7. Telescopes: Portals of Discovery

All of this has been discovered and observed these last days thanks to the telescope that I have [built], after having been enlightened by divine grace.

Galileo Galilei (1564 – 1642)
Astronomer & Physicist

Agenda

- Announce:
  - Test two weeks from today
  - Due this week: lens lab, tutorial
- What did you think of the lab last week?
- Feedback on what to cover (Solar System, Stars, Spacetime) …Next semester: Remainder, galaxies, cosmology
- Ch. 7: Telescopes

Visions of Science

http://www.visions-of-science.co.uk/

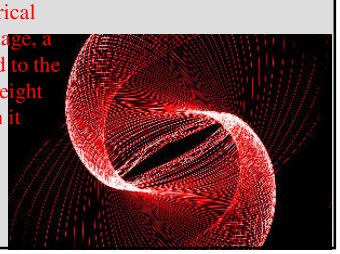
- This Culex mosquito is just emerging from its pupa (brown).
- LEO 1430 VO scanning electron microscope at 20 kV. Coloured using Adobe Photoshop 7.01

Visions of Science Winner

- Blue ink diffusing into water takes on the appearance of jubilant figures with raised arms, as if in prayer

Visions of Science Winner

- The track of a simple pendulum over five minutes is revealed here, showing its complex yet symmetrical path. To make the image, a red light was attached to the base of a swinging weight and a camera beneath it activated.



European Southern Observatory

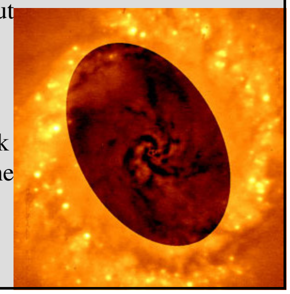
- Take a look at galaxy NGC 1097

European Southern Observatory

- Take a look at galaxy NGC 1097
- And zoom in to the center
- Ring of dust and clouds where stars form
- Look in center…dust spiraling in

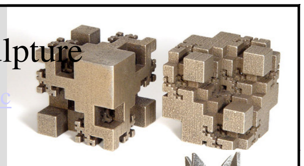
European Southern Observatory

- Now, take the same image and subtract out the central "glow"
- Spiral more clear
- Too small to see is a central, massive black hole (million times the Sun's mass)



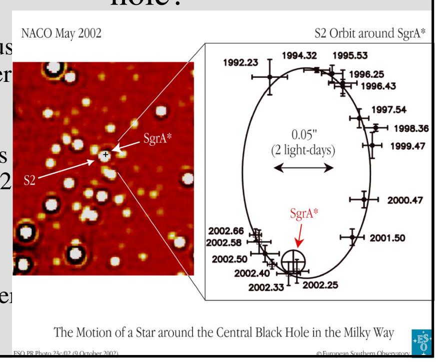
Mathematical Sculpture

- http://www.bathsheba.com
- 3D designs based on symmetry
- 3D printed—mass produced sculpture



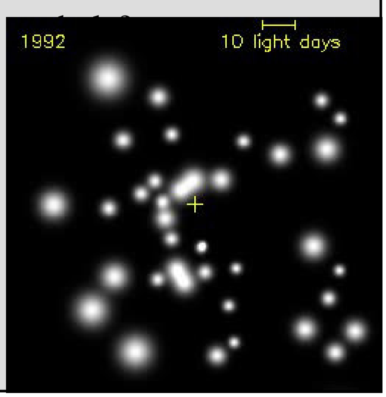

Want to see a star orbit a black hole?

- Sagittarius A—center of our galaxy with mass 2.6 +/- 0.2 million suns!
- S2—just some other star



Want to see a star orbit a black

- S2 orbits every 15 years
- Eccentricity of 0.87
- Closest distance only 3 times the Sun-Pluto distance!



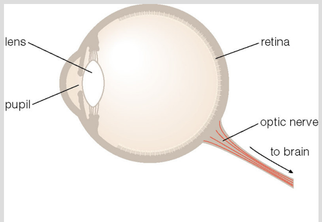
7.1 Eyes and Cameras: Everyday Light Sensors

Our goals for learning:

- How does an eye or lens form an image?
- Which is better – an angular resolution of 1° or 2°?

