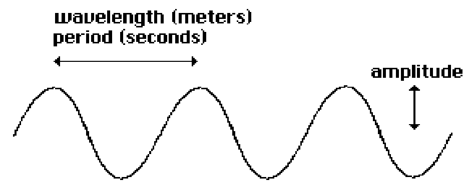
Chapter3: The Nature of Light and Telescopes

Astronomers learn about distant objects by observing the radiation that they transmit to us across space. This radiation consists of visible light (the radiation that we can see with our eyes), radio, infrared, ultra violet, x-rays, and gamma rays. All of these forms of radiation share common characteristics:

A. Wave Nature of Radiation



1. **Waves**

   a. period (T) - time for a wave to repeat itself.

   b. wavelength (λ) - distance between adjacent crests or troughs.

   c. amplitude (a) - maximum height above or below the undisturbed state.

   d. frequency (f) - number of crests or troughs that pass a given point in one second. Inversely related to the period.

   $$f = 1/T$$

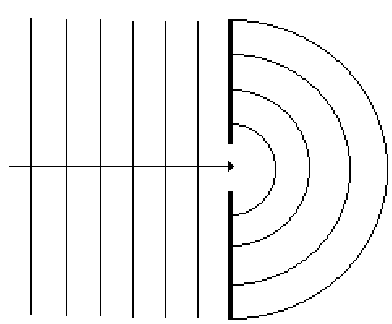
   e. wavelength and frequency are related.

   (Velocity = Wavelength x Frequency) $V = \lambda \times f$.

2. **Refraction**: The bending of light as it passes from one medium (air) into another medium (glass). This is how lenses form images. This is also how a prism breaks white light into the colors of the rainbow. We will see that this also causes problems with refracting type telescopes.

3. **Reflection**: When light strikes an object some or most of the light can be re-directed back in the direction that it came from. This is how we see ordinary objects around us. This is how reflecting telescopes form images.

4. **Diffraction**: Bending of waves around a corner. We will see that this puts a limit on the sharpness of a telescope's image.

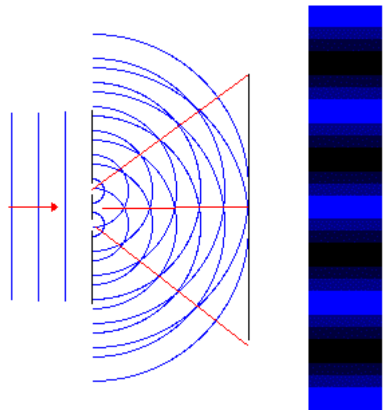


5. **Interference**: Ability of waves to reinforce or cancel one another.

a. Constructive Interference - reinforcement: waves are in phase.

b. Destructive Interference - cancellation: waves are out of phase.

6. Radiation can travel in a vacuum. It does not need a medium.



7. Relation to electromagnetism: All forms of radiation are made up of electromagnetic waves.

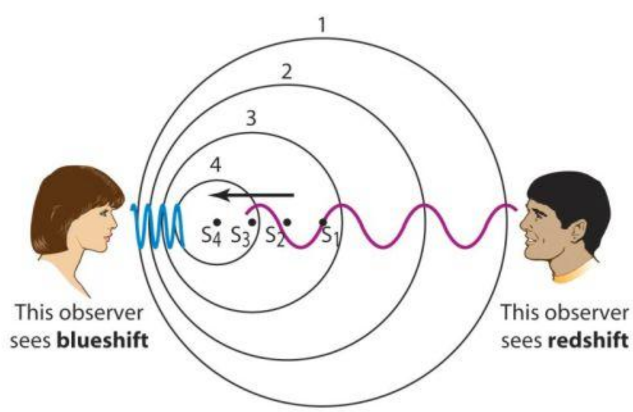
Radiation wave = Electromagnetic wave.

a. Radiation waves consist of oscillating electric and magnetic fields that are perpendicular to each other.

b. Travels at the speed of light (300,000 km/sec). We use the symbol c to represent the speed of light.

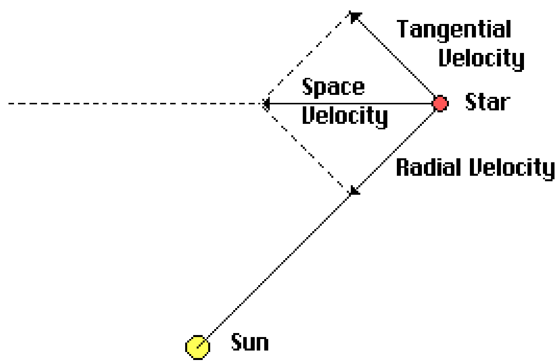
8. Doppler Effect.

a. Motion along the line of sight between an observer and a light source will cause the perceived wavelength to be redshifted if the relative motion is away from the observer and blueshifted if it is towards the observer. Motion that is perpendicular to the line of sight does not produce a Doppler shift.



b. Doppler Effect: Radial Velocity

The Doppler effect measures only the line of sight motion of a star or galaxy. In reality, celestial objects have a line of sight component and a component tangential to the line of sight called the proper motion. The two motions added together are referred to as the object's space motion. Proper motion is measured over many years using photographs, and only the nearest stars show any measurable proper motion.



B. Visible Light

1. **Components (colors of the rainbow - Spectrum)**

   a. six colors: **red, orange, yellow, green, blue, violet**.

      i. **red - wavelength = 700 nm** (least energy) (1 nm = 1×10^{-9} m)

      ii. **violet - wavelength = 400 nm** (most energy)

C. Electromagnetic Spectrum

Radio - longest wavelengths, least energy
Infrared
Visible light
Ultraviolet
X-rays
Gamma rays - shortest wavelengths, greatest energy

D. Opacity of the Earth's Atmosphere

1. The Earth's atmosphere is not transparent to all of the EM spectrum.
2. **Absorbers**:
   a. water vapor, oxygen - radio waves.
   b. water vapor, carbon dioxide - infrared waves.
   c. ozone layer - ultra violet, x-rays, and gamma rays.

E. Particle Nature of Radiation

1. **Photoelectric effect**: demonstrates a particle nature of radiation.

    a. Light striking a metal surface will dislodge electrons from the atoms if the light is of a certain color.

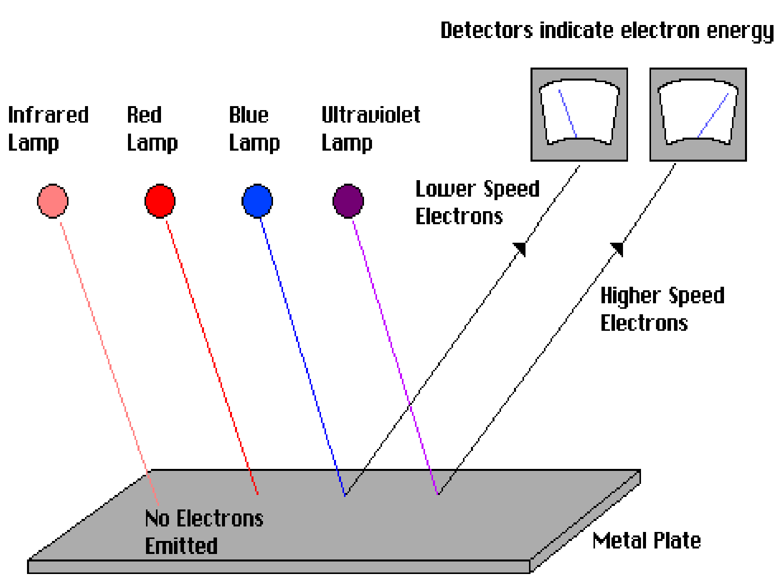
    b. Einstein explained this observation in terms of a particle nature of light (photons). He received the Nobel Prize for this.

        i. Energy of photons are proportional to their frequency.

        Energy = Planck's constant times wavelength divided by speed of light.

$$E = \frac{h\,c}{\lambda}$$

where h is Planck's constant and has the value 6.63 x 10^{-34} J s, and c is the speed of light

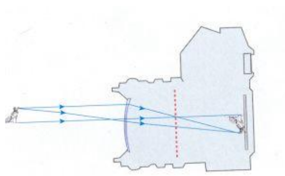


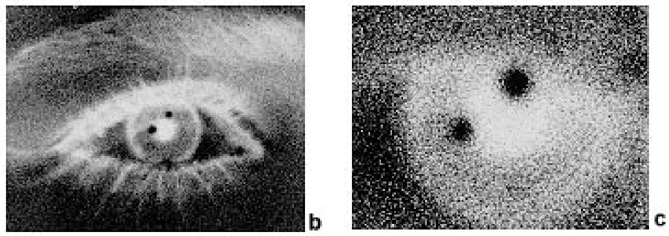
F. Example of the Dual Wave/Particle Nature of Light

Photographic Camera

1. Light passing through the lens obeys the laws of refraction. Light is behaving as a wave.

2. When light strikes the film individual grains of silver in the film are activated. The interaction of the film with the light is best explained in terms of the particle nature of light, where individual photons (particles) activate silver grains when they strike the film.





Wave behavior. Film grains representing particle (photon) behavior.

Images formed by lenses and mirrors

Focal Point: place where the light from a lens converges to form an image.

Focal Length: distance from the lens where an image is formed (when the rays from the object are parallel).

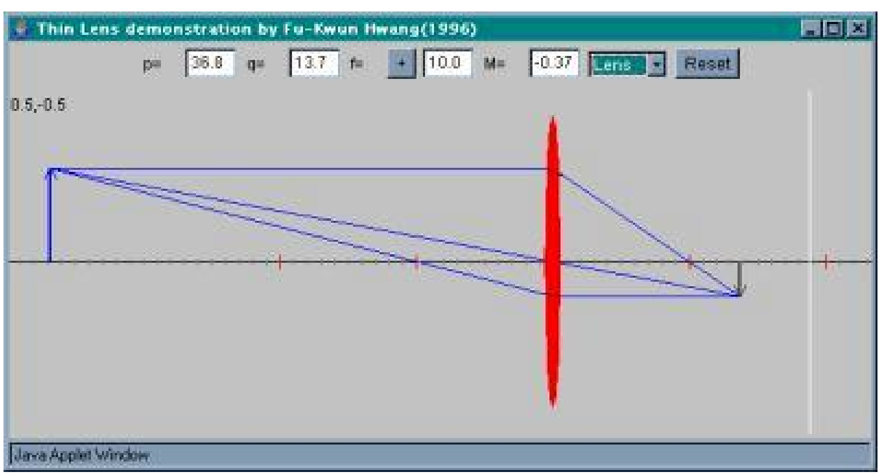


Image formed by a lens. Note that the image on the right is inverted

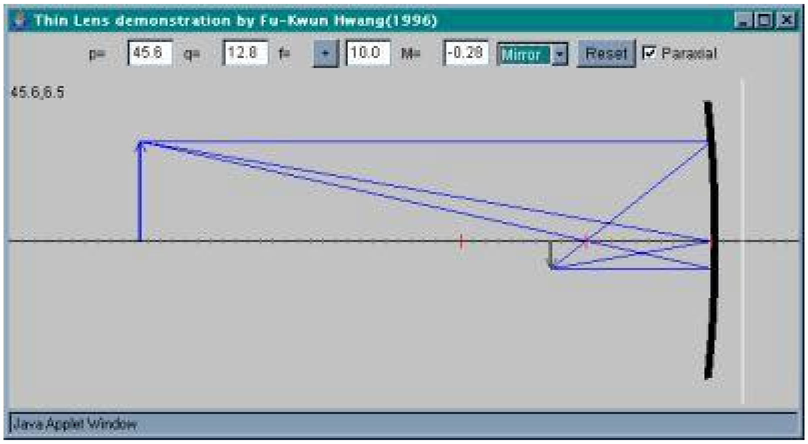
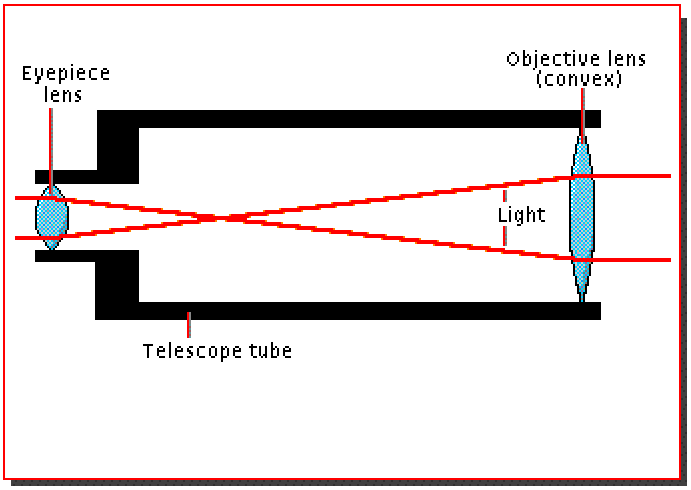


Image Formed by a Mirror. Notice that the image is again inverted.

Telescopes

A. Optical Telescopes

1. **Refractors** - use lenses to bring light to a focus.



a. **Disadvantages**:

i. **Chromatic aberration** - red and blue light are brought to a focus at different places. Minimized using two lenses with different refractive properties that tend to cancel out chromatic aberration. Before achromatic lenses were invented astronomers minimized chromatic aberration by making the focal lengths very long.

ii. Lenses supported at edges - large lenses sag out of shape.
Largest refractor (Yerkes refractor) is only 40 inches in diameter.

iii. Lenses absorb light and are opaque to nonoptical radiation.

2. **Reflectors** - use mirrors to bring light to a focus.

a. **Advantages**:

i. Do not suffer from chromatic aberration.

ii. Mirrors are supported from the back so that very large mirrors can be made.

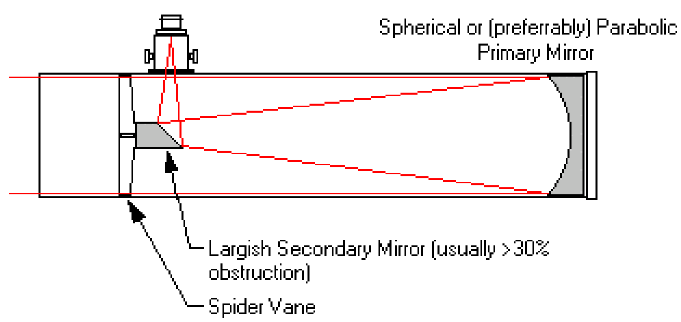
iii. Mirrors do not absorb nonoptical radiation (i.e. UV, Infrared, ...).

b. **Disadvantage**:

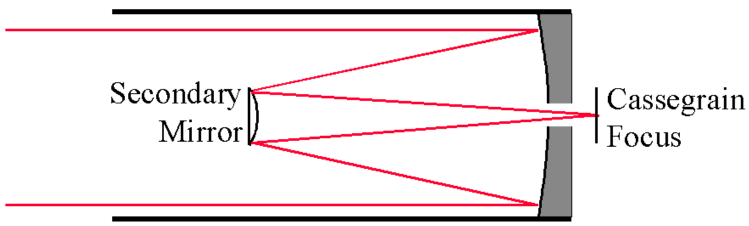
Suffer from spherical aberration. Minimized by adjusting the shape of the mirror from spherical to parabolic or using a corrective lens.

B. Types of Reflectors

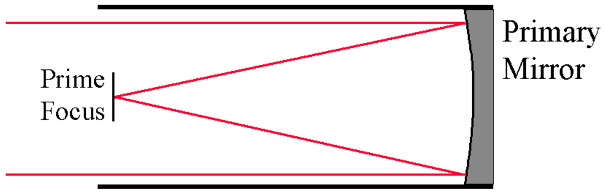
1. Newtonian - Invented by Isaac Newton



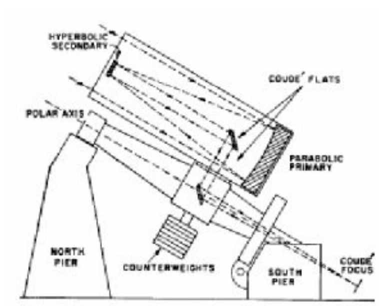
2. Cassegrain: most common type used by professional astronomers.



3. Prime Focus



4. Coude' Focus



C. Magnification

$$\text{magnification} = \frac{\text{focal length of objective}}{\text{focal length of eyepiece}}$$

For astronomers magnification is **not all that important**.

D. Instruments: A modern telescope is of little value without instruments.

1. Photographic Camera: records images on film.

2. Photometer: measures intensity of light in selected regions of the spectrum. This device has been largely replaced by the CCD chip.

3. Spectrograph: records spectra photographically or digitally

4. Charge Coupled Device (CCD): is replacing the camera and photometer. The detector is very much like the ones used in home video cameras but much more sensitive and expensive!

E. Light Gathering Power: depends on the diameter of the objective. **For astronomers this is the important factor when comparing telescopes**.

When comparing two lenses the light gathering ability of the larger lens over the smaller lens is:

$$\text{light gathering ability} = (D_l/D_s)^2$$

where D_l is the diameter of the larger lens and D_s is the diameter of the smaller lens.
For example, consider one telescope that is twice the diameter of a second telescope, the relative light gathering ability of the larger telescope over the smaller telescope would be:

$$\text{light gathering ability} = (2)^2$$

or

$$\text{light gathering ability} = 4$$

1. Large telescopes have a larger surface area and thus are able to collect more light.

2. The observed brightness of an object will depend upon the light gathering ability of the telescope.

F. Angular Resolution (Resolving Power):

The ability of a telescope to separate two closely spaced objects.

$$\underset{\text{(in degrees)}}{\text{Angular Resolution}} = 57.3 \times \frac{\text{wavelength of light}}{\text{diameter of objective}}$$

or

$$\underset{\text{(in arc seconds)}}{\text{Angular Resolution}} = \frac{10}{\text{diameter of objective (cm)}}$$

1. Angular resolution is the ability to distinguish between two adjacent objects in the sky.

2. Larger telescopes are better at resolving objects that have small angular separations.

3. Factor that limits a telescope’s resolution is:

    a. **Diffraction** - bending of light as it passes through the telescope.

        i. For a 1 meter telescope the angular resolution is 0.1 arc seconds.

ii. For a 5 meter telescope the angular resolution is 0.02 arc seconds.

iii. For an eight-inch telescope (0.20 meters) the angular resolution is 0.5 arc seconds.

These resolutions are what astronomers call the diffraction limits of a telescope.

4. In practice the images that are observed never reach the diffraction limit for ground based telescopes, unless the "seeing" is particularly good.

G. Atmospheric Blurring (Seeing)

1. Atmospheric turbulence reduces the resolution to not much better than one arc second.

2. Hubble Space Telescope is not effected by "seeing" so it operates at its diffraction limit.

H. Other Factors

1. Light Pollution - interfere with faint objects.

2. Altitude - higher elevations reduce the effects ot the Earth's atmosphere.

Astronomy at Other Parts of the Electromagnetic Spectrum

A. Radio Astronomy

1. Radio telescopes operate at one single wavelength. They must be tuned for other wavelengths.

2. Radio telescopes are not hindered by atmospheric seeing.

2. Radio telescopes have poor resolution due to diffraction.

   100 meter Green Bank Telescope - 1.2 arc minute resolution

4. Radio telescopes can observe 24 hrs a day.

5. Radio telescopes can observe through cloudy skies.

6. Radio telescopes can see the true extent of cosmic sources.

7. Radio telescopes can be combined to improve resolution through interferometry.

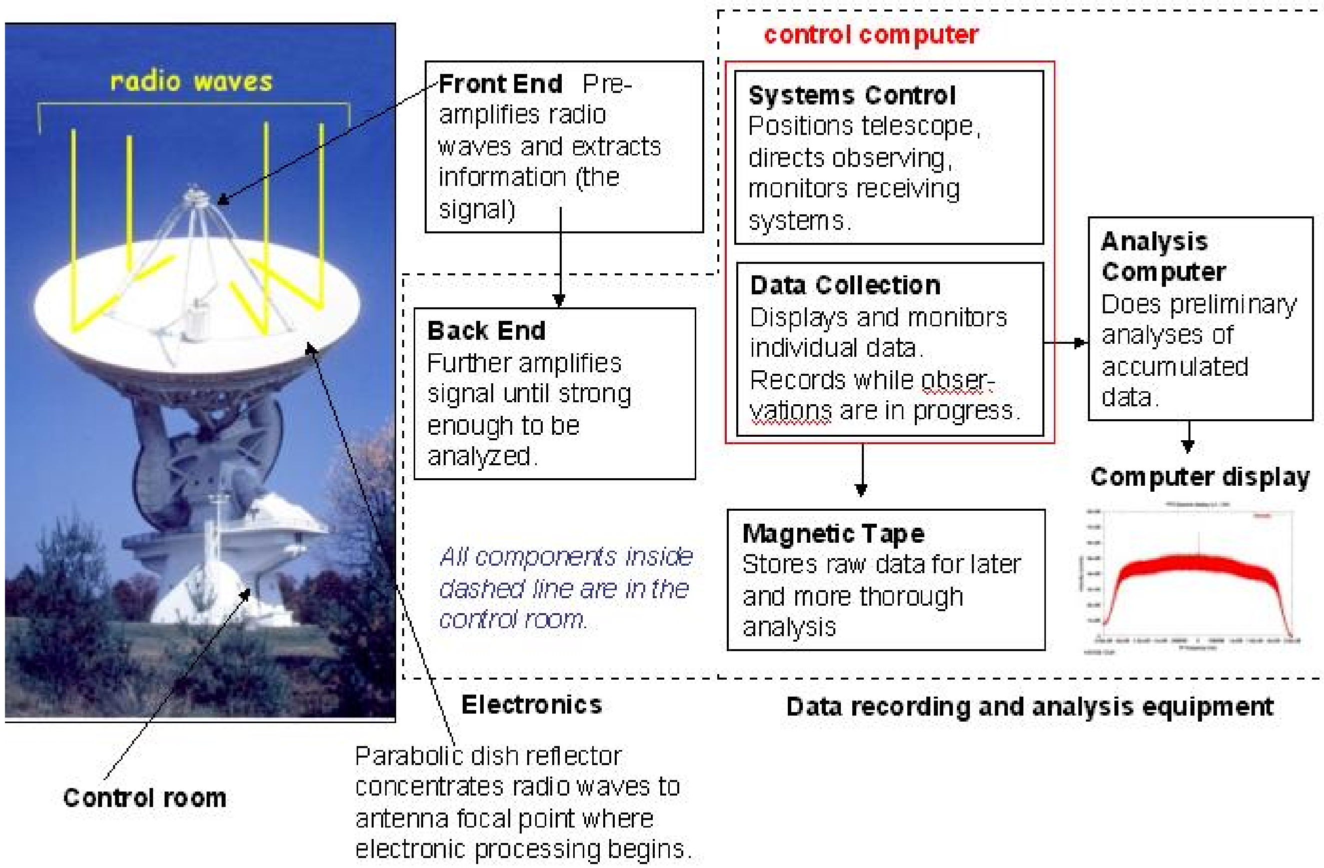
a. Combined instrument is called an interferometer.

b. An interferometer acts as a telescope having the diameter of the baseline (separation between the individual telescopes).

Very Large Array (VLA) in New Mexico - 0.2 arc second resolution.
Very Large Baseline Array (VLBA) - 0.0012 arc second resolution.
VLA and VLBA can be combined with the 100 meter GBT to give bright high resolution radio images.

c. Not as sensitive as single radio dishes. Can only observe bright features.

