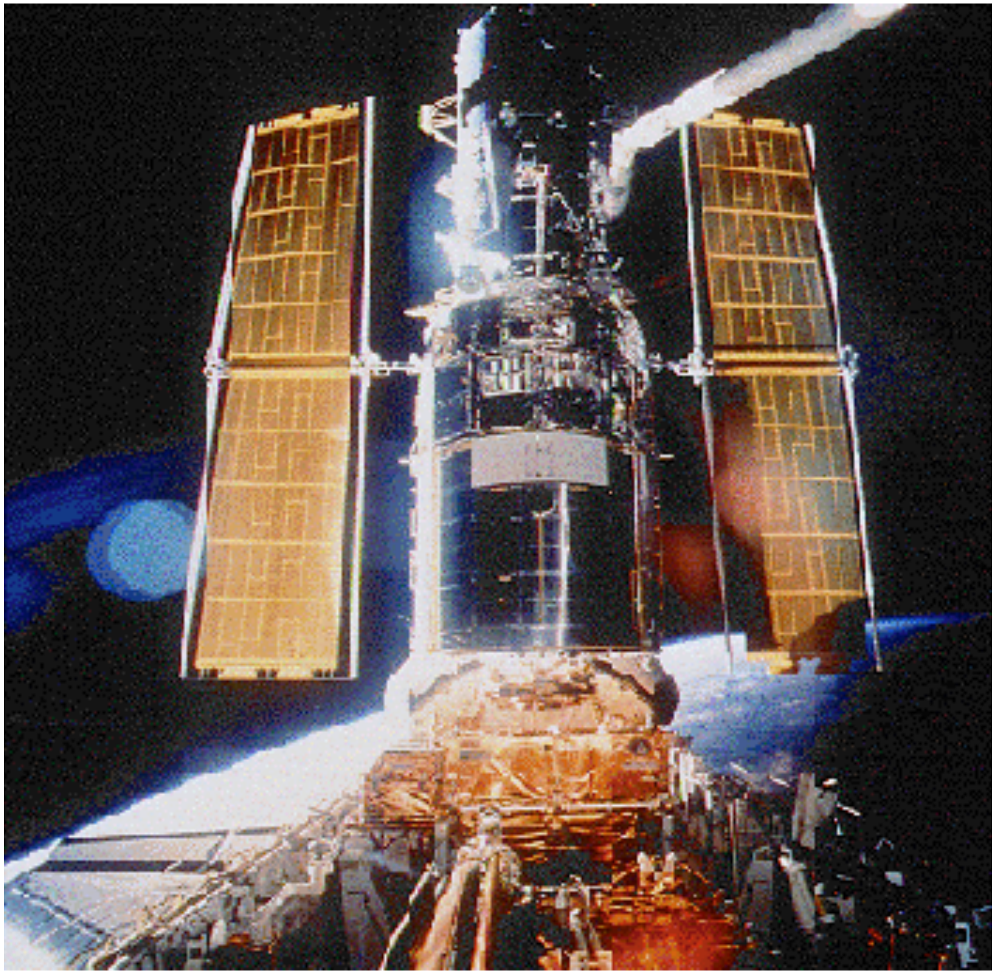
Betelgeuse from HST
viewed through Hubble Space Telescope

Hubble Space Telescope

Goal was to put an optical telescope in orbit to avoid these effects of the atmosphere.

Initially had problems with spherical aberration

Fixed!

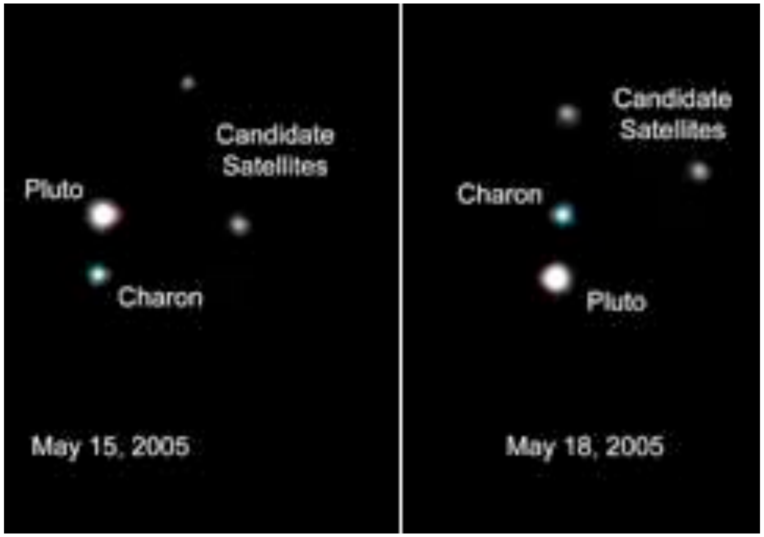


HST
Hubble Space Telescope

Hubble Space Telescope

These Hubble Space Telescope images, taken by the Advanced Camera for Surveys, reveal Pluto, its large moon Charon, and the planet's two new candidate satellites.

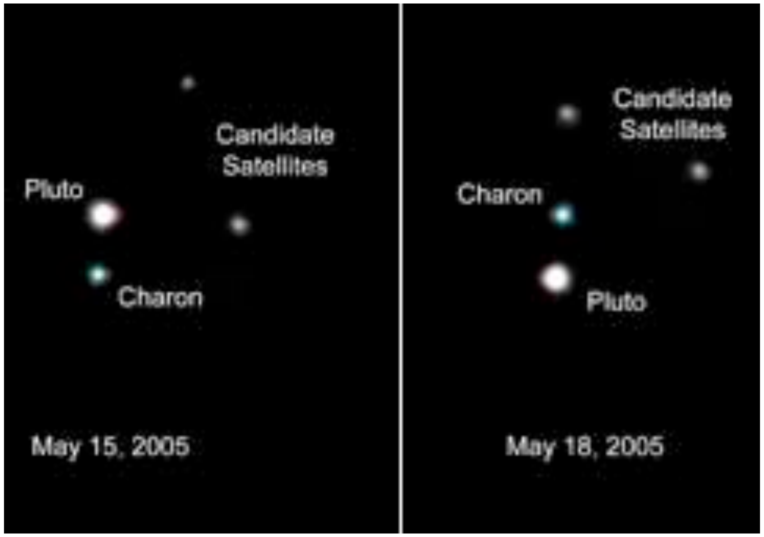
P1 and P2 are thousands of times less bright than Pluto and Charon.



Hubble Space Telescope

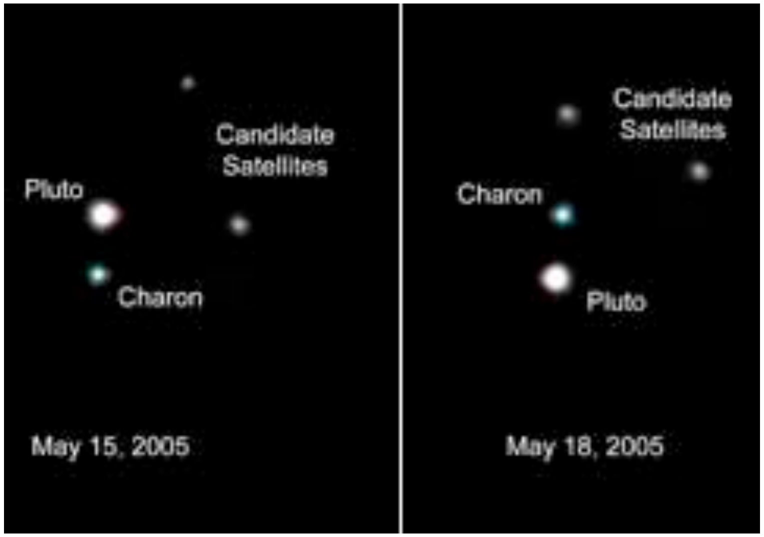
The enhanced-color images of Pluto (the brightest object) and Charon (to the right of Pluto) were constructed by combining short exposure images taken in filters near 475 nanometers (blue) and 555 nanometers (green-yellow).

The images of the new satellites were made from longer exposures taken in a single filter centered near 606 nanometers (yellow), so no color information available for them.



Hubble Space Telescope

Between May 15 and May 18, 2005, Charon, and the 2 newly discovered moons, P1 and P2, all appear to rotate counterclockwise around Pluto.



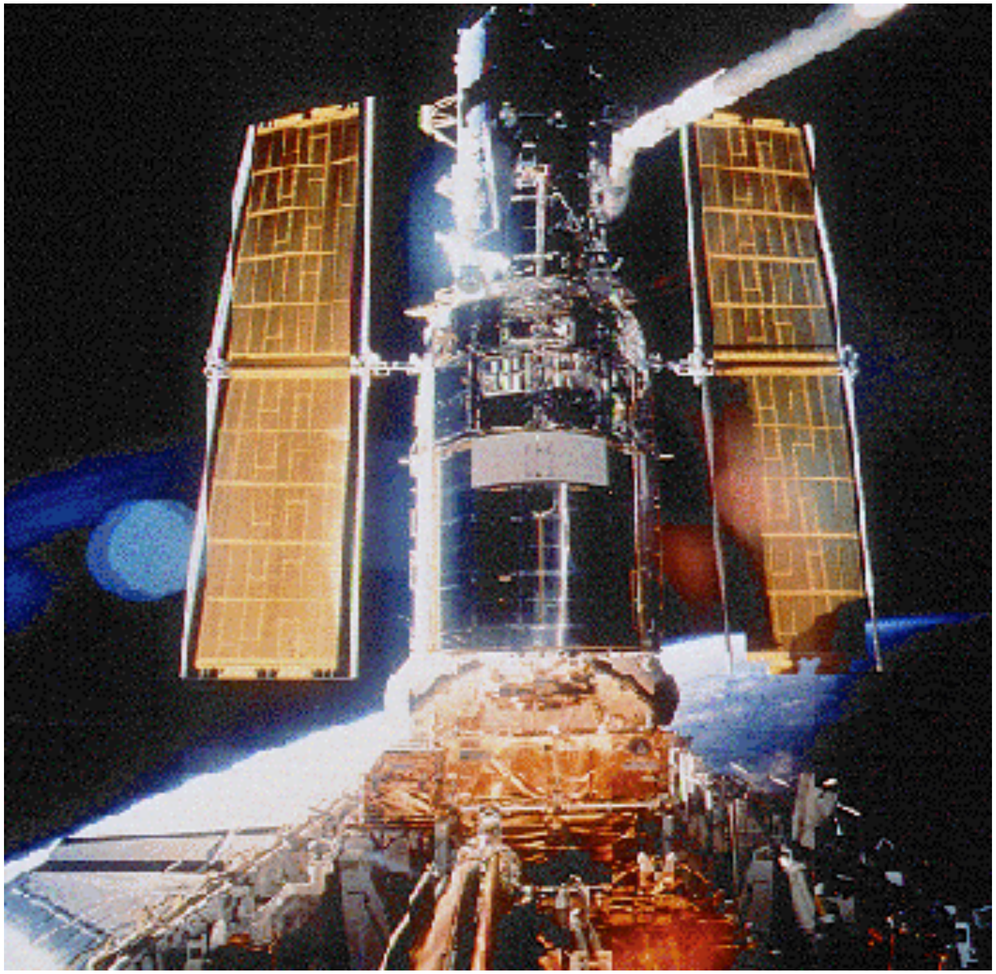
P1 and P2 move less than Charon, because they are farther from Pluto

They therefore would be orbiting at slower speeds.

