Lecture 10: Telescopes (part 2)

Read: Ch 4 of “Astronomy: a Physical Perspective” (M. Kutner)

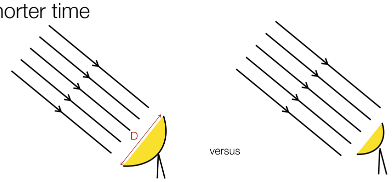
Prof Aline Vidotto

Quick recap of last lecture

Light-collecting area:

Telescopes with a larger collecting area can gather a greater amount of light in a shorter time

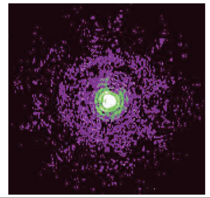
$$A = \pi \left(\frac{D}{2}\right)^2$$



Angular resolution

- The minimum angular separation that the telescope can distinguish
- Set by the limit of diffraction

$$\Delta\theta[\text{rad}] = 1.22\frac{\lambda}{D}$$

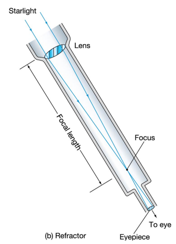


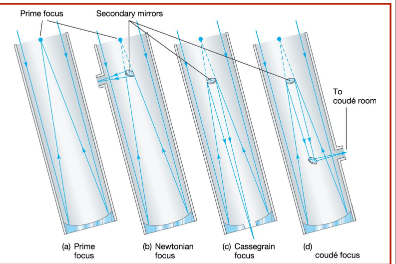
The rings in this image of a star come from interference of light wave.

Telescope designs:

Refracting telescope: focuses light with lenses

Reflecting telescope: focuses light with mirrors





What we will cover today…

Goal: learn the basic concepts behind observations in the visible and in other parts of the spectrum

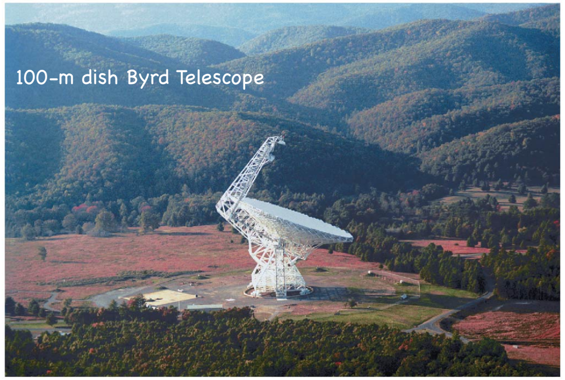
1. Radio astronomy
2. Space-based observatories
3. Types of observations
4. Data handling

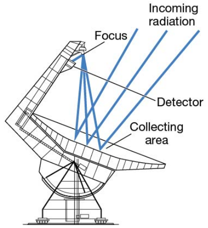
1. Radio Astronomy

Radio telescopes

- A radio telescope is like a giant mirror that reflects radio waves to a focus
  - Similar to optical reflecting telescopes
- Since wavelengths are large, we need a large collector to achieve high resolution

$$\Delta\theta[\text{rad}] = 1.22\frac{\lambda}{\text{D}}$$





Radio astronomy

- Last lecture: Surface of mirror must be perfect to within approximately λ/20 (λ: wavelength of light being observed). For λ≈500nm, surface must be accurate to within 25nm (≈250 atoms!)
- For radio waves at λ≈20cm, the surface of a radio telescope must be perfect to within approximately λ/20 ≈ 1cm
  - 1cm holes in radio telescopes have no effect on performance

300-m dish at Arecibo: dish is made of a mesh surface (imperfect, with holes!) set in a natural bowl

- Radio measurements can either be in continuum (like photometry in optical) or spectral line observations.