Basic Radio Telescope



Satellite TV System

Antenna—redirects energy to a point

Feed—collects energy for LNA

LNA—"low noise amplifier" amplifies signals

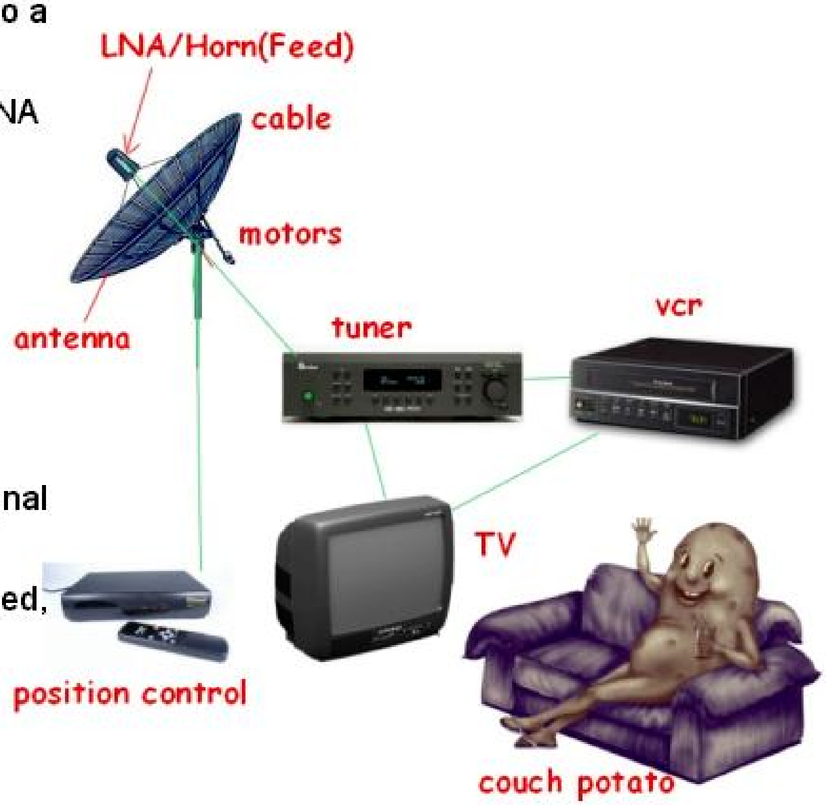
Cable—transposrts signal

Tuner—selects signal for viewing

TV—displays signal

VCR—records displayed signal for later viewing

Couch potato—creates a need, supplies $$



Concept Test
Which of the following would be the equivalent of light pollution sources for a radio telescope? a) Automobile spark plugs b) Hair dryer c) Cell phone d) Garage door remote closer e) Laptop computer f) All of the above

B. Infrared Astronomy: Must be done at high altitudes in order to get above as much water vapor, which strongly absorbs infrared radiation.

1. Ground based telescopes on tall mountains. These look like optical telescopes. In fact many of them are used for optical wavelengths. and many optical telescopes are also used for infrared observations. It is the attached instruments that are sensitive to the infrared wavelengths.

2. Balloons.

3. Aircraft.

4. Satellites.

    a. IRAS - Launched in 1983 and operated for 10 months.

    b. Hubble Space Telescope - NASA recently announced that there will no longer be any more repair missions.

C. Ultraviolet Astronomy: Must be done at extremely high altitudes (above the ozone layer).

1. Balloons.

2. Rockets.

3. Satellites.

    a. IUE (International Ultraviolet Explorer) - Launched April 1978 and operated until Oct. 1996.

    b. Hubble Space Telescope

D. High Energy Astronomy: X-rays and gamma-rays.

1. Satellites
    a. Chandra X-ray Telescope - Launched 1999.

    b. Compton Gamma-Ray Observatory - Launched 1991.

Modern Telescope Designs

1. Keck 10 meter telescopes: use segmented mirrors instead of solid mirrors.

    a. Each mirror consists of 36 hexagonal mirrors 1.8 meters across. The combined mirrors act as a single 10 mete mirror.

    b. Employs adaptive optics to compensate for the effects of "seeing". It uses an optical-mechanical system that senses the atmosphere-induced distortions of incoming starlight and compensates with a small, deformable mirror placed in the lightpath before it strikes the instrument detector. Without the adaptive optics the Keck telescopes are limited to about 1" resolution. When the adaptive optics are turned on they can resolve objects as small as 0.001".

    c. The two telescopes work together as an interferometer giving a combined angular resolution of an 85 meter mirror.

2. The Subaru 8.2 meter telescope uses a single monolithic mirror unlike the Keck telescopes. In the past large mirrors were thick and heavy, which required massive supporting structures (ex. 5 meter Hale telescope). By using very thin mirrors that have electro-mechanical thrusters that constantly adjust the shape of the mirror, astronomers can build large telescopes, while minimizing the weight of the supporting structure. This in turn keeps the costs to a minimum.

Factors that astronomers consider when selecting a site for an observatory

1. Good seeing (under 1 arc second).

2. Dark skies (far from city lights).

3. Large number of clear nights.

4. High elevation (get above most of the Earth's atmosphere). Very important for infrared astronomy.

5.Good coverage of most of the celestial sphere, which is achieved at lower latitudes such as southern Arizona, or Hawaii.

6. Dry climates, such as deserts.

Most major US observatories are located in the mountains of the desert southwest (New Mexico, Arizona, and California) or on top of Mauna Kea in Hawaii.