Hubble Space Telescope

The clarity of HST images may suggest that ground-based observational astronomy is no longer attractive

However, two techniques, *active optics* and *adaptive optics*, enable telescopes on ground to match the quality of Hubble, or better it

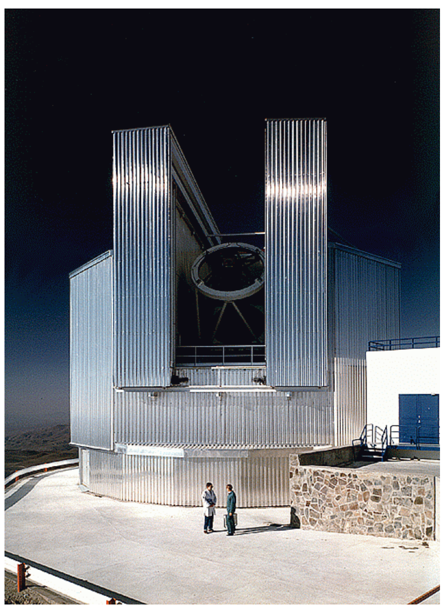


HST
Hubble Space Telescope

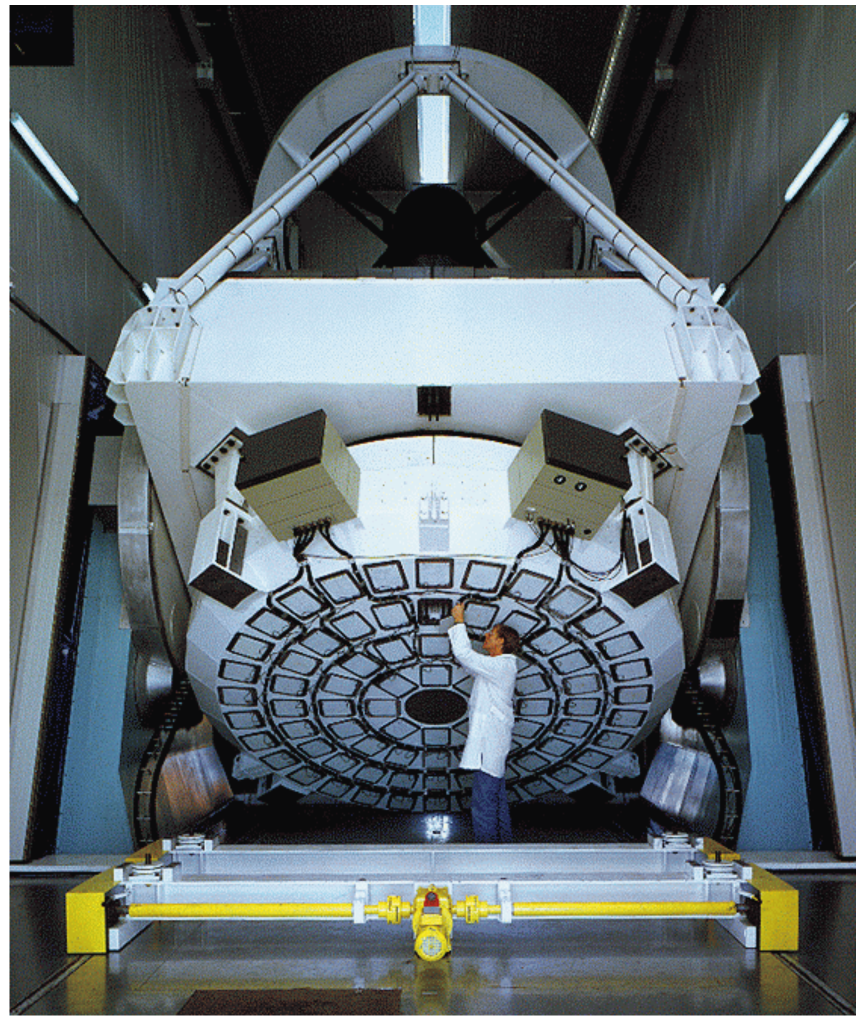
Active Optics

Corrects for changes in mirror shape due to temperature and gravity by adjusting the mirror every few seconds

The Keck telescopes in Hawaii & New Technology Telescopes (NTT) in Chile have active optics



NTT



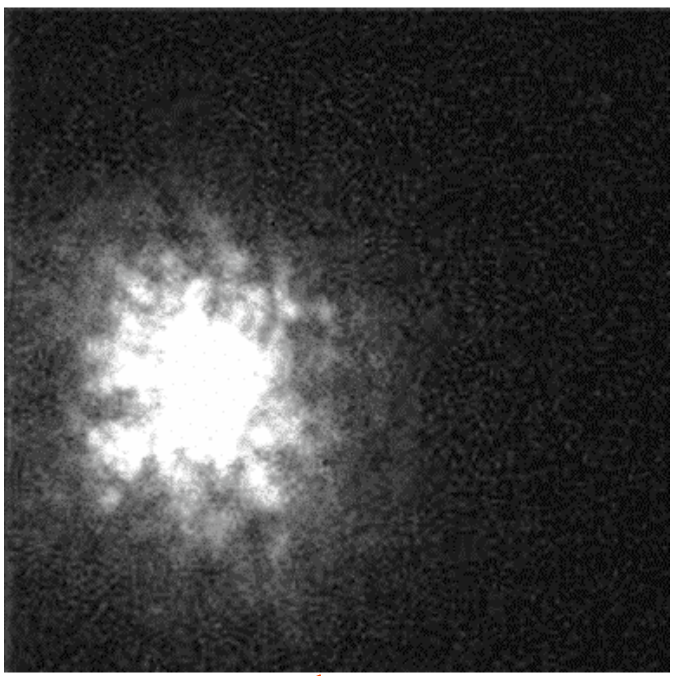
NTT's active optics

Adaptive optics

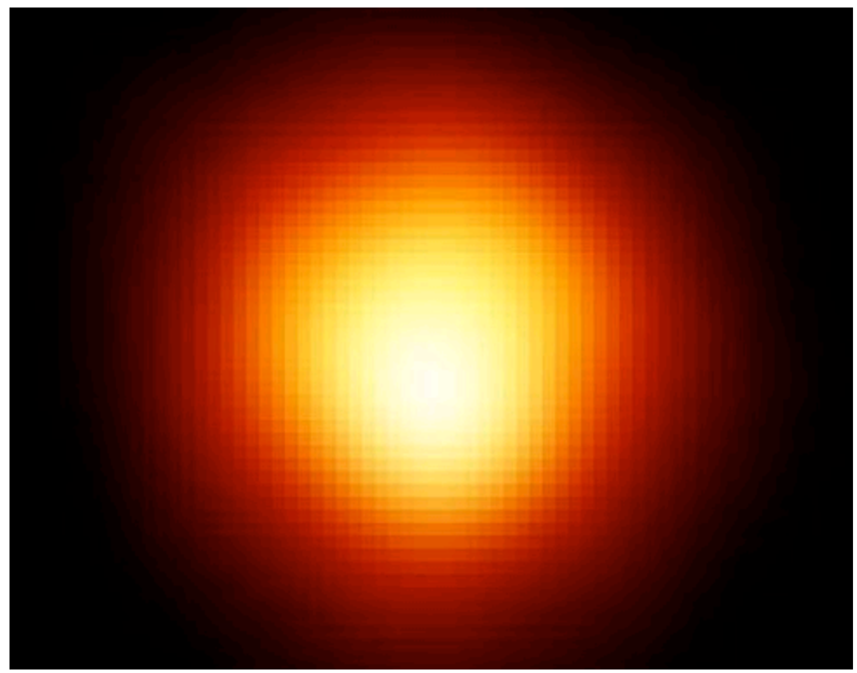
Stars twinkle because of atmospheric turbulence

Can attempt to compensate for this by reshaping the primary or by changing the optics further down the optical path

