Observing the Universe: Telescopes

Astronomy 2020 Lecture 6

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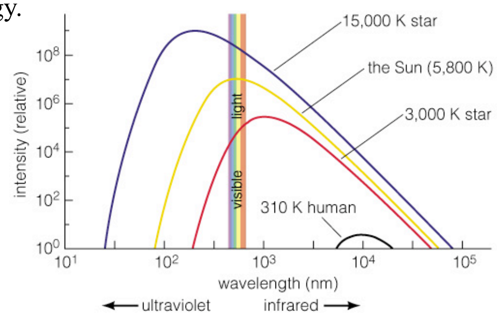
Today's Lecture:

1. A little more on blackbodies
2. Light, vision, and basic optics
3. Telescopes

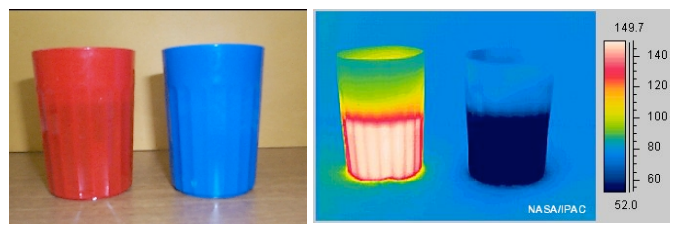
Properties of Thermal Radiation

1. Hotter objects emit more light at all frequencies per unit area.
2. Hotter objects emit photons with a higher average energy.



First: Some more on black bodies.

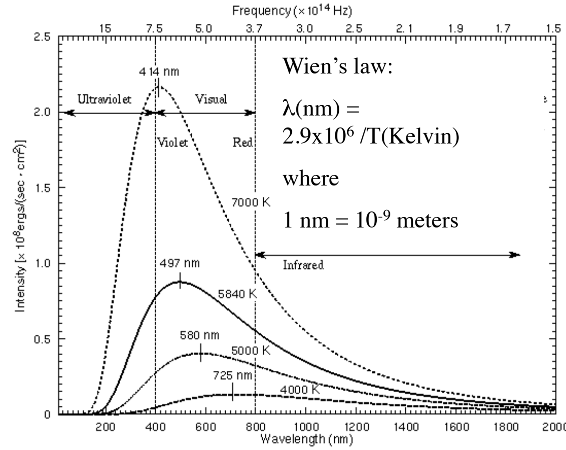
Two Cups - one hot, one cold.



Visible Light Infrared

Visible Light

Since neither cup is hot enough to emit in visible light, we see it in reflected light from the Sun or light bulb (both are hot enough to emit in visible).



Wien's law:

λ(nm) = 2.9×10^6 /T(Kelvin)

where

1 nm = 10^{-9} meters

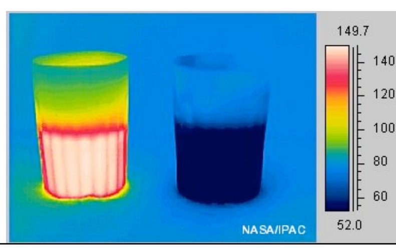
Picture from Nick Strobel's astronomy notes: www.astronomynotes.com

Infrared Light

In this picture, everything is emitting infrared light: the water, the cup, the background. At the same time everything is absorbing infrared light. If everything was at the same temperature, it would emit and absorb the same amount of light, and everything would be the same color (I.e. everything would be the same temperature).

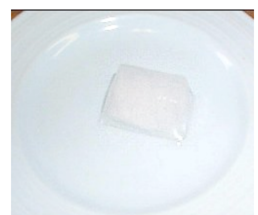
Since the hot water is hotter than its surroundings, it is emitting more light (glows more brightly) than it absorbs. It will eventually cool (conservation of energy)

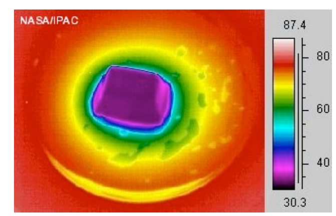
Since the cold water is colder than its surrounding, it absorbs more light than it emits. It will eventually warm up.



In this infrared picture, the color is the temperature of the blackbody radiation.

