Lenses, Mirrors, Telescopes

- Refraction: light is bent at the surface between two media, like an air-glass surface
- Spherical (parabolic) surfaces can focus light—collect over large area and gather to small
- Bend angle varies with color/frequency

Glass will “bend” light

Focal point changes with color

Convex lens and focal point
Reflecting Mirrors

Most big telescopes made from mirrors

- easier to make (especially if large up to 10 m). Only one “good” surface needed
- same focal point for all frequencies
- can make out of many (1000s) of small elements which can be computer controlled to adjust focal point (improves resolution)
Reflecting Mirrors

- a Newtonian focus
- b Cassegrain focus
- c Nasmyth focus or coudé focus
- d Prime focus
Applications

- Collect more light. Depends on area of primary lens = \( \pi(d/2)^2 \)
d=aperture

Magnify.: Power = \( \frac{\text{(focal length primary)}}{\text{(focal length eyepiece)}} \)

Telescopes are mostly used to collect more light with angular resolution and aperture being crucial criteria. Magnification usually not important. Often put camera at focal point/plane. Can “add” together light from multiple telescopes.
Telescope Quality

- Light gathering
  
  bigger mirror and/or sensitive electronic cameras can “see” dim objects $< 10^{-11}$ compared to the unaided eye

- Angular Resolution (or “Vision”) depends on mirror quality. Atmospheric turbulence limits to

  1 arc second ($1/3600$ degree). But placing outside atmosphere or using correctable lens surface or digitally correcting data can reduce

Hubble Space telescope and some on Earth surface have $1/20$ arc-second resolution
Detecting Light (not on tests)

- **Human Eye**
  - cannot easily “save” information
  - cannot collect light over long lengths of time

- **Photographic Film**
  - long time exposures-move telescope opposite to Earth’s rotation
  - can filter to “see” different colors

- **Electronic Devices (CCD, what is in video/digital cameras)**
  - much more sensitive than film (~100,000,000) \( \Rightarrow \) “see” single photon.
  - Often run at liquid nitrogen temperature (-196°C or -321°F)
  - have amount of light versus time (instead of just sum). Can statistically remove effects of atmospheric twinkling or look for rapid variations
  - data easier to collect, to make available to others, to analyze

- **100W lightbulb** \( \Rightarrow \) about \( 10^{20} \) photons/sec
“Vision”

• Good angular resolution allows 2 close objects to be clearly separated. Same as good “vision”

Good resolution.
See 12 objects

Bad Resolution 3 times worse. See 3 objects
Telescope Quality = Resolution
Poor vs Good
Good Resolution plus long time exposure →
depth space images

Hubble Space Telescope
2 stars the rest are galaxies
Maximize Telescope Quality

- Place at high altitude, away from cities, to aid in reducing atmospheric effects and light pollution. Low water content in air helps viewing in infrared.
- Near Equator good as can see almost all of the stars N/S.
- Telescopes located world-wide but best places are Hawaii and Chile.

Chile: Cerro Tololo
Hawaii: Mauna Kea and Heleakala

- Mauna Kea on Big Island, at 13,802 feet. Heleakala on Maui at 10,023 ft. Clouds tend to be at 5,000 ft and screen light pollution from (relatively small) cities on those 2 islands. Mostly very dry but can have water vapor in upper atmosphere. Relatively easy to get there and have facilities (beaches, motels) close by.

Mauna Kea (on left in distance) taken from Heleakala. Note cloud layer at 5-6,000 ft.
Hawaii: Mauna Kea

- Note no vegetation as very little rain. Occasionally snow (see videos on web page). A lot of facilities and there is local opposition to installing new telescopes without first removing some of the old ones. See links on web page.

Mauna Kea Observatory on big island in Hawaii. visible + infrared. At 13,000 ft very dry
Subaru Telescope – Mauna Kea Hawaii

Subaru: 8.2 m mirror  $300,000,000

30 m telescope planned. Really 492 1.4 m mirrors. $1,400,000,000 – artist sketch ➔
Hawaii: Heleakala, on Maui

Largest one atop building in left picture: The 3.67 m Advanced Electro Optical System Telescope is a Department of Defense telescope. The telescope is part of the Maui Space Surveillance Complex (MSSC)(mostly tracks satellites), which in turn is part of the Air Force Maui Optical and Supercomputing Site (AEOS). As DOD while in the National Park, visitors are restricted. Also seen in the right photo is the 2 m Faulkes telescope North which is paired with an identical device in Australia.

National Park visitor hut, highest location, where some other photos were taken
Chile: Cerro Tololo, Las Campanas, Cerro Pachon

• Northern Chilean desert. Very dry and very isolated. Cerro Tololo at 7,241 ft, Las Campanas at 7,810 ft, Cerro Pachon 8,980 ft. Have a few other observatories on nearby mountains.