Results in images comparable to those from the HST

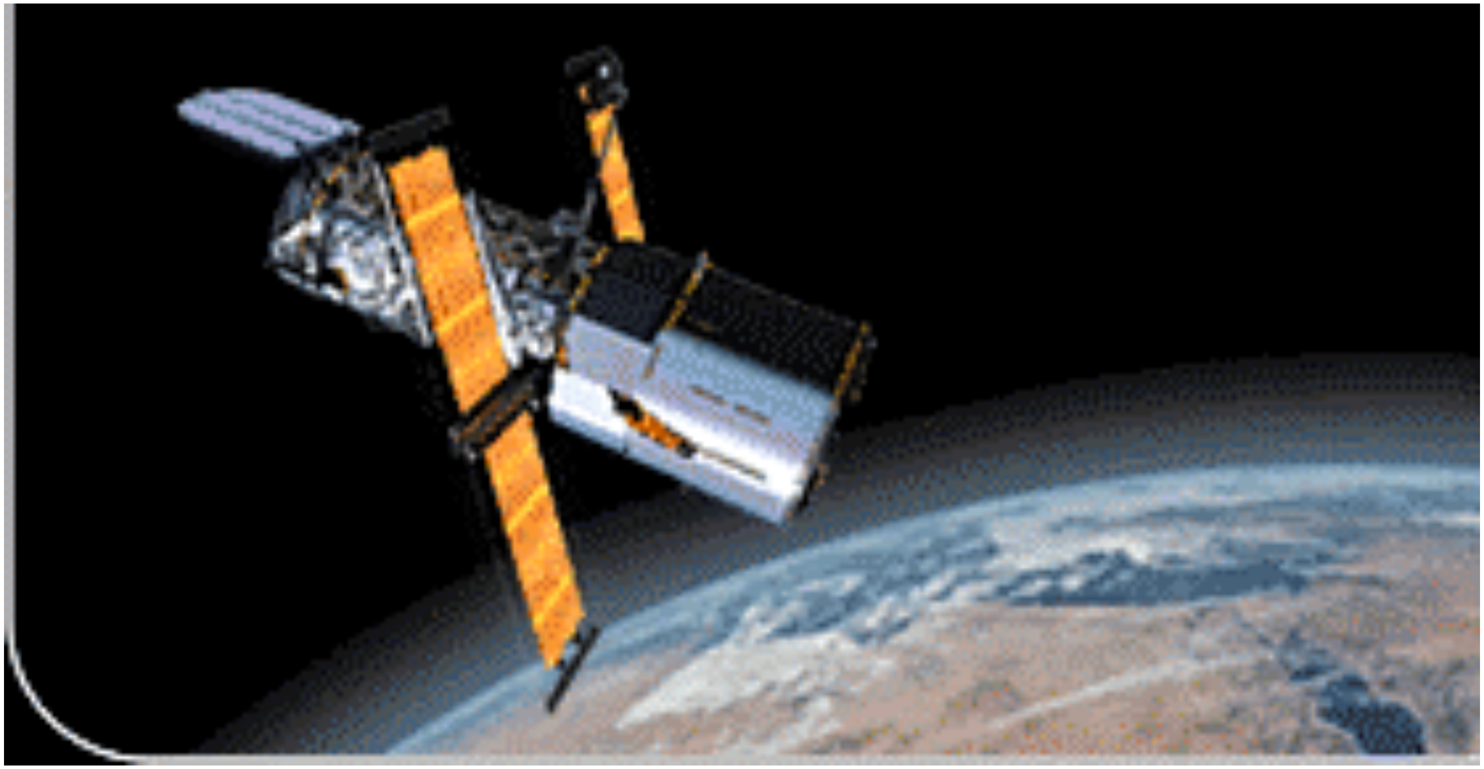


Betelgeuse
twinkling as viewed through atmosphere



Betelgeuse from HST
viewed through Hubble Space Telescope

Images from Space

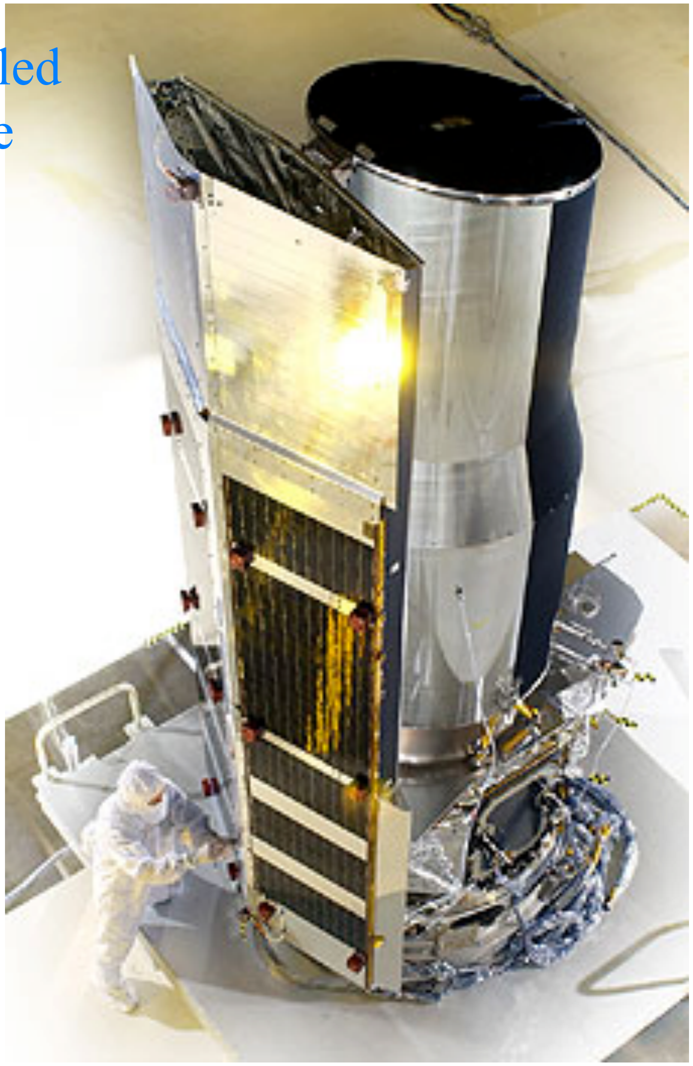


HST can observe at near-IR, optical, and near-UV

Infrared

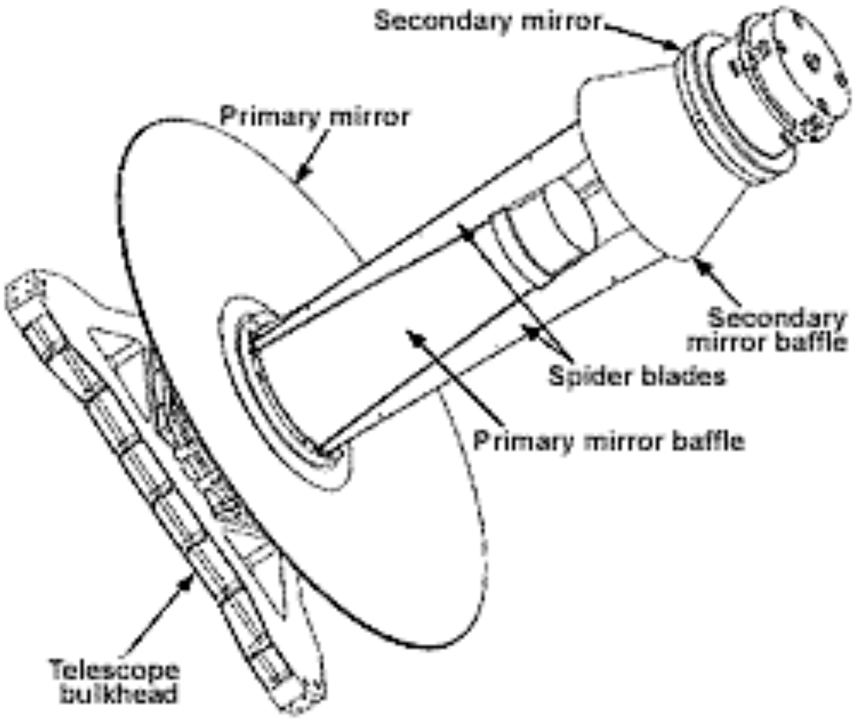
In this image from Lockheed Martin, a fully assembled SIRTF (Space Infrared Telescope Facility) sits in the assembly bay as a technician works on it.

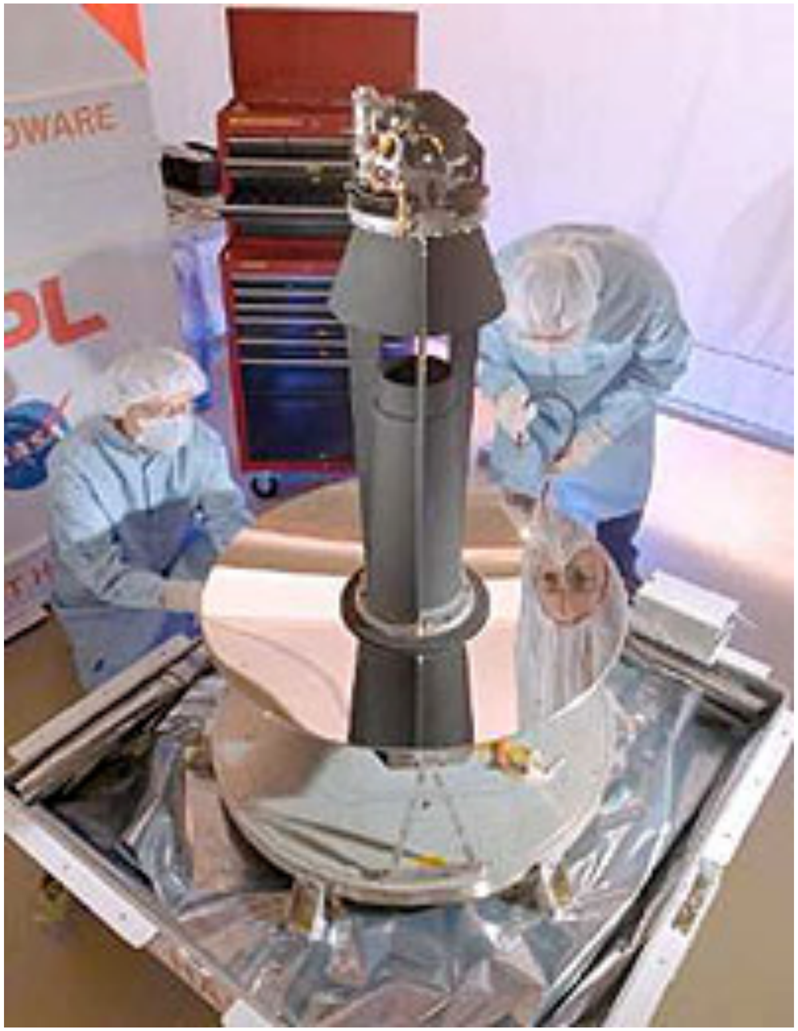
SIRTF was launched in 2003.



Infrared

Consisting of a 0.85-meter telescope and three cryogenically-cooled science instruments, SIRTF is the largest infrared telescope ever launched into space.