Melting Ice Cube



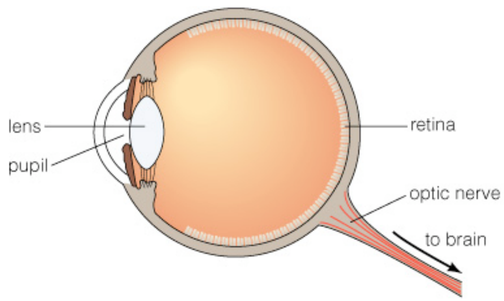


Cold ice cube radiates less light than surrounding water.

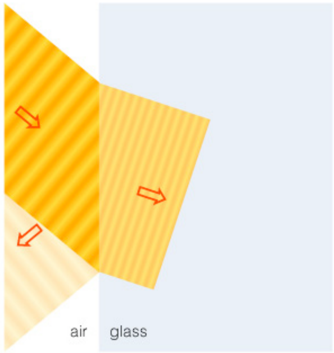
Materials that are transparent in visible light, may absorb much infrared radiation (as well as some visible light).

For example: Glass, water, air absorbs infrared radiation

How does your eye form an image?



Refraction

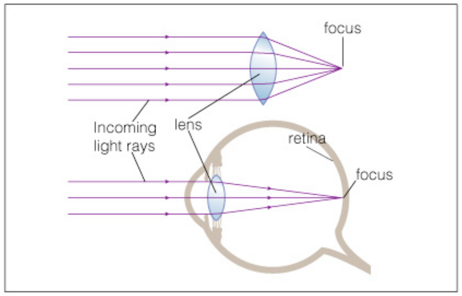


- Refraction is the bending of light when it passes from one substance into another
- Your eye uses refraction to focus light

Example: Refraction at Sunset

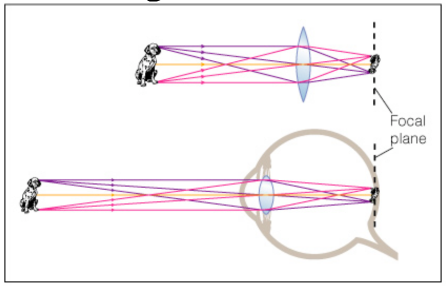
- Sun appears distorted at sunset because of how light bends in Earth's atmosphere

focusing Light



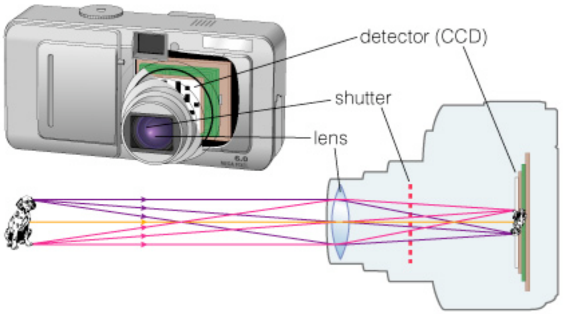
- Refraction can cause parallel light rays to converge to a focus

Image Formation

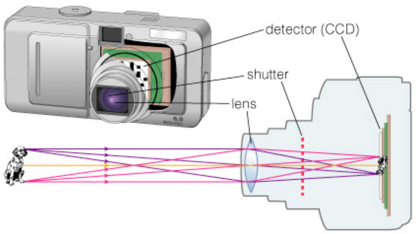


- The focal plane is where light from different directions comes into focus
- The image behind a single (convex) lens is actually upside-down!

How do we record images?



Focusing Light



Digital cameras detect light with charge-coupled devices (CCDs)

- A camera focuses light like an eye and captures the image with a detector
- The CCD detectors in digital cameras are similar to those used in modern telescopes

What are the two most important properties of a telescope?

1. **Light-collecting area:** Telescopes with a larger collecting area can gather a greater amount of light in a shorter time.
2. **Angular resolution:** Telescopes that are larger are capable of taking images with greater detail.

Light Collecting Area

- A telescope's diameter tells us its light-collecting area: Area = $\pi(\text{diameter}/2)^2$
- The largest telescopes currently in use have a diameter of about 10 meters

Angular Resolution

Angular Resolution is give by:

$\theta = 1.22\ \lambda$ (meters)/D (meters)

Where θ is the angular resolution of a telescope in radians, λ is the wavelength of light, and D is the diameter of the telescope.