Angular resolution in radio

- Example: Calculate the angular resolution of a 76-m dish at λ = 21 cm:

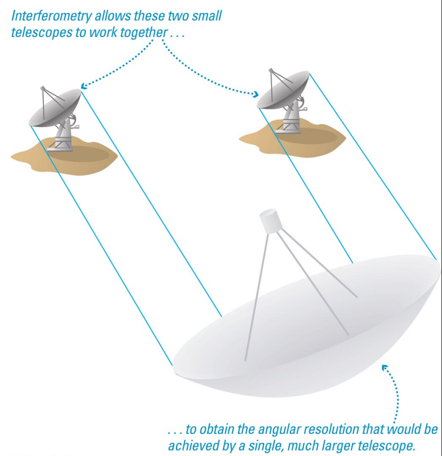
$$\Delta\theta[\text{rad}] = 1.22\frac{\lambda}{\text{D}} = 1.22\frac{0.21\text{m}}{76\text{m}}$$

$$= 3.4 \times 10^{-3}\ \text{rad} = 11.6\ \text{arcmin}$$

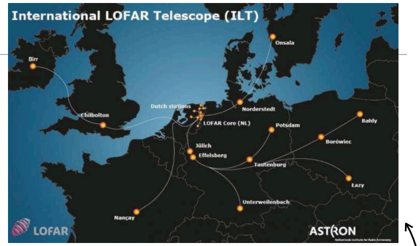
  - 12 times worse than human eye!

- Poor angular resolution of radio telescopes can be improved by using combinations of telescopes, called interferometers

Interferometry: using arrays of telescopes to improve resolution



Radio telescope arrays



LOFAR: Low Frequency Array across Europe, including one station at Birr (construction led by Prof Peter Gallagher, TCD/DIAS)

Conceptual question

Radio dishes are large in order to

(a) improve angular resolution.
(b) give greater magnification.
(c) increase the range of waves they can collect.
(d) detect shorter waves than optical telescopes for superior resolution.

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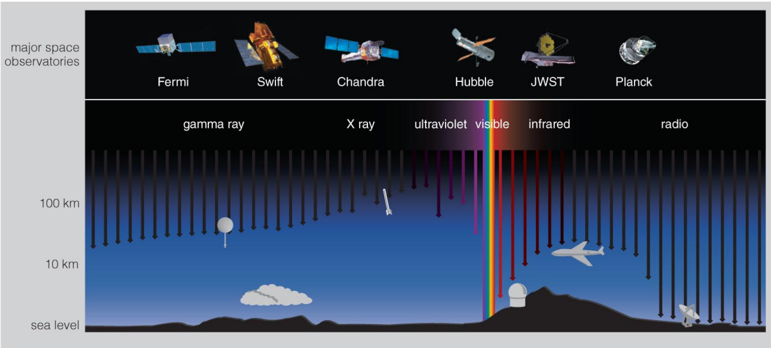
Explanation: Resolution is worse with long-wave light, so radio telescopes must be large to compensate.

2. Space-based observatories

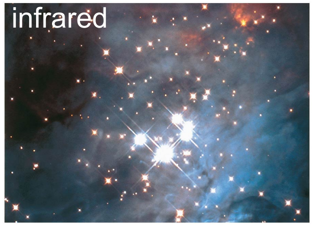
Two main reasons to put telescopes into space

1) Much sharper images are possible because there is no turbulence (example: optical astronomy with Hubble)
2) Forms of light other than radio and visible do not pass through Earth's atmosphere.

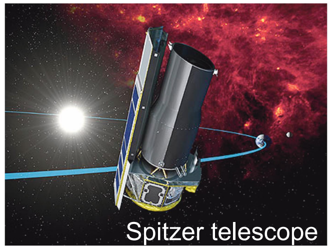


Infrared telescopes

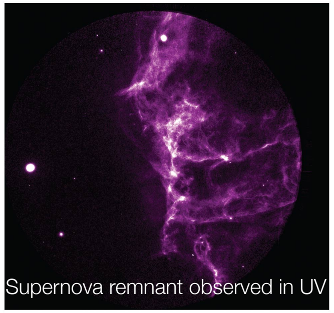
- Infrared radiation can image where visible radiation is blocked by interstellar matter or atmospheric particles.

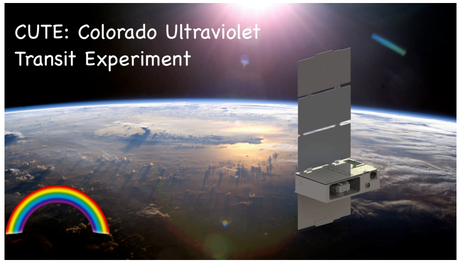


- Infrared (and ultraviolet light) telescopes operate like visible-light telescopes but need to be above atmosphere to see all wavelengths.