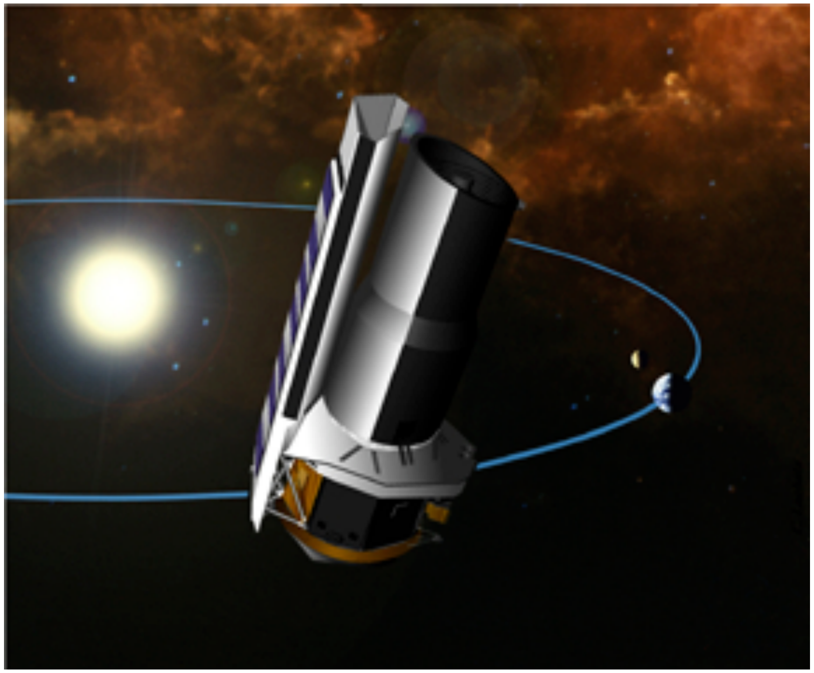


Infrared

Infrared light can penetrate interstellar clouds that are opaque at other wavelengths, allowing us to see regions of star formation, the centers of galaxies, and newly forming planetary systems.

Infrared also brings us information about the cooler objects in space, such as smaller stars which are too dim to be detected by their visible light, extrasolar planets, and giant molecular clouds.

Also, many molecules in space, including organic molecules, have their unique signatures in the infrared.



SIRTF in heliocentric orbit

Types of EM radiation

Low frequency/long wavelength *LOW ENERGY*

Radio

Millimeter

Sub-millimeter

Mid frequency/mid wavelength *MID ENERGY*

Infrared

Optical

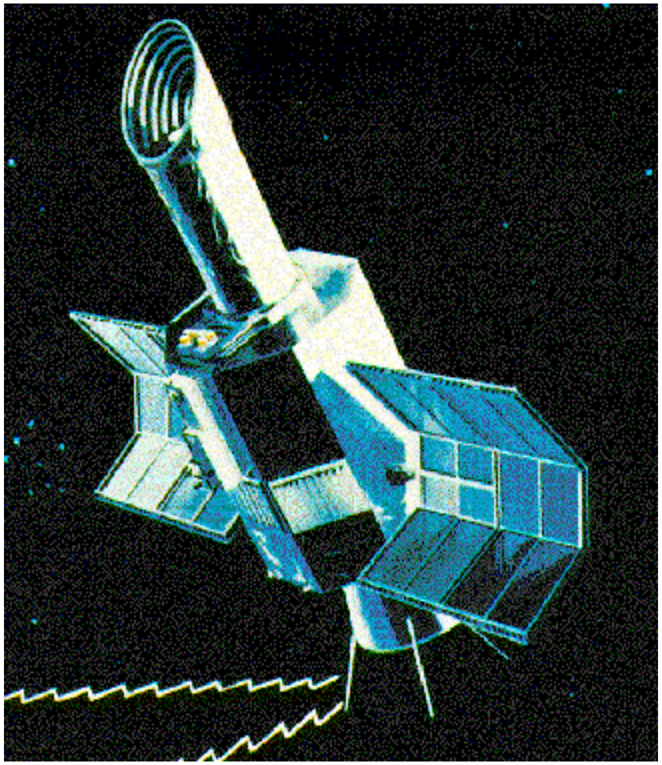
High frequency/short wavelength *HIGH ENERGY*

Ultraviolet

X-ray

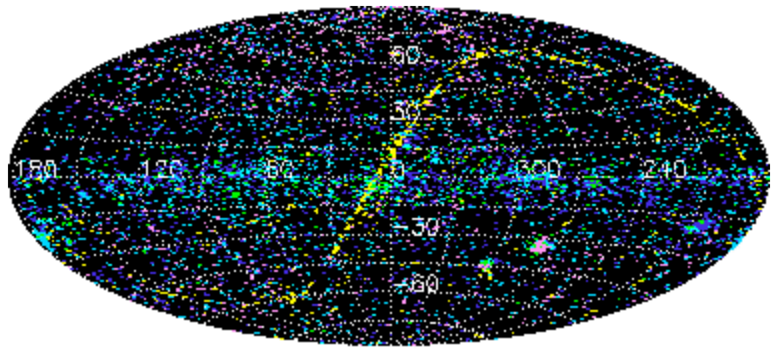
Gamma ray

Near-Ultraviolet
1150 Å and 3200 Å



International Ultraviolet Explorer
Near-IR 1150 Å and 3200 Å

Operated from 1978-1996



Map of IUE Observations

The telescope is a 45-cm aperture, f/15 telescope of Ritchey-Chretien design.

The primary mirror is made of beryllium. Thermal heaters mounted on the back of the mirror and on the camera deck are used for focus control.

Far-Ultraviolet
825 to 3200 Å

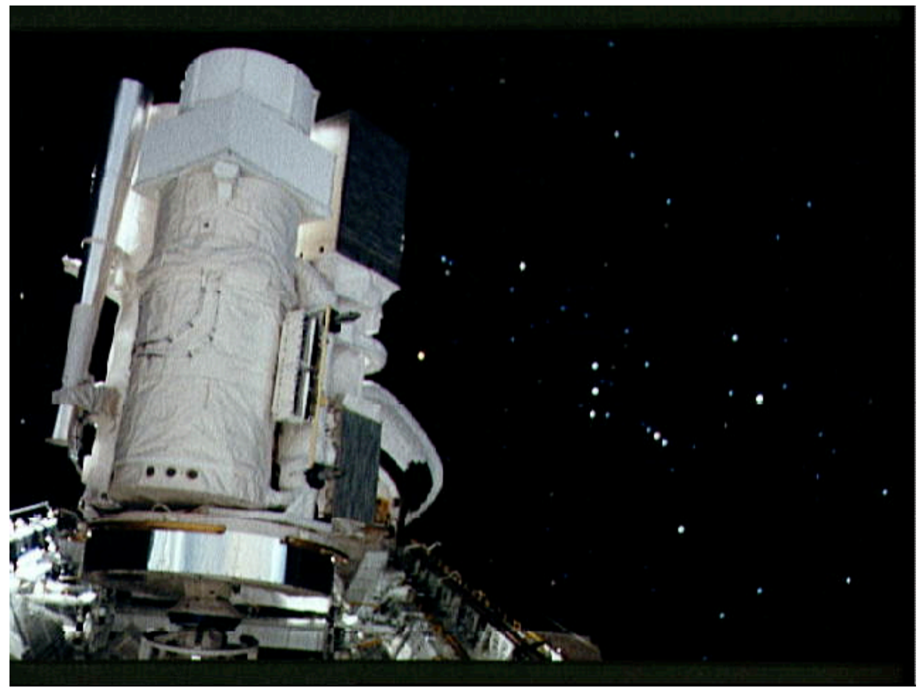
The *ASTRO Observatory* was comprised of three instruments:

Ultraviolet Imaging Telescope (UIT)
1200 to 3200 Å

Hopkins Ultraviolet Telescope (HUT)
825 to 1,850 Å

Wisconsin Ultraviolet Photo-Polarimeter Experiment (WUPPE)

The *ASTRO Observatory* flew on two Shuttle flights

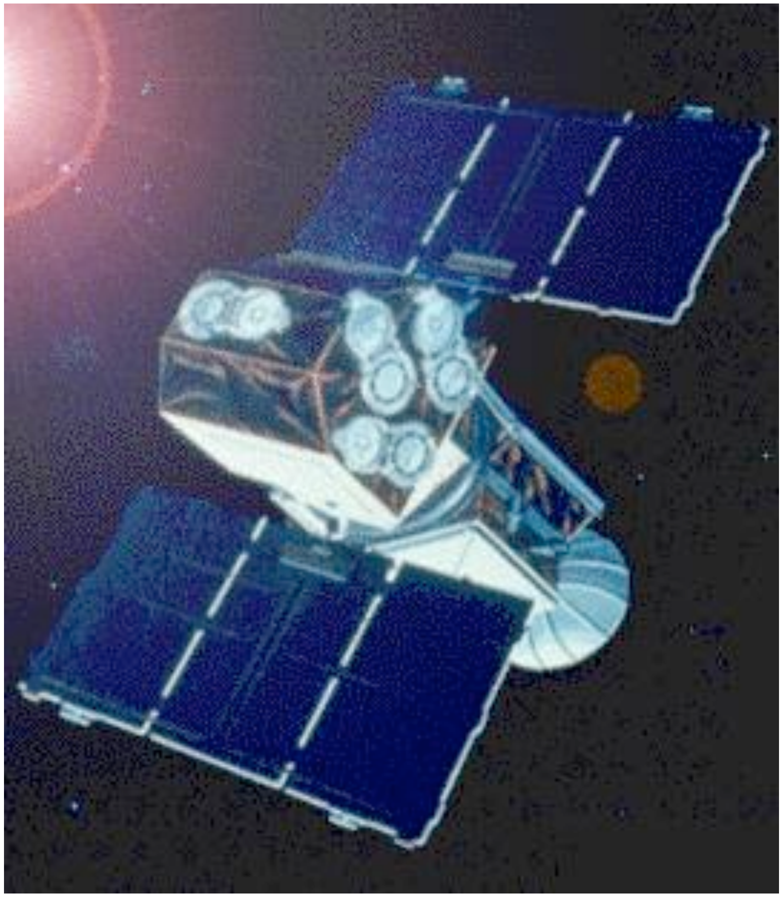


Hopkins Ultraviolet Telescope
Far UV

Extreme-Ultraviolet
70 to 760 Å

The Extreme Ultraviolet Explorer (EUVE), a NASA explorer class satellite mission, was launched on June 7 1992 and it operated till January 31, 2001.