In units of arcseconds (a full moon is 1800 arcseconds in diameter)

θ(arcseconds) = $2.5 \times 10^5\ \lambda/D$

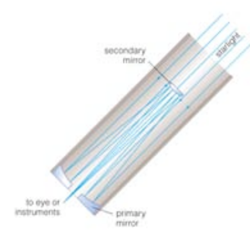
L = 650 nm or 650 x 10-9 meter (red light)
D = 10 meter (biggest telescope)
θ = 0.016 arcsecond
which is 30 meter at the distance of the moon

- Ultimate limit to resolution comes from interference of light waves within a telescope.
- Larger telescopes are capable of greater resolution because there's less interference
- However, resolution is often limited by atmospheric turbulence

What are the two basic designs of telescopes?

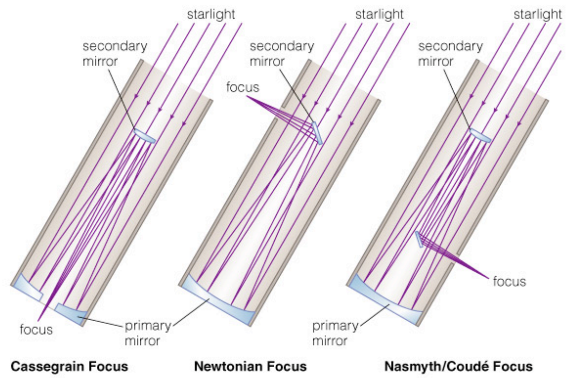
- **Refracting telescope:** focuses light with lenses
- **Reflecting telescope:** focuses light with mirrors

Reflecting Telescope



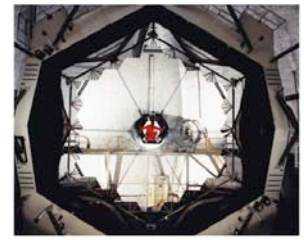
- Reflecting telescopes can have much greater diameters
- Most modern telescopes are reflectors

Designs for Reflecting Telescopes



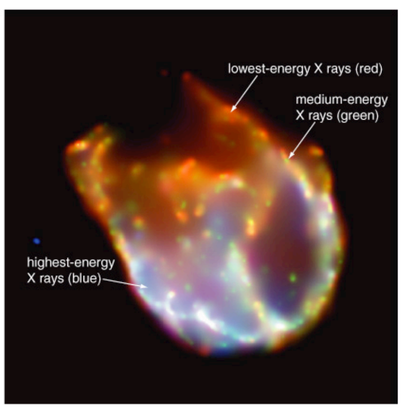
Mirrors in Reflecting Optical/ Infrared Telescopes

Twin Keck telescopes on Mauna Kea in Hawaii



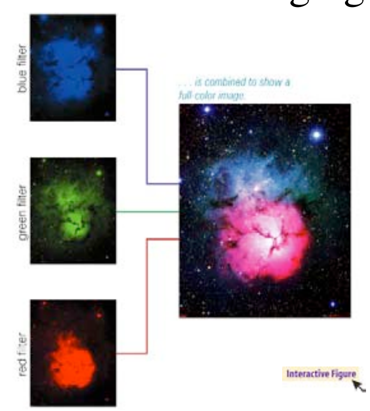
Segmented 10-meter mirror of a Keck telescope

Imaging



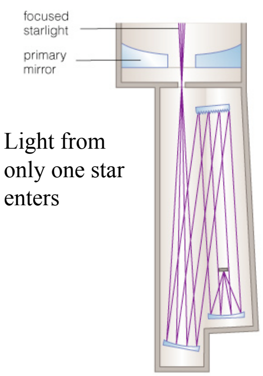
- Astronomical detectors can record forms of light our eyes can't see
- Color is sometimes used to represent different energies of nonvisible light

Imaging



- Astronomical detectors generally record only one color of light at a time
- Several images must be combined to make full-color pictures