Ultraviolet light telescopes

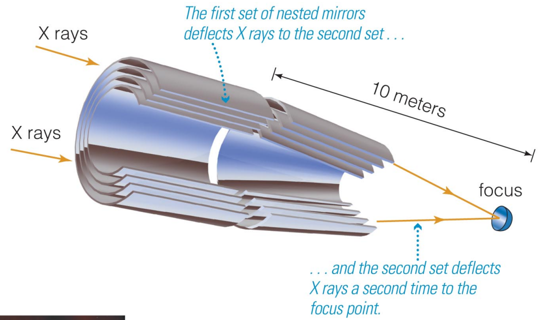




CUTE is a NASA cubesat mission (3.5 million USD), with participation of TCD. It will observe exoplanetary transits in the ultraviolet to reveal escaping atmospheres. Expected to launch in 2020.

X-ray telescopes

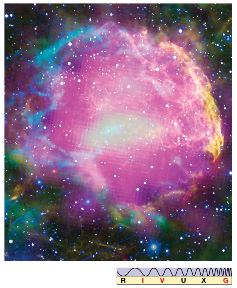
- X-rays and gamma rays will not reflect off mirrors as other wavelengths do; need new techniques.
- X-rays will reflect at a very shallow angle and can therefore be focused.

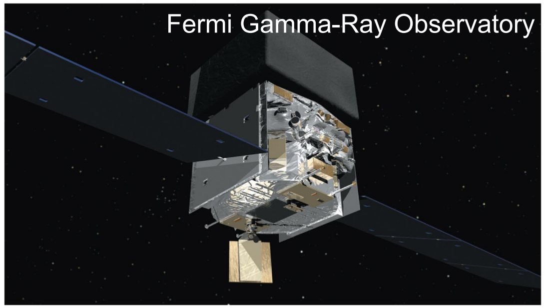


X-rays are gently guided to a focus

Gamma-ray telescopes

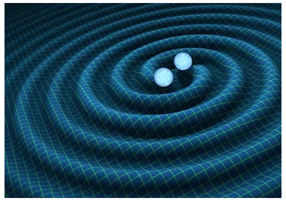
- Gamma rays are the most high-energy radiation we can detect. This supernova remnant would be nearly invisible without the Fermi satellite and its gamma-ray detector.



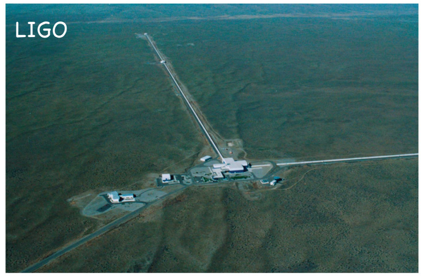


Looking beyond light

- We can also gain knowledge by collecting other signals using different sorts of “telescopes”: neutrinos, cosmic rays, gravitational waves



LIGO and Virgo are giant interferometers to detect gravitational waves



Conceptual question

The Hubble Space Telescope (HST) offers sharper images than ground telescopes primarily because

(a) HST is closer to planets and stars.
(b) HST uses a larger primary mirror.
(c) it gathers X-ray light.
(d) HST orbits above the atmosphere.
(e) it stays on the nighttime side of Earth.

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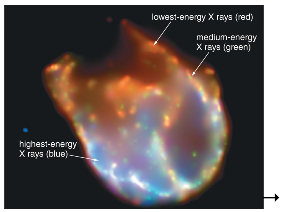
Explanation: HST orbits 540 km above Earth—not much closer to stars and planets! But it can gather UV, visible, and infrared light, unaffected by Earth's atmosphere.