• From Chicago, it takes 15 hours to get to La Serena (Chi→Miami→Santiago→La Serena). You stay in “spartan dorms” in La Serena, and it is a 90 minute van drive (funded by US agency NOAO) to Cerro Tololo, where there are other minimal dorms. You don’t want to stay at high altitude too long.
Chile: Las Campanas, Cerro Pachon

- Las Campanas is where a supernova in 1987 and Dark Energy in 1998 were first observed (later in course). Cerro Pachon has one of the twin 8.1 m telescopes with its other twin on Mauna Kea. Again very dry.
Blanco Telescope – Cerro Tololo Chile

Located at 7,240 ft and in operation since 1965 by US-Chile collaboration

4 m mirror plus new 640 mega-pixel camera built at Fermilab. NIU student Matt Wiesner at Cerro Tololo has world’s best camera. Dark Energy Survey (DES) 2012-2018. DECam will continue to operate until ~2028
Maximize Telescope Quality

- Operate cameras at low temperature (in liquid Nitrogen bath) and calibrate (example: lasers create artificial star, use to correct for atmospheric effects which improve angular resolution)

![twin 10 m Keck telescopes]
A 60 ms exposure of a bright binary star system (a) shows the characteristic speckling caused by atmospheric turbulence. (b) Those speckles become blurred together and thus undetectable in a longer-exposure image. The diffuse image here illustrates so-called seeing-limited resolution. (c) Mathematical reconstruction based on many speckled images can resolve the two stars that are not separately imaged in panels a and b. The stars here are separated by approximately 0.3 arcseconds; panels a–c are all $1 \times 1$ arcsec in size. (d) Images of Jupiter, the speckle image yields higher resolution than the seeing-limited case and better reveals the structure of the cloud bands.

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Maximize Quantity → Surveys

- Modest size telescope with wide angle camera to “survey” a large part of the sky
- Observe large numbers of galaxies, supernovas, etc but with poorer resolution → large data sets
- Analyze data, find interesting objects, obtain better images at telescopes with better resolutions
- Pioneered by Fermilab (particle physics: large data sets, invented world wide web with Fermilab being the first web site after CERN)

Sloan Digital Sky Survey – 2.5m Arizona

Dark Energy Survey – 4m Chile

NIU students involved in both

DES camera built at Fermilab

Kepler and TESS used for exoplanet searches, will discuss later
Radio Telescopes

- Easy to make large. Atmosphere (including clouds) do not really effect
- angular resolution is worse as longer wavelength. Improve by making either with large aperture or “faking” large using many dishes at same time → can get similar angular resolution to visible light

Very Large Array. 27 dishes in New Mexico

VLA

Arecibo Puerto Rico
305 m (1000 ft) aperture
Both in movie

Contact
Future US funding of Arecibo uncertain

← 500 m aperture ASRT in China. Now world’s largest
Radio Telescopes

- Very Large Baseline Array and High Sensitivity Array. Spread out over continents
- Uses modern “time” information to add together signals from different radio telescopes and obtain best angular resolution
South Pole Telescope

• 10 m diameter, millimeter range (microwaves)
• Chicago, Berkeley, Illinois, Case Western, Smithsonian, others, and now Fermilab for upgrade
• Primarily studies Cosmic Microwave Radiation, which is leftover from about 1,000,000 years after the Big Bang, and so helps in studies of “Dark Energy”
• At south pole at high altitude and very cold which minimizes water vapor. Possibly driest spot on Earth
South Pole Telescope

The receiver/camera is built in Illinois, at Argonne (makes bolometers) and Fermi (attaches wires) National Labs with system tested at Fermilab and Chicago.

NIU graduate Donna Kubik helped to build camera and was at South Pole in 2018-2019 to aid in operations.
Observing a Black Hole

• In 2019 an image of a black hole was released. It used 1.3 millimeter photons (microwaves) from data collected over 4 days in 2017

• Event Horizon Telescope team: 8 radio telescopes combined: 2 in Hawaii, 2 in Arizona, 1 each in Chile, Mexico, Spain, and the South Pole Telescope. The “size” of the combined telescope was then “Earth size” giving a 40 micro arcsecond angular resolution (roughly the size of the date on a quarter if seen from 3000 miles away)

• Telescopes also had to remove atmospheric effects (like on slide 19) to see the image. Techniques partially developed by MIT grad student Katherine Bowman

• Image shows light from hot gases falling into a black hole in galaxy M87 55 million Light years away
Gravity “Telescopes”

- Large changes in gravitational fields cause gravitons, or gravitational waves, to be emitted (examples later include from neutron star and/or black hole mergers).
- Have been observed in detectors in the US and Italy which look for very tiny changes in the size of their instruments due to the gravity wave moving through the detector. First observed in 2015, > 20 observations through 8/19.

Two neutron stars in orbit around each other emitting gravity waves
Gravity “Telescopes”

- LIGO (US) uses 2 locations, each with 4 km “legs” which are perpendicular to each other. Mirrors on the ends bounce light down the legs allowing the distance to be measured very accurately. A gravity wave distorts one leg, causing a change in its length. VIRGO (Pisa, Italy) uses 3 km long legs.

(above) how light is bounced around two legs to measure their length
← VIRGO installation
Lecture Feedback

E-mail me a few sentences describing one topic you learned from this set of presentations. Please include the phrase “Placing a telescope at high altitude reduces the effects of the atmosphere” in your mini-report but do not use that as your “one topic”.