Parts of the Human Eye

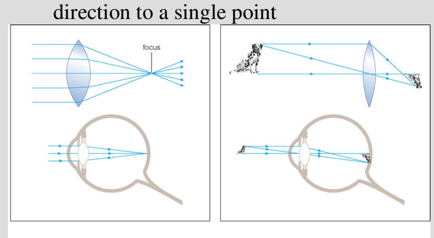
- **pupil** – allows light to enter the eye
- **lens** – focuses light to create an image
- **retina** – detects the light and generates signals which are sent to the brain



A camera works in the same way where the *shutter* acts like the *pupil* and the *film* acts like the *retina*!

The Bending of Light

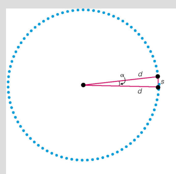
Focus – to bend all light waves coming from the same direction to a single point

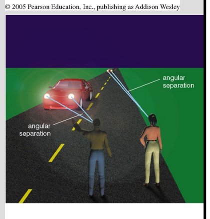


Light rays which come from different directions converge at different points to form an *image*.

Angular Resolution

- The ability to separate two objects.
- The angle between two objects decreases as your distance to them increases.
- The smallest angle at which you can distinguish two objects is your *angular resolution*.
- Our eyes can resolve about 1 arcminute…most stars binary, but we wouldn't know because they're separated by less than 1 arcminutes





7.2 Telescopes: Giant Eyes

Our goals for learning:

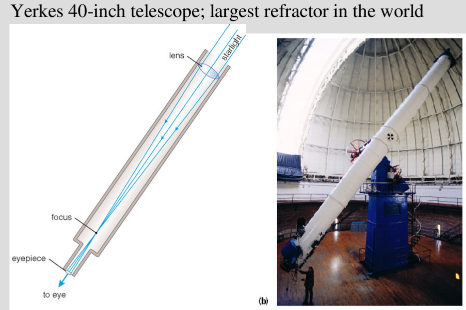
- What's the difference between a refracting telescope and a reflecting telescope?
- What are the two most important properties of a telescope?

Telescope Types

- Refractor
  - focuses light using lenses
- Reflector
  - focuses light using mirrors
  - used exclusively in professional astronomy today

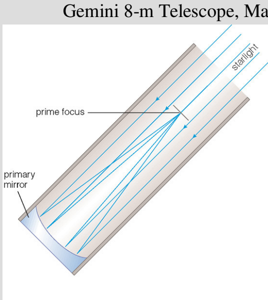
Refractor

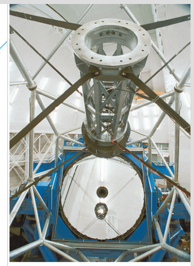
Yerkes 40-inch telescope; largest refractor in the world



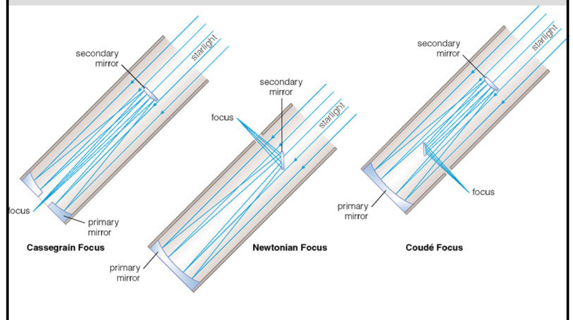
Reflector

Gemini 8-m Telescope, Mauna Kea, Hawaii

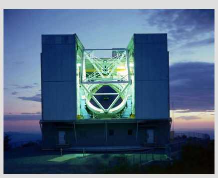




Reflectors



Reflectors



MMT – Mt. Hopkins, AZ

SUBARU – Mauna Kea, HI

Reflector -- Radio

Heinrich Hertz Telescope – Mt. Graham, AZ

Two Fundamental Properties of a Telescope

1. Resolution
   - smallest angle which can be seen
   - $\theta = 1.22\ \lambda / D$
2. Light-Collecting Area
   - think of the telescope as a "photon bucket"
   - its area: $A = \pi\ (D/2)^2$

7.3 Uses of Telescopes

Our goals for learning:

- What are the three primary uses of telescopes?
- How can we see images of nonvisible light?

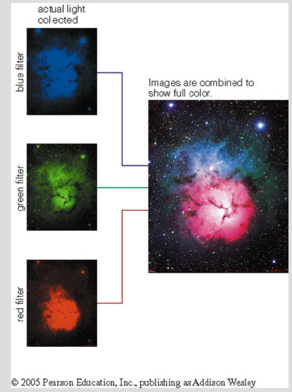
Instruments in the Focal Plane

How do astronomers use the light collected by a telescope?