3. Types of observations

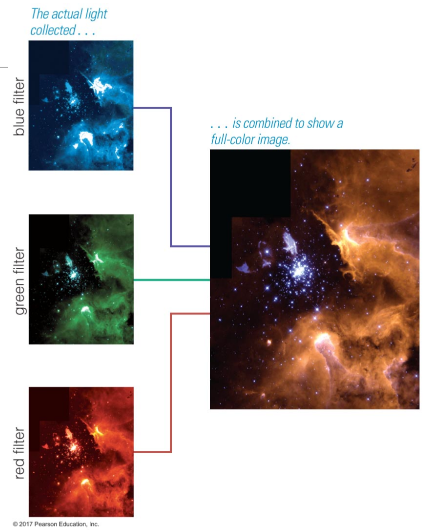
- **Imaging**: taking pictures of the sky
- **Photometry**: measuring of light, including measuring the flux through certain filters
- **Spectroscopy**: breaking light into spectra, with sufficient detail to allow the study of spectral lines.

Imaging

- an imaging instrument is simply a camera
- often, we place filters in front of a camera to allow only particular wavelengths (or colours) of light to pass through
- As astronomical detectors can record forms of light our eyes can't see, colour is sometimes used to represent different energies of non-visible light.

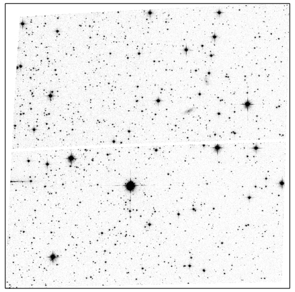


→ False-colour image



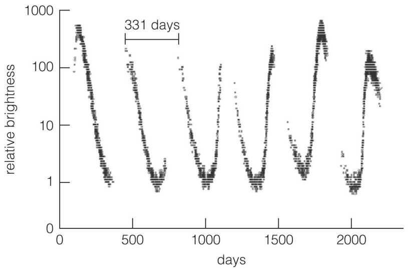
Photometry and time monitoring

- Photometry is the measurement of photons (i.e., flux or brightness)



- Count rates (flux) are associated to each star in the image above

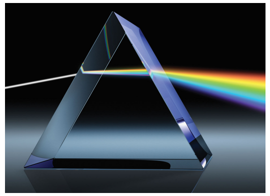
- A series of brightness measurements made over a period of time lets us construct lightcurves



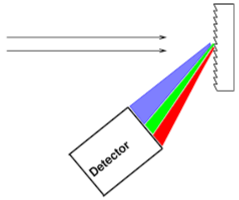
Spectroscopy

breaking light into spectra, with sufficient detail to allow the study of spectral lines. Spectrum of an object reveals: chemical composition, temperature, motion.

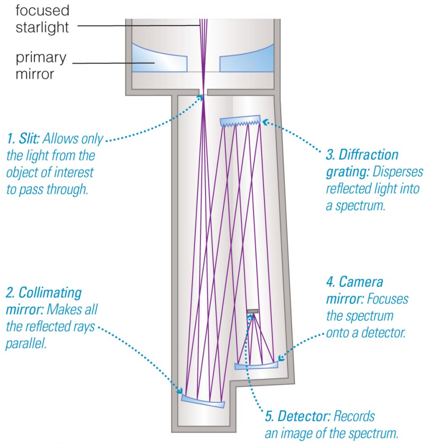
Prisms does not spread light very much (low dispersion instrument)



Diffraction grating is preferred, as they have higher dispersion



Spectrograph: separates the different wavelengths of light before they hit the detector



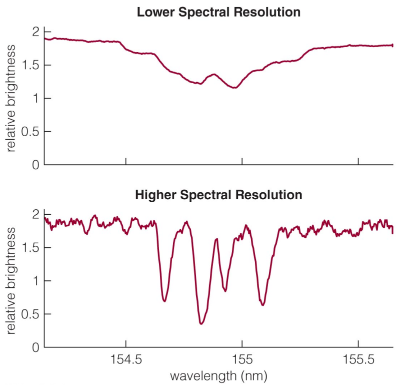
Spectroscopy: spectral resolution

- For an image, we aim at having high angular resolution
- For a spectrum, we aim at having high spectral resolution
  - spectral lines are merged together at lower spectral resolution
- Spectral resolution R depends on how widely the spectrograph spreads out light, i.e., how well we can separate two lines that are $\Delta\lambda$ apart:

$$R \equiv \frac{\lambda}{\Delta\lambda}$$

- however, the more the light is spread out, the more total light we need to record a spectrum

Spectrum: brightness at each wavelength



- spectrum requires longer exposure times than images
- high-res spectrum requires long exposure times than low-res spectrum

Conceptual question

Which of the following is NOT an instrument typically attached to the focal plane of a large, research-grade telescope?

a) An eyepiece lens.
b) A camera.
c) A spectrograph.