Spectroscopy



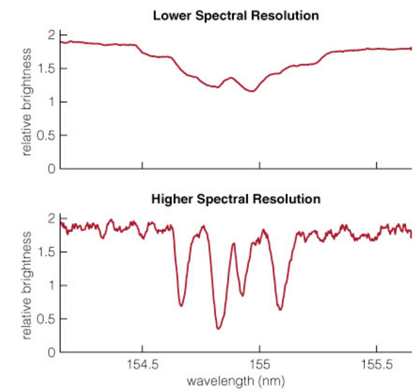
Light from only one star enters

Diffraction grating breaks light into spectrum

Detector records spectrum

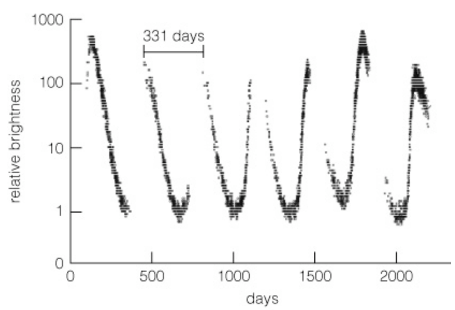
- A spectrograph separates the different wavelengths of light before they hit the detector

Spectroscopy



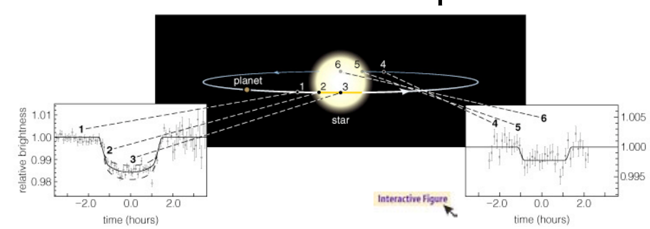
- Graphing relative brightness of light at each wavelength shows the details in a spectrum

Timing



- A light curve represents a series of brightness measurements made over a period of time

Timing Example: Transits and Eclipses



- A **transit** is when a planet crosses in front of a star
- The resulting eclipse reduces the star's apparent brightness and tells us planet's radius
- No orbital tilt: accurate measurement of planet mass
- If the temperature and radius of the star are known, the radius of the planet can be determined.

Timing Example: Transits and Eclipses

Radio Telescopes

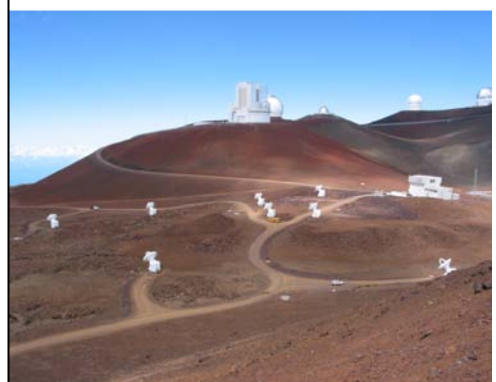
Arecibo telescope (305 meter)

- A radio telescope is like a giant mirror that reflects radio waves to a focus
- The wavelength (l) is much larger for radio telescopes (1 mm or larger)..
- Even 305 meter radio telescopes have lower angular resolution than 1 meter optical/infrared telescopes

Milky Way in Visible and Radio-Wavelength Light

Radio emission (λ = 3 mm) comes from CO molecules in the dark clouds (cold dark clouds emit at radio wavelengths - cooler objects emit at longer wavelengths)

Radio Interferometry



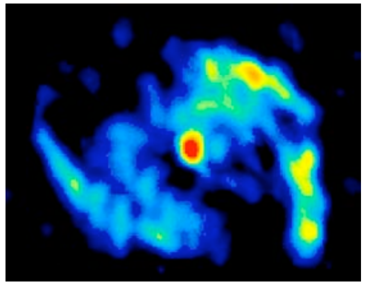
The 8 antenna SubMillimeter Array

Interferometery is a technique for linking two or more telescopes so that they have the angular resolution of a single large one. Often used in radio astronomy where the wavelength is large.

λ = 1 mm
D (telescope) = 6 meter
θ (telescope) = 42 (arcsec)
D (array) = 508 meters
θ (array) = 0.5 (arcsec)

M51 Galaxy Resolved by Submillimeter Array

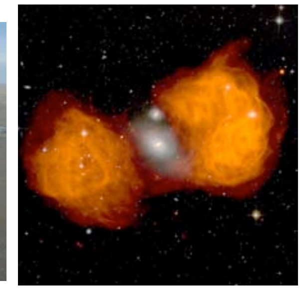
Hubble Image (visible light)



SMA Image (submillimeter)

Gurwell & Butler (2005)

Radio Interferometry Example
The Very Large Array



Radio map is shown in Orange

Calm, High, Dark, Dry

Summit of Mauna Kea, Hawaii

- The best observing sites are atop remote mountains
- Best sites in the world are on Mauna Kea in Hawaii and high mountain tops in the Chilean Andes.
- Antartica may be the best site for infrared astronomy.