Used *grazing incidence mirrors* and microchannel plate (MCP) detectors



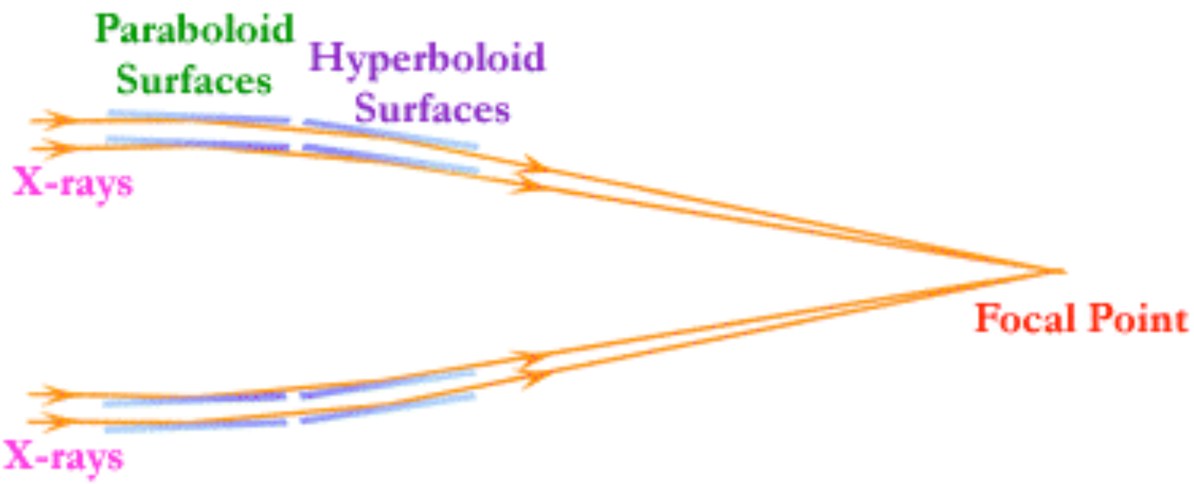
EUVE Extreme Ultraviolet Explorer

Mirrors to focus high energy radiation

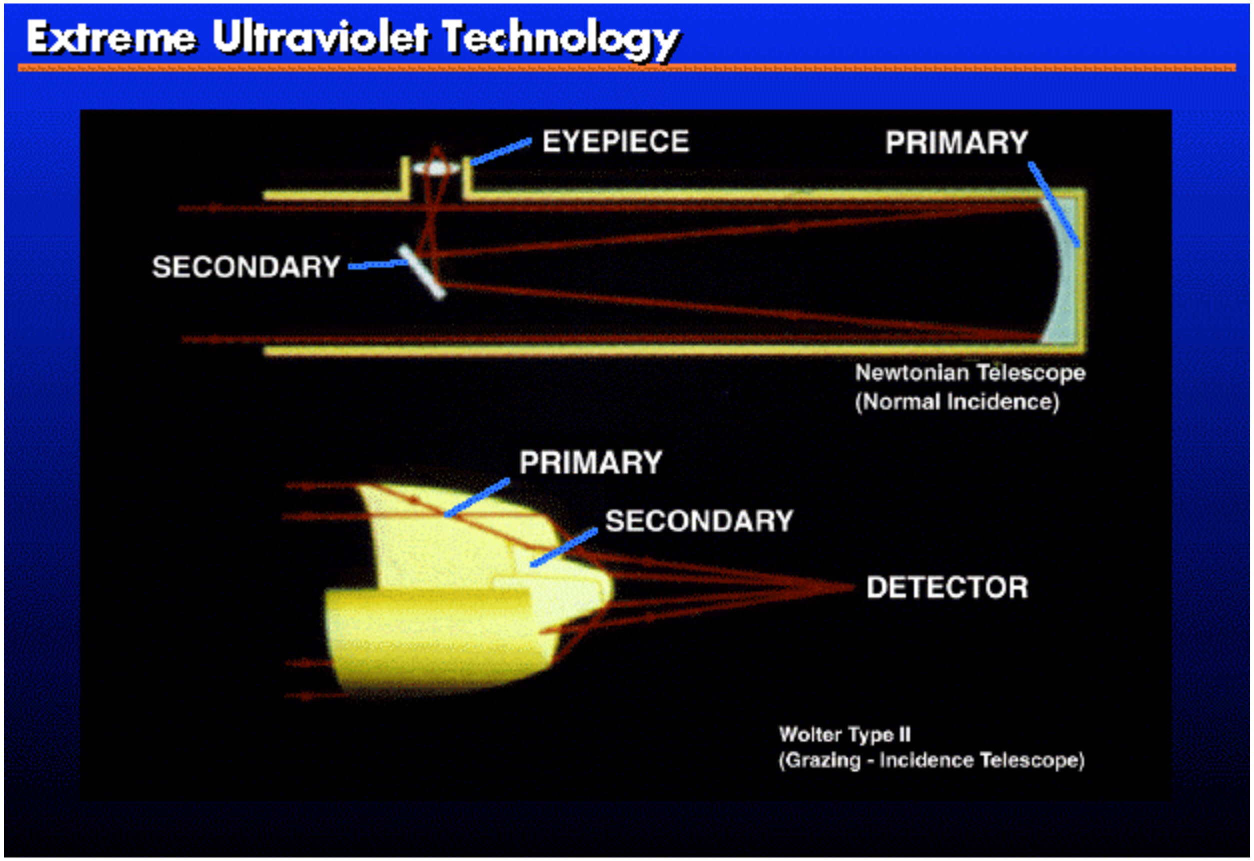
X-ray telescope mirrors also use *grazing incidence mirrors*

The mirrors have shallow angles of reflection, because the wavelengths of X-rays are so short they only reflect at angles almost parallel to the rays themselves.

At steeper mirror angles the rays won't reflect; instead they will penetrate the mirror like a bullet embedding themselves in the mirror surface.



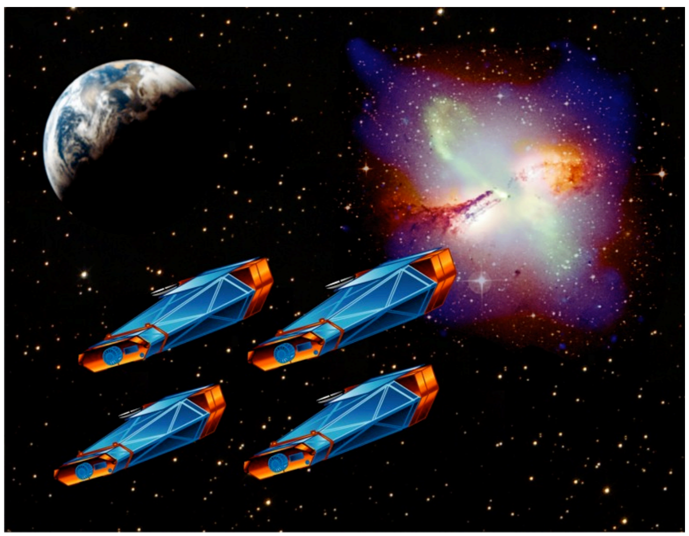
Grazing Incidence Mirrors (Wolter Type II)



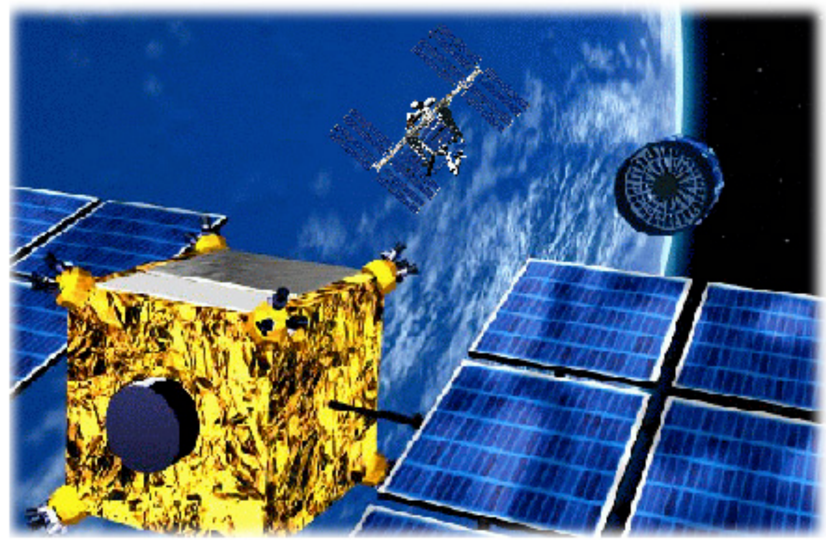
Full scale XEUS grazing-incidence mirror plates

Constellation X and XEUS

Two x-ray telescopes under development are Constellation X and XEUS



Constellation X is a NASA project



XEUS is an ESA project

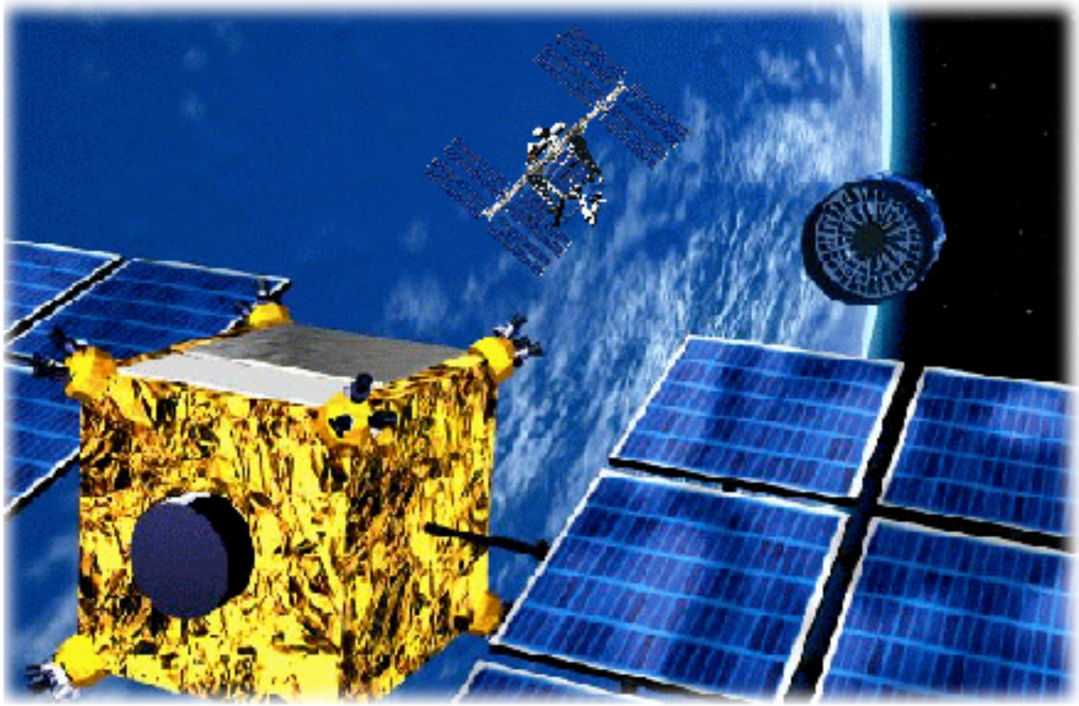
Constellation X

The Constellation-X Mission will place in orbit an array of X-ray telescopes that will work in unison to improve our view of the Universe by a hundredfold.