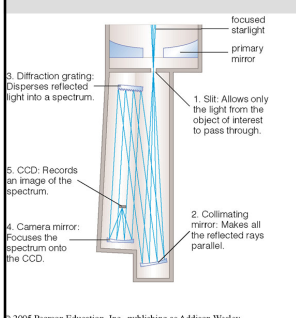
1. Imaging
   - use a camera to take pictures (images)
   - Photometry → measure total amount of light from an object
2. Spectroscopy
   - use a spectrograph to separate the light into its different wavelengths (colors)
3. Timing
   - measure how the amount of light changes with time (sometimes in a fraction of a second)

Imaging

- *Filters* are placed in front of a camera to allow only certain colors to be imaged
- Single color images are superimposed to form true color images.



Spectroscopy



- The spectrograph reflects light off a *grating*: a finely ruled, smooth surface.
  (similar to CD surface)
- Light interferes with itself and disperses into colors.
- This *spectrum* is recorded by a digital detector called a CCD.

Nonvisible Light

- Most light is invisible to the human eye.
- Special detectors/receivers can record such light.
- Digital images are reconstructed using false-color coding so that we can see this light.

Chandra X-ray image of the Center of the Milky Way Galaxy

7.4 Atmospheric Effects on Observations

Our goals for learning:

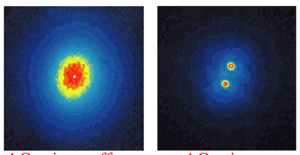
- What is light pollution?
- Do stars really twinkle?
- What atmospheric problems for astronomy can not be solved with technology on the ground?

Seeing Through the Atmosphere

- Earth's atmosphere causes problems for astronomers on the ground.
- Bad weather makes it impossible to observe the night sky.
- Air turbulence in the atmosphere distorts light.
  - That is why the stars appear to "twinkle".
  - Angular resolution is degraded.
- Man-made light is reflected by the atmosphere, thus making the night sky brighter.
  - this is called **light pollution**

Adaptive Optics (AO)

- It is possible to "de-twinkle" a star.
- The wavefronts of a star's light rays are deformed by the atmosphere.
- By monitoring the distortions of the light from a nearby bright star (or a laser):
  - a computer can deform the secondary mirror in the opposite way.
  - the wavefronts, when reflected, are restored to their original state.

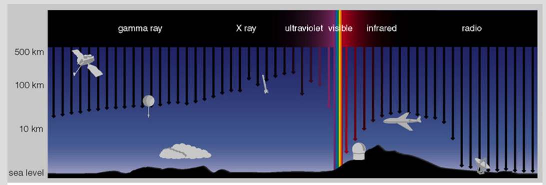


AO mirror off   AO mirror on

- Angular resolution improves.
- These two stars are separated by 0.38″
- Without AO, we see only one star.

Atmospheric Absorption of Light

- Earth's atmosphere absorbs most types of light.
  - good thing it does, or we would be dead!
- Only visible, radio, and certain IR and UV light make it through to the ground.



To observe the other wavelengths, we must put our telescopes in space!

Space Based Telescopes

Chandra X-ray Obs.

Hubble Space Telescope

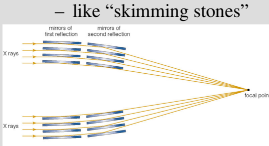
7.5 Telescopes Across the Spectrum

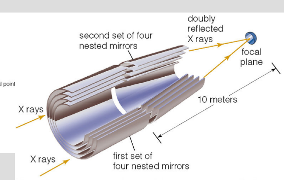
Our goals for learning:

- Why do we need different telescope designs to collect different forms of light?
- Of what use is interferometry?

X-ray Telescopes

- Different types of photons behave differently.
- X-rays will pass right through a mirror.
- They can only be reflected/focused at shallow angles
  - like "skimming stones"



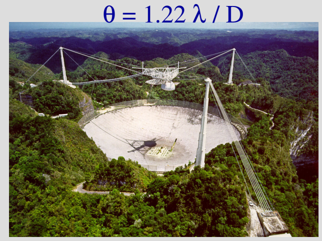


Mirror elements are 0.8 m long and from 0.6 m to 1.2 m in diameter.