Turbulence and Twinkling

Turbulence in the air above the telescope distorts the image of the star, causing it to move and change in shape. This blurs the image of a star, and also causes the twinkling of stars to the naked eye.

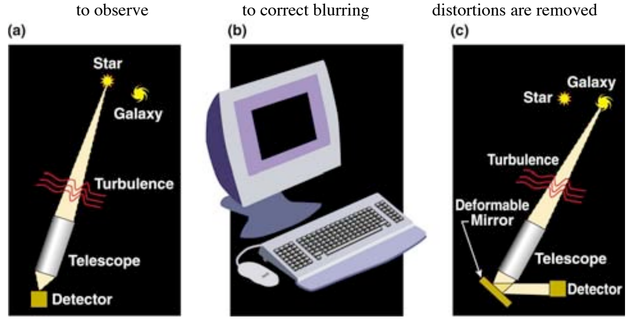
Slide from Claire Max: http://www.ucolick.org/~max/289C/

How does adaptive optics help? (cartoon approximation)

Measure details of blurring from "guide star" near the object you want to observe

Calculate (on a computer) the shape to apply to deformable mirror to correct blurring

Light from both guide star and astronomical object is reflected from deformable mirror; distortions are removed



Slide from Claire Max: http://www.ucolick.org/~max/289C/

Adaptive Optics

Star viewed through turbulent atmosphere

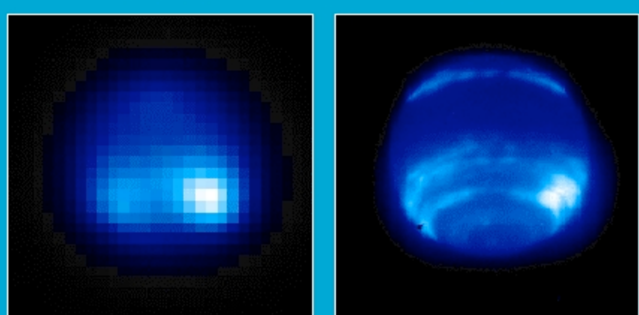
Same star corrected with adaptive optics.

By rapidly changing the shape of a mirror in the telescopes light path, the variations from turbulence can be corrected.