The mission is a key element in NASA's Structure and Evolution of the Universe theme, dedicated to unlocking the mysteries of black holes, galaxy formation, and the still undetected matter in the Universe.

XEUS: X-ray Evolving Universe Spectroscopy Mission

ESA's XEUS will be a permanent space-borne x-ray observatory



DVD about XEUS...

Constellation X and XEUS

NASA's redirection away from International Space Station (ISS) has impacted the European/Japanese XEUS X-ray mission, which no longer plans to utilize the ISS for assembly and then operate nearby in order to allow servicing.

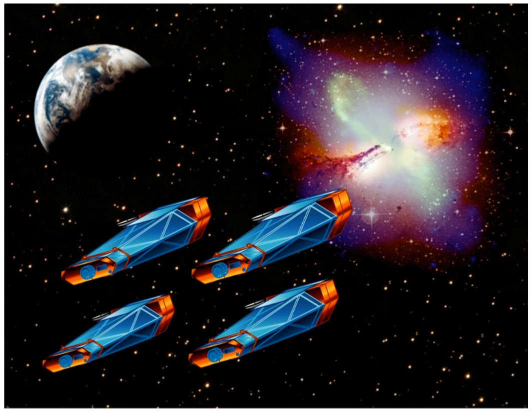
Instead, XEUS will operate at L2, as Con-X will.

While the primary XEUS science is imaging of very faint objects, and that of Con-X is high resolution spectroscopy of brighter objects, both are large area, high throughput missions.

This has opened up the possibility of a collaboration between ESA, JAXA and NASA.

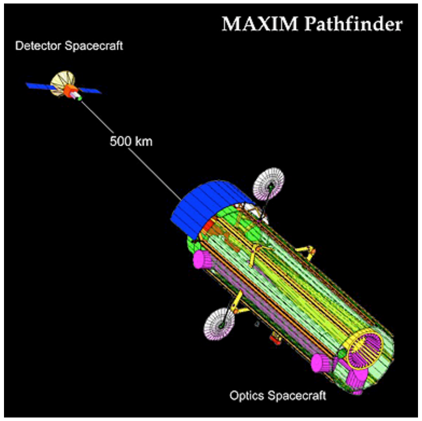
MAXIM X-ray interferometer

Constellation-X is not an interferometer. The idea of Con-X is to use an array of x-ray telescopes *to increase collecting area.*



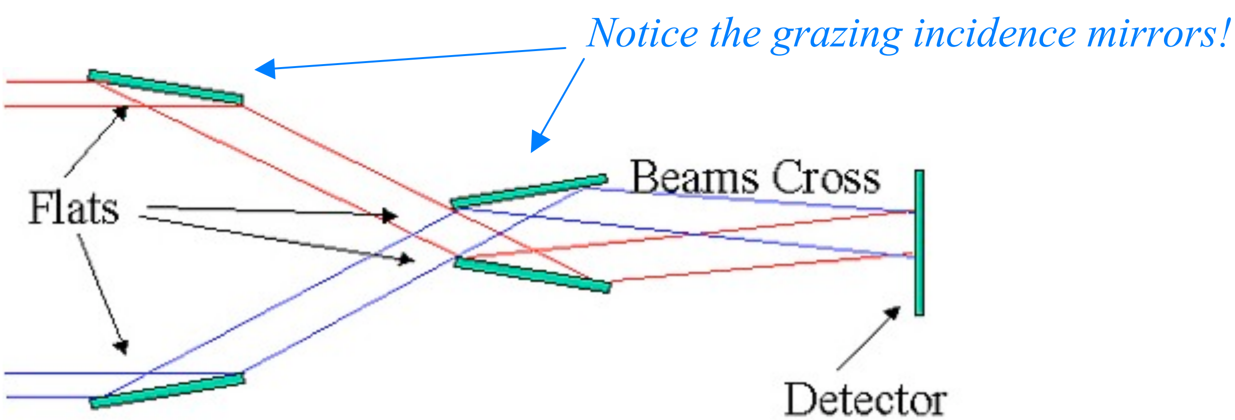
Constellation X

However, MAXIM plans to use an array of x-ray telescopes as an x-ray interferometer *to increase the resolution*



MAXIM X-ray interferometer

The MAXIM (Micro Arcsecond X-ray Imaging Mission) concept utilizes x-ray interferometry to achieve micro-arcsecond angular resolution.



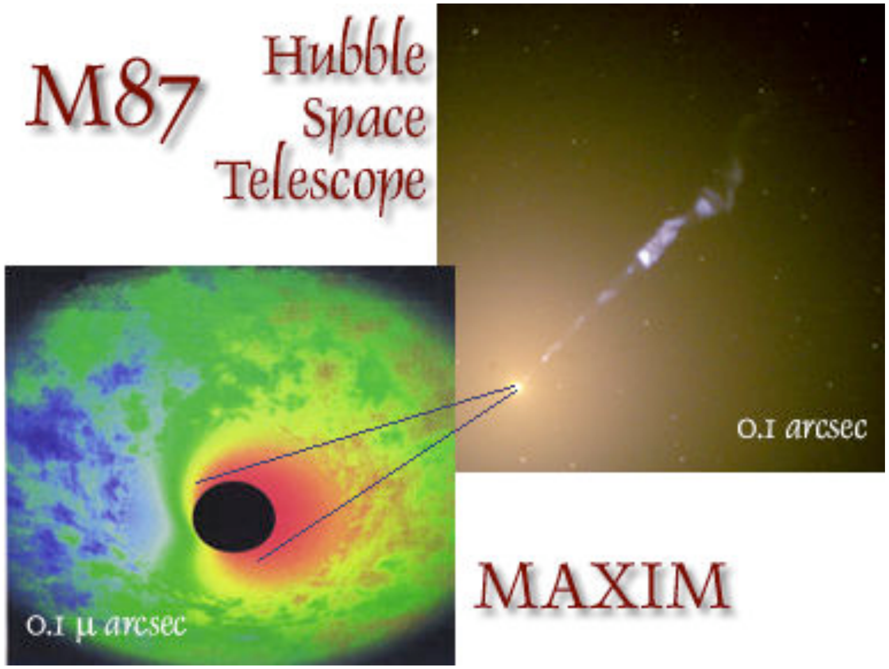
A NASA mission built around this concept could achieve resolution as fine as 300 nano-arcseconds.

This resolution is 3,000 times finer than VLBI and 300,000 times finer than HST

MAXIM X-ray interferometer

X-rays are emitted only under extreme conditions: temperatures of millions of degrees and magnetic fields of millions of Gauss can create X-rays.

They are often associated with the dramatic events of both the birth death of astronomical objects

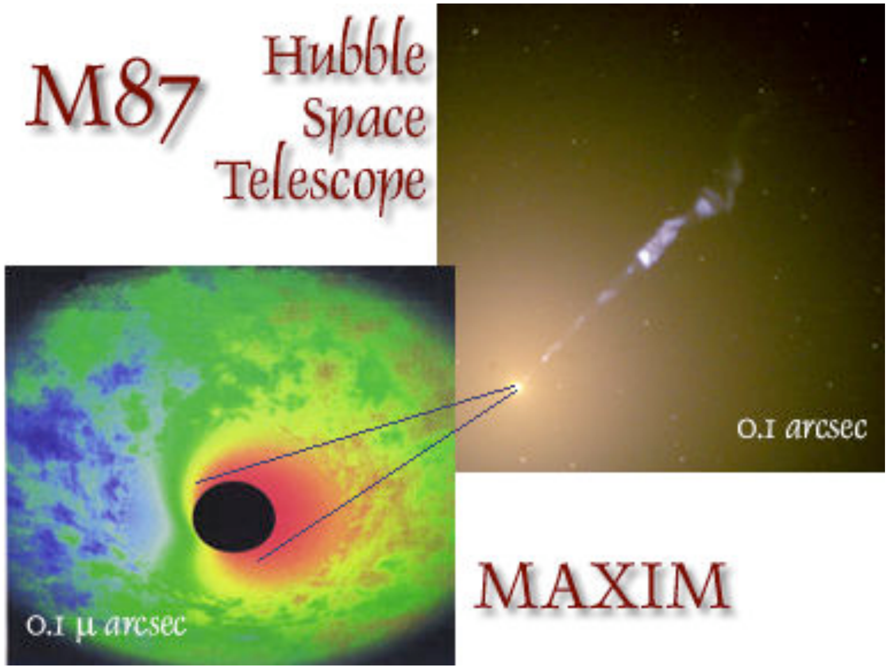


MAXIM X-ray interferometer

X-rays come from compact regions and image the core structures in some of the most interesting events in the Universe.

This is the antithesis of structures viewed in radio VLBI, which are usually created by high energy electrons expanding away from the central structure.

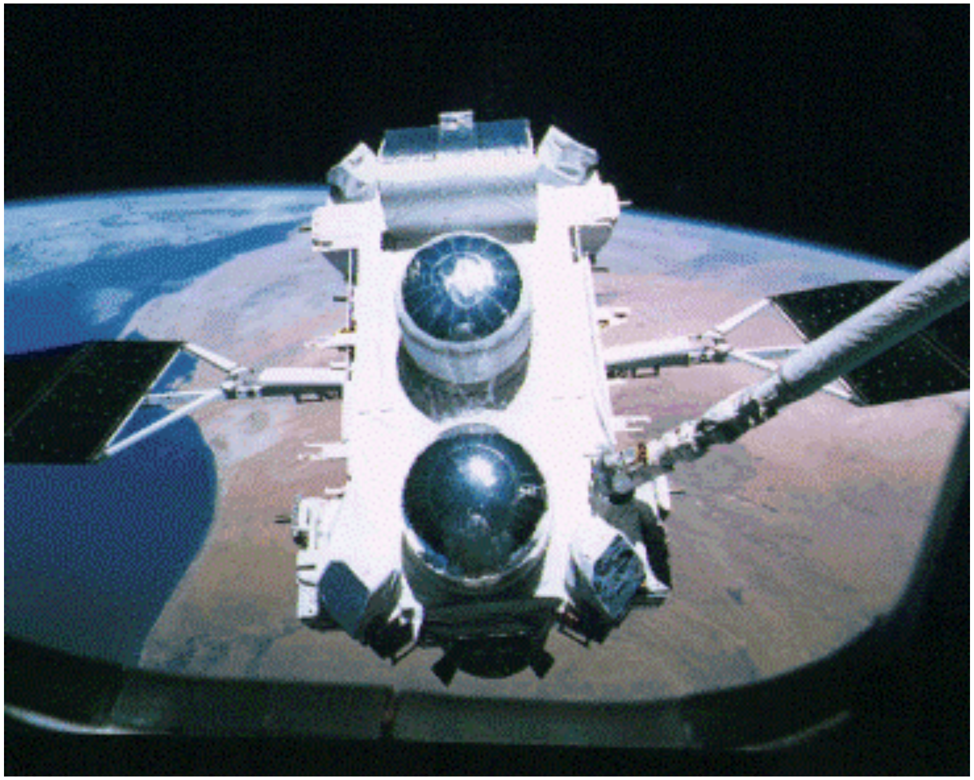
With X-rays we see the central engine itself.



CGRO
Compton Gamma Ray Observatory

CGRO was launched on April 5, 1991 aboard the space shuttle Atlantis. Compton was safely deorbited and reentered the Earth's atmosphere on June 4, 2000.

CGRO had four instruments that covered an unprecedented six decades of the EM spectrum from 30 keV to 30 GeV.



CGRO
Compton Gamma Ray Observatory

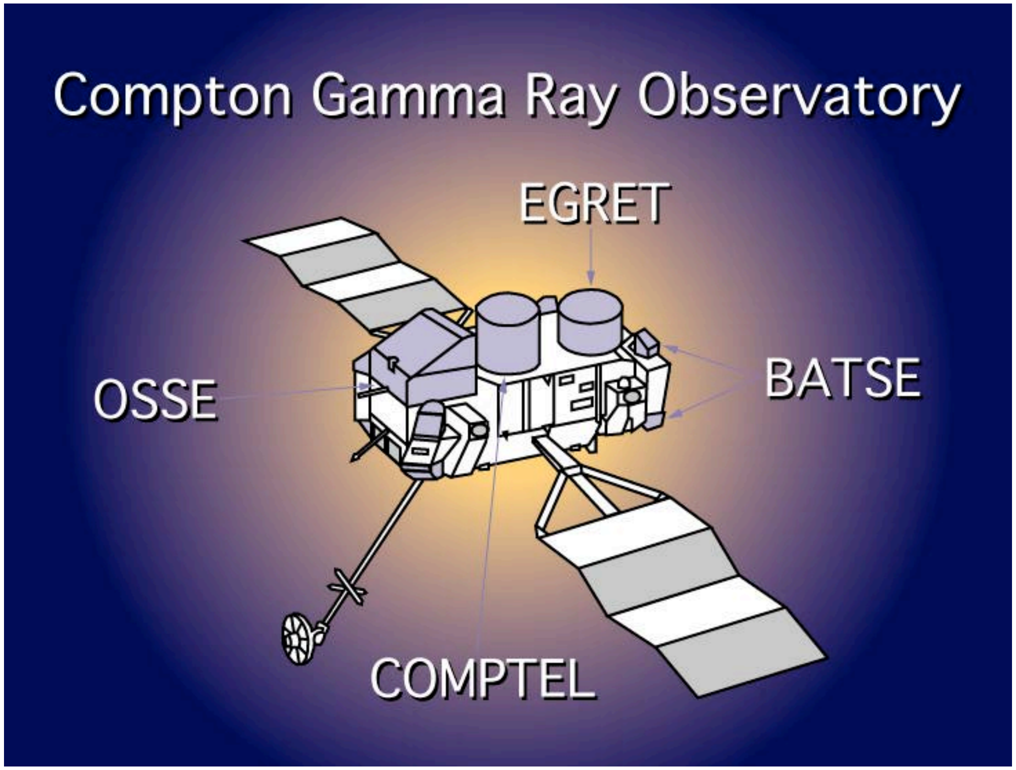
In order of increasing spectral energy coverage, these instruments were:

Burst And Transient Source Experiment (BATSE)

Oriented Scintillation Spectrometer Experiment (OSSE)

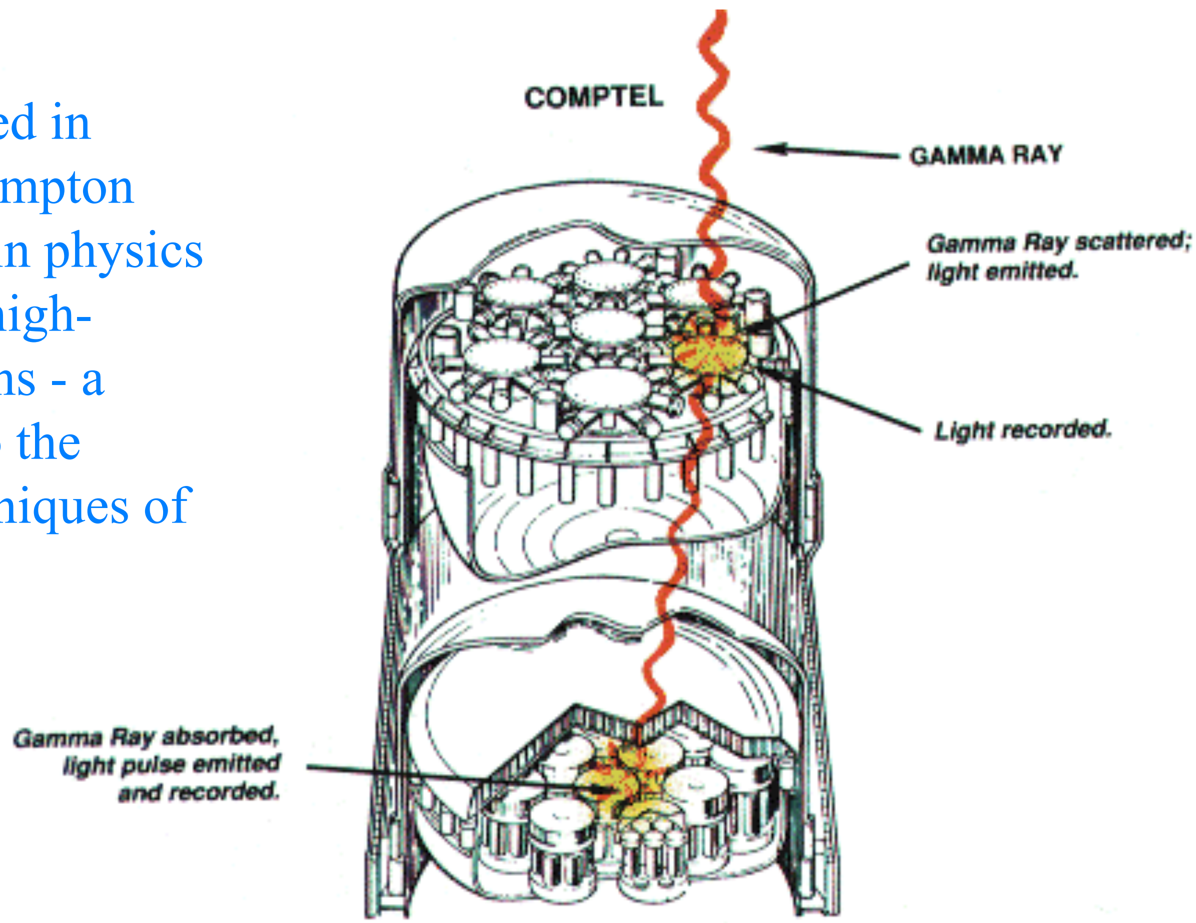
Imaging Compton Telescope (COMPTEL)

Energetic Gamma Ray Experiment Telescope (EGRET)



CGRO
Compton Gamma Ray Observatory

The observatory was named in honor of Arthur Holly Compton who won the Nobel prize in physics for work on scattering of high-energy photons by electrons - a process which is central to the gamma-ray detection techniques of all four instruments.



GLAST
Gamma-ray Large Area Space Telescope

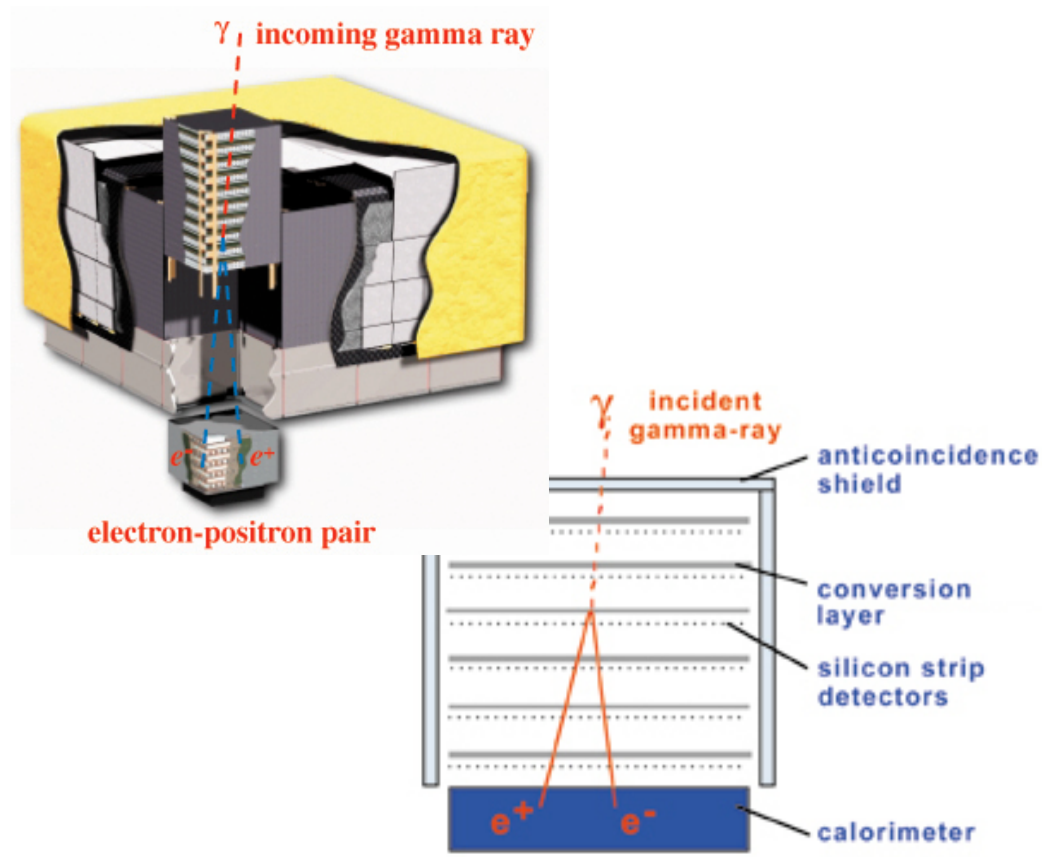
The Gamma-ray Large Area Space Telescope (GLAST) is an international and multi-agency space mission that will study the cosmos in the energy range 10 keV - 300 GeV

GLAST
Gamma-ray Large Area Space Telescope

GLAST will detect gamma rays by using a concept known as pair production

An incident gamma ray interacts with a layer of dense material in the telescope (tungsten in the case of GLAST), producing an electron and positron (e+ e-) pair

These e+ e- pairs are then tracked through the telescope using silicon strip detectors, and continue down through the telescope to the calorimeter.



