Lecture 3

September 21, 2017
Telescopes and Observing
News

• Note there are a few changes in lab assignments.
• Lab 2
  – Completed the observing: 2 groups, partially completed: 3 groups, clouded out 4 groups. Observing will continue in the coming week.
  – Lab is now due October 5. But work on writing up if you can – may hand out Lab 3 next week.
• Rutgers Astronomical Society (RAS)
  – help with public observing nights (tonight is cancelled)
• Society of Physics Students (SPS)
Most Important properties of a telescope

• **Light-collecting area**: Telescopes with a larger collecting area can gather a greater amount of light in a shorter time.
  – Area of primary mirror (minus area shadowed by secondary mirror).

• **Angular resolution**: Telescopes that are larger are capable of taking images with greater detail.
Angular Resolution

• The *minimum* angular separation that a telescope can distinguish.
  – Two stars closer than this minimum appear to be a *single* object.

• Better angular resolution means distinguishing smaller angles.

Improving angular resolution
Angular Resolution

- An unavoidable limit to resolution comes from the **diffraction** of light waves entering a telescope.
  - Is like the water waves entering a harbor – the waves spread out after passing through the entrance.
  - The diverging rays caused by diffraction are not brought to a sharp focus. Even a point source of light appears as a small disk surrounded by faint rings.
Angular Resolution

- Angle resolved $\approx$ wavelength/diameter $= \lambda/D$
  - Large diameter $\Rightarrow$ better angular resolution
  - Short wavelengths $\Rightarrow$ better angular resolution

Note: no focusing lenses in these apertures.

big diameter, small diameter
less diffraction more diffraction
Angular Resolution

• Quantum view of angular resolution: apply the uncertainty principle to a photon passing through an aperture.

– Photon momentum:
\[ p_x = E / c = (h \nu) / c = (h(c / \lambda)) / c = h / \lambda \]

– Momentum uncertainty:
\[ \Delta p_y \approx h / \Delta y = h / D \]

– Thus, the angular uncertainty is:
\[ \theta = \Delta p_y / p_x = \frac{h / D}{h / \lambda} = \frac{\lambda}{D} \]
Angular Resolution

• Diffraction broadens the image of a point of light into a disk surrounded by rings.
  • The signal is the square of the spatial fourier transform of the entrance aperture (see Ch. 6 of Birney et al.).
  • This limit on angular resolution is known as the diffraction limit.

Close-up of a star (a point of light) imaged with the Hubble Space Telescope.
Schommer Obs. Telescope Properties

• **Light-collecting area:**
  - \( \text{Area} = \pi (d/2)^2 = \pi (0.5m/2)^2 = 0.20m^2 \)
  - Minus the \( \sim 20\% \) central obscuration

• **Angular resolution:**
  - \( \theta_{\text{Rayleigh}} = 1.22 \left( \frac{\lambda}{d} \right) \)
  - \( = 1.22 \left( \frac{500\text{nm}}{0.5 \times 10^9 \text{nm}} \right) = 1.2 \times 10^{-6} \text{rad} = 0.25" \)
  - Limited to 1–2 arcsec by atmospheric turbulence (can be as good as 0.5 arcsec at best sites).
Angular Resolution

• The atmosphere is usually more important in limiting the angular resolution of ground-based telescopes: “seeing”.
The atmosphere acts like many lenses, bending incoming light rays.
The result is that turbulence in the Earth’s atmosphere blurs our view of the cosmos.

It is like looking at the bottom of a swimming pool
* still water = a clear view
* someone jumps in = a changing, distorted view

Astronomers call this blurring *seeing*. Usually limits the angular resolution to about 1 second of arc (2 or more locally).
• Seeing causes image motion in small apertures and multiple “speckles” in large apertures.

Image of binary star ζ Bootis (0.8” separation) taken with Nordic Optical Tel.
• Seeing
  – Fried parameter, $r_0$: 10 – 20 cm at optical wavelengths at good sites.
  – Coherence time: ~10’s of milliseconds
  – Isoplanatic patch: the size on the sky over which the seeing is the same.
    • $\approx$ angular diameter of $r_0$. Usually a few tens of arcseconds.
• Shape of a stellar image – the “point spread function” (PSF)

The core is caused by a) the bending of light in the rapidly changing inhomogeneous atmosphere – seeing and b) quality of the optical system (how well it is focused, …). It often varies over a night and within an image.

The origin of the halo is less well understood, but it is probably caused by diffraction from the telescope aperture and scattered light from dust and “micro-ripple” imperfections on surfaces of mirrors, filters, and other optical elements. The halo is constant at least over the several nights of an observing run.
Angular Resolution

• A solution to atmospheric distortion: *adaptive optics*
  – Bend your telescope mirror to remove the deflections introduced by the atmosphere.
  – Significantly increases complexity of telescope and needs fast computer processing.
  – Not perfect, but does help.
Example of adaptive optics on globular cluster M13

Adaptive optics image using ALTAIR on Gemini North, near-IR 1.65 microns

Wide-field image of M13 by Canada-France-Hawaii Telescope

Gemini North, no adaptive optics
Another solution: put your telescope in space, above the atmosphere.

Main problem: very expensive. Hubble cost $1.5 billion to launch and requires $100 million/yr to run.
Bright star viewed with ground-based telescope

Same star viewed with Hubble Space Telescope

There is another reason for putting telescopes in space … observing wavelength of light that are not transmitted by the atmosphere.
Other Telescope Properties

- **Image Scale:** The relation between angular size on the sky and linear size in the image plane ($\theta_1$ and $s$ below).
  - