Telescopes: "light bucket"

Primary function: to gather light from a given region of the sky and concentrate that light into a focus.

Secondary functions: to resolve detail in image; to magnify angular size of objects.

Telescopes can be designed to gather visible and invisible radiation.

Optical Telescopes

- Designed to collect wavelengths of light that are visible to the human eye.
- Data observed by human eyes or recorded on photographs or in computers.

Astronomical Instruments: The Human Eye

First “telescope” used to observe and study heavens.

The Human Eye: Shortcomings

- Eye has limited size.
  - limited light gathering power.
- Eye has limited frequency response.
  - only detects E - M radiation in visible wavelengths.
- Eye distinguishes new image multiple times/second.
  - cannot be used to accumulate light over long period to intensify faint image.
- Eye cannot store image for future reference.
  - unlike photographic plate or CCD.

Optical Telescope Design

- Hans Lippershey, a Dutch spectacle maker, is credited for making the principles of the optical telescope widely known in early 1600s.
- Basic telescope has two parts:
  1. Objective: function is to gather light a lens or mirror of longer focal length and larger diameter than the second lens,
  2. Eyepiece: function is to magnify image made by objective a lens with a shorter focal length than the objective.
- Optical Telescope Types
  - Refractors: telescopes with objective lenses
  - Reflectors: telescopes with objective mirrors.
  - Catadioptric: telescopes with both lenses and mirrors (e.g. Schmidt-Cassegrain)
**Basic Optical Telescope**

Image of source is formed on focal plane and magnified by eyepiece.

**Objective**

**Eyepiece**

**Focal Length**

- Convex lens
- Concave lens
- Convex mirror
- Concave mirror

- $C =$ centre of curvature
- $F =$ focus
- $F =$ focal length

**Optical Telescopes**

- **Reflector**
- **Refractor**

**Catadioptric:** combination and mirrors and lenses (Schmidt-Cassegrain)

**Refracting Telescope**

- **Refracting Telescope animation**
- **Yerkes Observatory, William’s Bay, WI**
- **1 m refractor** (largest in world)
Refractors: Disadvantages

- Quality optics require high tolerance
  - all lens surfaces must be perfect
  - glass will absorb light, especially IR and UV.
  - changes in orientation, temperature may flex lenses
  - large size very heavy, hard to support
- Chromatic aberration
  - light passes through glass
  - refraction a function of wavelength
  - all wavelengths focus different distances from lens
  - correctable with compound lenses
  - expensive to correct

Chromatic Aberration

- Lens is equivalent to stacked set of prisms of varying side angle and thickness.
- All prisms refract blue light more than red light.

Reflecting Telescope

- Dispersion of light through optical material causes blue component of light passing through lens to be focused slightly closer to lens than red component.
- Known as chromatic aberration.

Anglo-Australian Observatory

- 4-m reflector
Reflecting Telescopes: Designs

- Four designs:
  - Prime focus
  - Newtonian focus
  - Cassegrain focus
  - Coudé focus

Note: secondary mirrors for (c) Cassegrain and (d) Coudé slightly diverging, move focus outside telescope.

Newtonian Reflector

Cassegrain Reflector

Schmidt Cassegrain

Why four designs?
- Prime focus
  - Good for very faint objects
  - Shorter focal length, less magnification
- Newtonian
  - Least expensive amateur telescope
- Cassegrain
  - Secondary mirror convex
  - Increases focal length of objective mirror
- Coudé
  - Allows image to be in same position, independent to motion of telescope
  - Often used in research with heavy detectors

Keck Telescopes

Twin 10-m telescopes
Mauna Kea 13,700 ft elevation
Telescope Mountings
• Telescopes have special mountings that allow them to continue pointing at the same part of the sky as it appears to move overhead.
• Equatorial mounting – telescope rotates about axis parallel to Earth’s rotational axis – compensates for Earth’s rotation
• Other mountings that allow motion in altitude and azimuth are easier and cheaper to build, but more difficult to use.
  – Computers often used to keep the field of view centered by moving the telescope in two directions.

POWERS OF THE TELESCOPE

1. LIGHT GATHERING POWER
   – The ability to see faint objects.
2. RESOLVING POWER
   – The ability to see fine details.
3. MAGNIFYING POWER
   – The ability to enlarge an image.

LIGHT GATHERING POWER
• Light gathering power is the ability to see faint objects.
• It is the most important power for most astronomers.
• It varies directly with the surface area of the objective (diameter²).
• The human eye has an aperture of about 1/5" and can see about 6,000 stars.
• With a 2" telescope about 110,000 become visible.

RESOLVING POWER
• Resolving power is the ability to see fine details.
  • It varies directly with the diameter of the objective.
  • The human can resolve and angle of about 70 arc seconds.
  • The theoretical limit for the largest telescopes on Earth is less than 0.1 arc second.
  • Resolving power also depends on the wavelength of light being observed and the atmospheric seeing conditions.
    • Seeing = 2.5 x 10⁻⁵ (wavelength/D)

MAGNIFYING POWER
• Magnifying power is the ability to enlarge an image.
• Magnifying power = f_objective/f_eyepiece
• A practical limit to magnifying power can be found:
  50 x diameter_objective (inches).
• Normally, magnifying power is the least important for astronomers.
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Magnification

- A telescope forms a real image, but that image is not very large.
- The eyepiece lens is used to magnify the real image produced by the objective.
- The overall magnification of a telescope depends on both the size of the image formed by the objective and the amount the eyepiece magnifies that image.

\[ \text{Magnification} = \frac{\text{focal length of objective}}{\text{focal length of eyepiece}} \]

Light-Gathering Power

- The objective’s area collects light.
- The larger the area, the greater the light-gathering power of the telescope.
- The objective’s diameter is the most important feature or design parameter of a telescope.

\[ \text{Light-gathering power proportional to} \quad \text{(objective diameter)}^2. \]

Resolving Power

- Ability to see small details and sharp images.
- Objects that are so close together in sky that they blur together into single blob are easily seen as separate objects with a good telescope.
**Diffraction and Resolution**

- Imaging ability limited by diffraction.
- Diffraction varies
  - directly with wavelength of light, $\lambda$
  - and inversely with diameter of telescope, $(1/D)$
- For given diameter $D$,
  - as wavelength increases, diffraction increases,
  - and angular resolution decreases.
  - blue light (shorter $\lambda$) resolved better than red light (longer $\lambda$).

$$\text{angular resolution (arc sec)} = 0.25 \frac{\text{wavelength (\text{nm})}}{\text{mirror diameter (m)}}$$

**Angular Resolution**

- Measure of fuzziness produced by diffraction.
- Minimum distinguishable angular separation.
- Recall, one arc second is the breath of a human hair viewed from 10 m or a penny viewed from 3.6 km.
- For 1-m telescope,
  - blue light $\lambda=400$ nm, angular resolution=0.1"
  - infrared $\lambda=10,000$ nm, angular resolution=2.5"
- For 5-m telescope,
  - blue light $\lambda=400$ nm, angular resolution=0.02"
  - 5 times that of the 1-m telescope;
  - and the human eye has a resolution of ~0.5"

**Seeing through the Atmosphere**

“Seeing” - describes effects of atmospheric turbulence

- Individual photons from distant star strike detector in telescope at slightly different locations because of turbulence in Earth’s atmosphere.
- Over time, individual photons cover a roughly circular region on detector, and even point-like image of a star is recorded as a small disk, called the seeing disk.

**Why is the Sky Blue?**

Blue light scatters more than red light. When the Sun is high in the sky you will see all of the colors if you look right at the Sun. But looking in other directions, you will see $\lambda_{blue}$ at the blue colors because some of the blue sunlight will be scattered back to you. When the Sun is near the horizon, the blue sunlight is scattered away leaving only the red and orange sunlight—the Sun appears red.

**Site Selection**

- Where are the best places for ground-based observatories?
- Important factors
  - dark
  - light pollution
  - good weather
  - dry air
  - air turbulence

**Detection**

- Light collected detected in many ways
  - image observed and recorded
    - eye, photographic plate, CCD
  - measurements
    - intensity and time variability of source
      - photometer
    - spectrum of source
      - spectrometer
CCD Imaging

- A charge-coupled device (CCD)
  - Wafer of silicon divided into a two-dimensional array of many tiny elements, known as pixels.
  - When light strikes a pixel, electric charge builds up on device.
  - Amount of charge is directly proportional to the number of photons (or intensity) at that point striking each pixel.
  - Charge buildup monitored electronically.
- Advantages over photographic plates
  - Efficiency
    - Speed, 10x
    - Recording ability, 90%
  - Digital format

Improving Resolution

- Resolving power of all telescopes limited by diffraction.
- Ground-based telescopes’ resolution is further limited by atmospheric effects.
  - Turbulence
  - Temperature variations
- Resolution improved by
  - Computer processing of image
  - Active optics
  - Adaptive optics

Image Processing

- Computer processing of images can
  - Reduce background noise
    - Faint, unresolved sources
    - Light scattered by atmosphere
    - Electronic detector noise
  - Compensate for known instrument defects
  - Compensate for some atmospheric effects

Active Optics

- Techniques designed to maximize angular resolution of ground-based telescopes.
  - Changes configuration of instrument as orientation and temperature changes.
  - Used to maintain best possible focus.

Adaptive Optics

- Most ambitious technique intended to correct for atmospheric turbulence.
- Intended to remove distortions in wavefronts before light is detected, forming improved image in real-time.
- Deforms the shape of mirror’s surface (under computer control) while measurement is being taken.

Laser-based Adaptive Optics

- Lasers probe the atmosphere for information about air turbulence.
- A computer modifies the mirror configuration 1000’s of times each second to compensate for atmospheric problems.
- Observations of the nearby double star Castor with and without adaptive optics.
- The two stars are separated by less than one arc second.
Electromagnetic Spectrum

Radio Astronomy: Origins

- In the early 1930’s, Karl Jansky discovered that some of the interference affecting transatlantic radiotelephone transmissions was coming from a region in the sky that moved in the same way as the stars.
- These were radio emissions from the center of our galaxy.
- Grote Reber, amateur astronomer and professional radio technician, made the first map of the radio sky from a small radio telescope set up in his backyard in Illinois.

Radio Astronomy: Wavelength Advantages

- Many objects that appear to be uninteresting faint stars when viewed optically are powerful radio emitters.
  - Quasars, pulsars
- Radio waves pass with little dimming through clouds of interstellar dust in our galactic plane.
- Daytime sky is not as bright in radio wavelengths.
- Cloudy skies do not block radio waves.
- Dish does not need to be highly polished and is often light weight.

Radio Telescopes

- Much larger than reflecting optical telescopes.
- Most radio telescopes built in basically the same way.
  - large, horseshoe-shaped mount supporting a huge, curved metal dish.
- The dish captures cosmic radio waves and reflects them to the focus, where a receiver detects the signals and channels them to a computer.

Arecibo Observatory: Largest Radio and Radar Dish

- 1000-ft radio dish
- used to
  - create maps of Moon, Venus, and Mars
  - discover pulsars and galaxies
  - measure the rotation rate of Mercury
  - discover planetary systems outside of our solar system

Interferometry

- Two or more radio telescopes used
  - to observe same object
  - at same wavelength and at the same time.
- Individual signals sent to central computer
- Computer combines and stores the data.
- Imaging requires superposition of individual telescope signals
  - analysis of interference patterns
**Principles of Interferometry**

Telescopes connected together to make an interferometer can make even sharper images than a single large telescope. The interferometer is bigger than the large telescope. Images for same two stars are shown.

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**Very Large Array (VLA) in New Mexico**

- 27 antennas, each 25 m in diameter
- Effective diameter = 36 km
- Yields radio-image details comparable to optical resolution

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**Neutral Hydrogen (21 cm) Sky**

- First detected radio radiation of astronomical origin.
- ~3/4 of all interstellar gas is hydrogen.
- Neutral atomic hydrogen confined to flat layer.