Radio Telescopes

- The wavelengths of radio waves are long.
- So the dishes which reflect them must be very large to achieve any reasonable angular resolution:

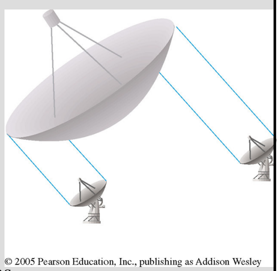
$$\theta = 1.22\,\lambda / D$$



305-meter radio telescope at Arecibo, Puerto Rico

Interferometry

- Two (or more) radio dishes observe the same object.
- Their signals are made to interfere with each other.
- An image is reconstructed with the angular resolution one would get from a dish the size of the distance between them.
- The light-collecting area is still only the sum of the areas of the individual dishes.



The Very Large Array (VLA)

What have we learned?

- How does an eye or lens form an image?
  - Parallel rays of light from the object being viewed must converge at the focal plane to form an image.
- Which is better – an angular resolution of 1° or 2°?
  - The smaller angle means we can see finer details.
- What's the difference between a refracting telescope and a reflecting telescope?
  - A refractor bends light through a lens to a focus. A reflector collects light with a mirror that reflects it up to a smaller, secondary mirror and then onto eyepieces or instruments.

What have we learned?

- What are the two most important properties of a telescope?
  - Its light-collecting area, which determines how much light it gathers, and its angular resolution, which determines how much detail we can see in its images.
- What are the three primary uses of telescopes?
  - Imaging to create pictures of distant objects, spectroscopy to study the spectra of distant objects, and timing to study how a distant object's brightness changes with time.

What have we learned?

- How can we see images of nonvisible light?
  - Detectors can record light that our eyes cannot see, and we can then represent the recorded light with some kind of color coding to reveal details that would otherwise be invisible to our eyes.
- What is light pollution?
  - Light from human activity that can interfere with astronomical observations.

What have we learned?

- Do stars really twinkle?
  - It's not the stars themselves the twinkle – it's their light that twinkles when it passes through our turbulent atmosphere. Above the atmosphere, we do not see any twinkling.
- What atmospheric problems for astronomy can not be solved with technology on the ground?
  - Technology can correct for distortion caused by turbulence, but it cannot do anything about the fact that our atmosphere absorbs most of the light in the electromagnetic spectrum. To see this light, telescopes must be put in space.

What have we learned?

- Why do we need different telescope designs to collect different forms of light?
  - Photons of different energy behave differently and require different collection strategies.
- Of what use is interferometry?
  - It allows two or more small telescopes to achieve the angular resolution of a much larger telescope, thereby enabling us to see more detail in astronomical images.

The largest optical telescopes are designed to have

1. high magnification, large collecting area, and high angular resolution.
2. high magnification, large collecting area, and low angular resolution.
3. low magnification, large collecting area, and low angular resolution.
4. large collecting area and high angular resolution - the magnification is of secondary importance.
5. large collecting area and low angular resolution - the magnification is of secondary importance.

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Some telescopes are put in space for which of the following reasons:

1. To get closer to the stars.
2. To avoid the blurring effects of the Earth's atmosphere.
3. To avoid the atmospheric absorption of some wavelengths of light.
4. To achieve higher spectroscopic resolution.
5. To avoid clouds, high winds, and other inclement weather.

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By using a CCD, I can photograph the Andromeda Galaxy with a shorter exposure time than I would need with photographic film.

1. Yes, but the CCD would have lower resolution.
2. Yes, CCDs are more sensitive than photographic film.
3. No, the exposure times are the same and only depend on the size of the telescope.
4. No, photographic film is more sensitive than CCDs.
5. No, but I can obtain an image immediately with a CCD.

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New technologies will soon allow astronomers to use X-ray telescopes on Earth's surface.

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2. Yes, but the resolution will be lower than from space.
3. No, X-rays cannot be focused because of the blurring effect of the atmosphere.
4. No, X-rays are absorbed by the atmosphere and don't reach the Earth's surface.
5. No, no such technology exists.

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Thanks to interferometry, a properly spaced set of 10-meter radio telescopes can achieve the angular resolution of a single, 100-kilometer radio telescope.

1. Yes, but with much lower sensitivity than a single, 100-kilometer telescope.
2. Yes, and the resulting interferometer will have exactly the same properties as a single, 100-kilometer telescope.
3. Yes in principle, but such an interferometer has never been constructed.
4. No, interferometry only works over much smaller distances.
5. No, the blurring effects of the Earth's atmosphere limit the achievable angular resolution.

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