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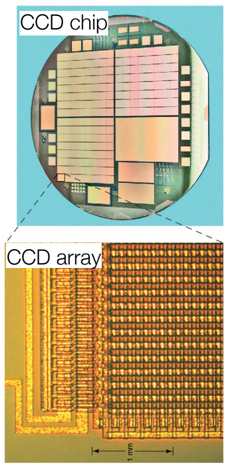
4. Data handling

Wherever type of observations being made, data must be recorded in a **detector**

Detection: Charge-coupled devices (CCDs)

- CCDs are electronic devices that can record and store observational data



- CCD consists of many pixels. When light strikes a pixel, an electric charge builds up on the device (photoelectric effect)
- The amount of charge is proportional to intensity of the light at that point
- Charge build up is monitored electronically

Typical data from chip is an array of numbers.

0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	1	3	3	3	1	0	0	0	0	0	0	0	0	0	0	0
0	0	0	1	3	5	6	5	3	1	0	0	0	0	0	0	0	0	0	0
0	0	0	1	3	6	7	6	3	1	0	0	0	0	0	0	0	0	0	0
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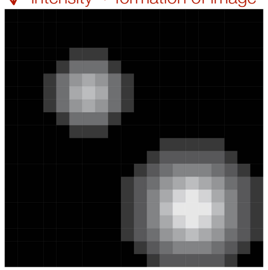
0	0	0	0	0	0	0	0	0	1	2	4	7	9	9	9	7	4	2	1
0	0	0	0	0	0	0	0	0	1	2	4	6	8	9	8	6	4	2	1
0	0	0	0	0	0	0	0	0	1	2	3	5	6	7	6	5	3	2	1
0	0	0	0	0	0	0	0	0	0	1	2	3	4	4	4	3	2	1	0
0	0	0	0	0	0	0	0	0	0	0	1	2	2	2	2	2	1	0	0

Each number represents an intensity→ formation of image



Efficiency and noise of detectors

- Not all photons striking a CCD create electrons
- **Quantum efficiency (QE)**: fraction of photons that are detected:

$$\mathrm{QE} = \frac{\text{\#read out electrons}}{\text{\#incident photons}}$$

- Photographic plates (no longer used): QE~ 5%
- CCDs: QE ~ 75% or even larger
  - CCDs can image objects 10 to 20 times fainter (or the same object 10 to 20 times faster) than a photographic plate

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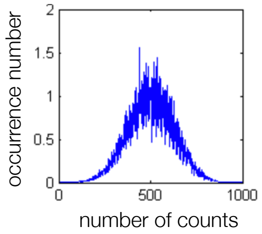
- **Dark current:** any detector produces some background level. This dark current originates from thermal emission from the detector
  - reduce the background noise by cooling the detector
- this background must be subtracted from any measurement
- background also produces random fluctuation (statistical error)

Signal to noise ratio (S/N)

- You want to determine the average rate at which you are counting photons from a given source
  - you measure total counts during a given time T (ie, the exposure time)
  - repeat the measurement many times, as number of counts is not always the same
- histogram of the number of times each result comes out:
  - gaussian centred on some value (best estimate of number of photons detected in time T)
  - width of gaussian: standard deviation



- For counting experiment: you measure N events. The uncertainty is $\sqrt{N}$ (Poisson noise)

$$\text{signal to noise ratio} = \frac{N}{\sqrt{N}} = \sqrt{N}$$

If you want to increase the S/N ratio by a factor of 2, you need to increase the counts by a factor of 4

Conceptual question

An advantage of charge-coupled devices (CCDs) over photographic film is that

(a) they don’t require chemical development.

(b) digital data are easily stored and transmitted.

(c) CCDs are more light sensitive than film.

(d) CCD images can be developed faster.

(e) all of the above are true.

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