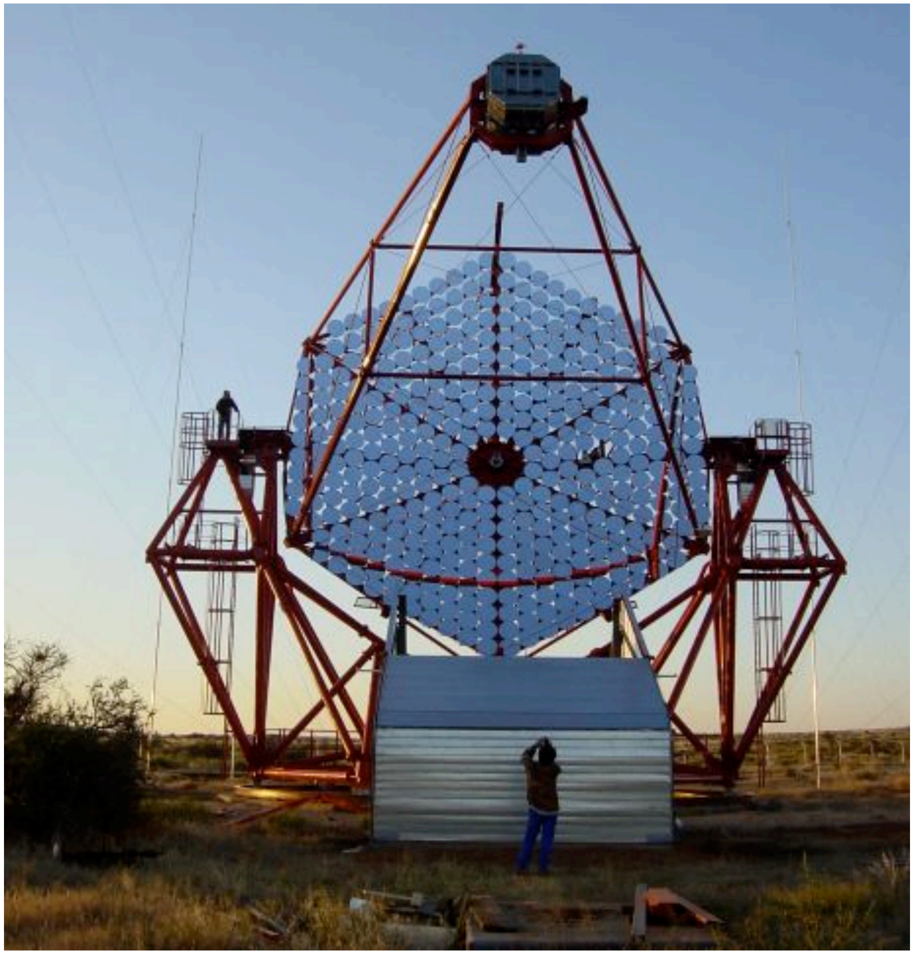
Cutaway of the GLAST LAT (Large Area Telescope)

Not all gamma ray telescopes are in space

HESS

(High Energy Spectroscopic System) actually requires the atmosphere to operate!

Gamma rays can't penetrate Earth's atmosphere, but they do produce e+ e- pairs as they travel through the atmosphere.



HESS, Namibia

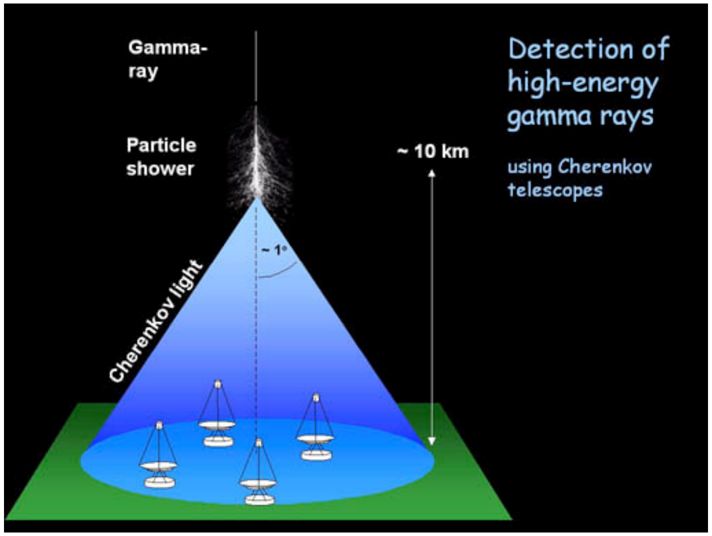
The highest energy gamma rays are detected on Earth!

These are extremely energetic particles which means that they are traveling very close to the speed of light.

In fact, these particles are traveling faster than the speed of light *in the medium of the atmosphere*.

Remember that nothing can travel faster than the speed of light in a vacuum, but that the speed of light is reduced when traveling through most media, like glass, water, air, etc.

HESS, Namibia

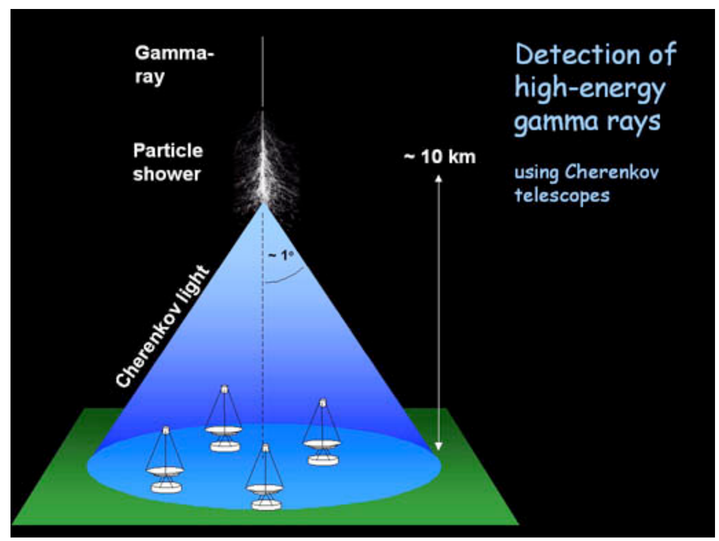


The highest energy gamma rays are detected on Earth!

This results in the emission of a faint, bluish light known as *Cerenkov radiation*.

The telescopes detect these brief flashes of *optical* light.

HESS, Namibia



All-wave telescope

Ideally, would like an observatory that could look at all parts of the electromagnetic spectrum simultaneously

Matched telescopes could be aligned to look at the same object at the same time.

A device containing all the different types of telescopes would necessarily have to be a satellite so that X-rays and gamma rays could be detected.

All-wave telescope

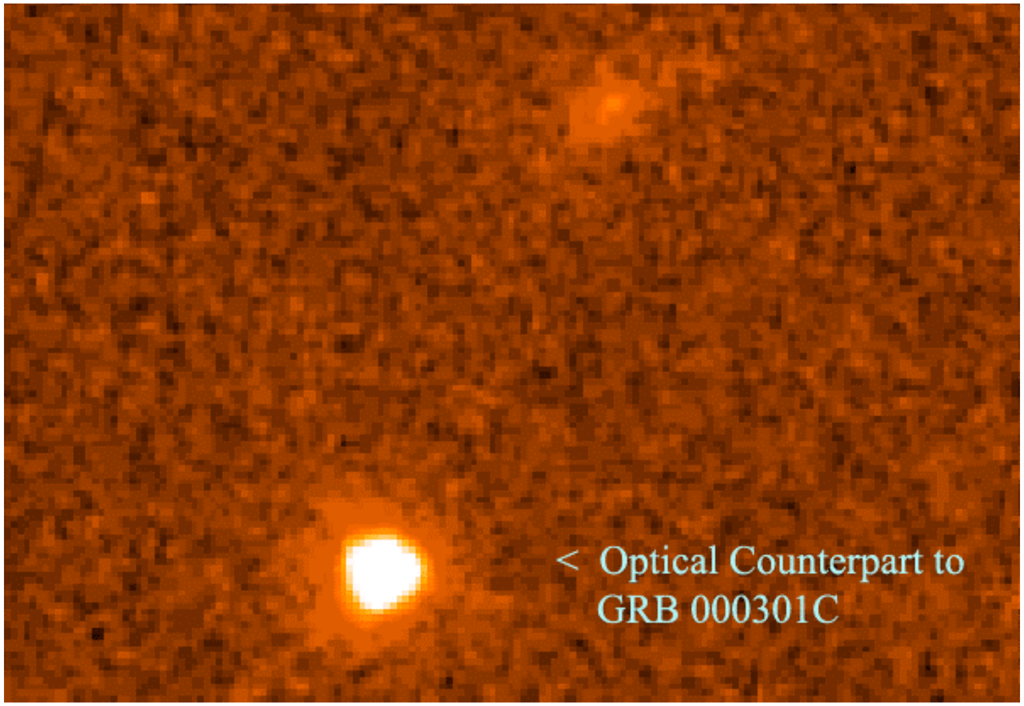
Several multi-wavelength observatories have already flown - Skylab, the Solar Maximum Mission, and the Solar and Heliospheric Observatory (SOHO).

Launched in 1973, Skylab had eight coordinated telescopes The eight telescopes studied the Sun's spectrum from x-ray almost down to infrared, all with very high quality resolution.

Skylab was coordinated with ground-based astronomers as well.

All-wave telescope

But, because specialized telescopes are so well developed and are still strongly supported by scientists, the most logical approach nowadays would be to coordinate the telescopes already in existence, as is often done to study gamma ray bursts (GRBs)



A GRB 000301C Symphony

http://antwrp.gsfc.nasa.gov/apod/ap010603.html