Slide from Claire Max: http://www.ucolick.org/~max/289C/

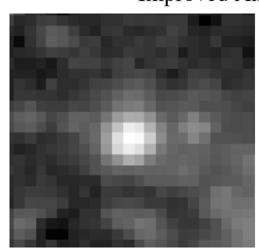
Adaptive optics: Neptune

without *with*

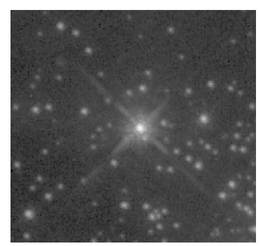


Telescopes in Space

Advantage Number 1 of Space Based Telescopes: Improved Angular Resolution



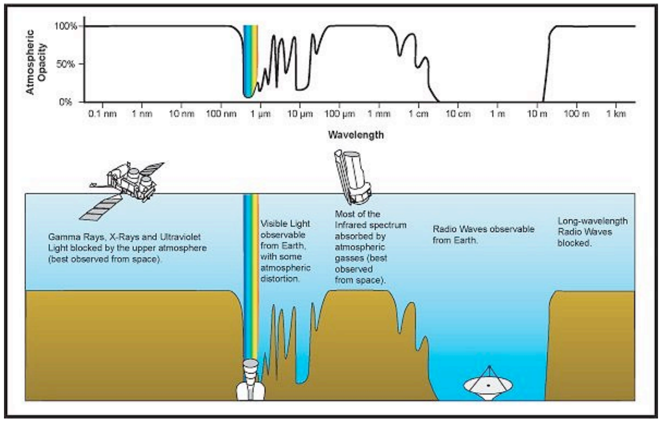
Star viewed with ground-based telescope



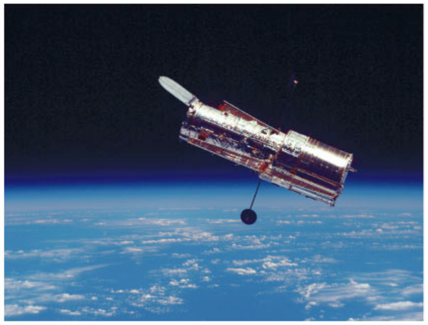
Same star viewed with Hubble Space Telescope

- Turbulent air flow in Earth's atmosphere distorts our view, causing stars to appear to twinkle
- Adaptive optics cannot yet provide a full correction, particularly at visible wavelengths.

Advantage Number 2 of Space Based Telescopes:
Observing Outside The Atmospheric Windows



Optical and UV Telescopes

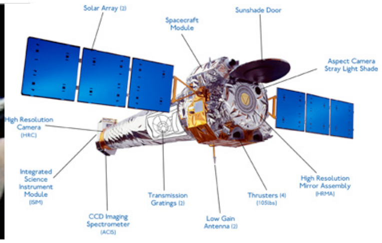


Hubble Space Telescope

- Avoid bluring by atmosphere.
- Can detect UV radiation which is absorbed by atmosphere.
- Space is darker than night sky on Earth, thus observations can be more sensitive.

Gamma Ray and X-ray Telescopes

Compton Gamma-Ray Observatory

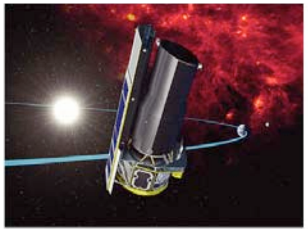


Chandra X-Ray Observatory

- X-ray and Gamma ray telescopes also need to be in space
- focusing X-ray and gamma rays is extremely difficult, normal reflecting mirrors don't work

Infrared Telescopes

SOFIA



Spitzer

- Infrared telescopes operate like visible-light telescopes but need to be above atmosphere to see all IR wavelengths.
- Moving to space also reduces the infrared glow from the atmosphere and telescope and greatly increases the sensitivity of the telescope.

August 25, 2003 – Cape Canaveral

The Observatory

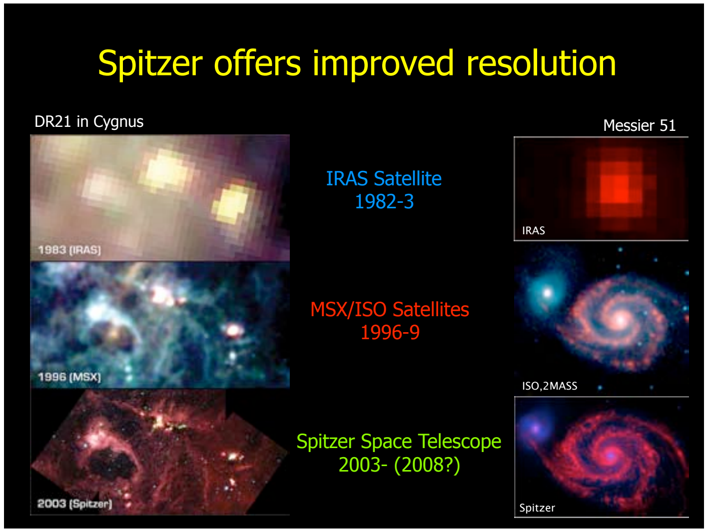
To conserve liquid Helium & extend mission lifetime:

1. Warm launch
2. Radiative Cooling
3. Solar orbit

Instrument detectors cooled by He to lower detector noises (5 K)

Telescope cooled to 20 K by radiating into deep space, and then to 6 K by venting Helium

Instrumentation



The Herschel Space Observatory

Things to know

What is a reflecting telescope?

When we state the diameter of a telescope, it is the diameter of what part?

What are the two most important properties of a telescope?

What is the difference between imaging and spectroscopy?

What s a radio telescope?

What is an interferometer?

The relationship between telescope size, wavelength and angular resolution

What are the advantages of observing from space?