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**Wavelength Windows in Earth’s Atmosphere**

- Infrared Telescopes
  - Infrared wavelengths: $10^{-9} \text{ m to } 10^{-3} \text{ m}$
  - Shortest are at long wavelength end of photographic and CCD detection ability.
    - for $\lambda < 10^{-6} \text{ m}$ use optical style telescopes
    - for $\lambda > 10^{-6} \text{ m}$ use crystals with heat sensitive electrical resistance (e.g., germanium)
  - Background noise:
    - $T_{\text{Earth}} = 300\text{ K}$
    - Wien’s Law: $\lambda_{\text{max}} = \frac{(3,000,000)}{T} \times 10^{-9}\text{ m}$
    - $\lambda_{\text{max}}(300\text{ K}) = 10^{-4}\text{ m}$
  - Must shield detectors from heat, water vapor

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**View of the Earth in Infrared**
SIRTF
Space InfraRed Telescope Facility
- Launch Date: July 2002
- Estimated Lifetime: 2.5 years (minimum)
  4 years (goal)
- Orbit: Earth-trailing, Heliocentric
- Wavelength Coverage: 3 - 180 microns
- Telescope: 85 cm diameter (33.5 inches), Si2 lightweight Beryllium, cooled to less than 5.5 K
- Diffraction Limit: 6.5 microns
- Science Capabilities:
  - Imaging / Photometry, 3-180 microns
  - Spectroscopy, 5-40 microns
  - Spectrophotometry, 50-100 microns
- Planetary Tracking: 1 arcsec / sec
- Cryogen / Volume: Liquid Helium / 360 liters (95 Gallons)
- Launch Mass: 950 kg (2094 lb)

Hubble Space Telescope

HST’s View of the Universe

Extreme UV Telescope
Wavelengths: 400 nm to ~2-3 nm
Atmosphere opaque below 300 nm
International Ultraviolet Explorer
1978-1996
Extreme UV Explorer
launched 1992, studied interstellar space near Sun

Far Ultraviolet Spectroscopic Explorer (FUSE)
- Uses four mirror segments
  - two silicon carbide coated to reflect short UV
  - two Al and Li fluoride coated to reflect longer UV
- Light from each mirror dispersed by four gratings
- Optical wavelength sensor (FES) provides visible wavelength pictures of the field of view.

Gamma Ray Observatory
- Utilizes different detection equipment to capture high energy photons.
  - High energy photons less abundant, hard to detect, hard to focus and measure.
Compton Gamma Ray Observatory (CGRO)

- Operated from 1991 to 2000
- Created all-sky map in gamma ray frequencies
  - pulsars and blazars
- 3 methods of detection
  - partial or total absorption of $\gamma$-ray energy within high density medium (large crystal of sodium iodide)
  - collimation using heavy absorbing materials to block out sky and create a small field of view
  - conversion process from $\gamma$-rays to electron-positron pairs in a spark chamber

All-Sky Map from CGRO

- Galactic plane energy from cosmic rays interacting with interstellar material.
- Bright spots on right side are pulsars
  - Vela (supernova remnant), Geminga, Crab
- Bright spot above plane is a blazar 3C279

Chandra X-Ray Observatory

Orbits the Earth
200x higher than HST
or
1/3 of way to Moon

X-ray Imaging

- x-ray telescopes and medical x-rays are similar
  - source = x-ray machine or distant object
  - absorber = bones or gas cloud
  - detector = film or Chandra

Detecting X-rays

- Very high energy radiation
- At normal incidence, X-ray photons slam into mirrors as bullets slam into walls.
- But at grazing angles, X-rays will ricochet off mirror like bullets grazing a wall.
- Mirrors must be almost parallel to incoming X-rays; designed like barrels.

Chandra’s Mirrors

- Mirrors coated with iridium
- Smoothest and cleanest mirrors made to date
Alternate Skies

- Radio All Sky
- Infrared All Sky
- Visible All Sky
- X-Ray All Sky
- Gamma-Ray Sky

Crab Nebula at Different Wavelengths

- x-ray
- far UV
- near UV
- visible
- infrared
- radio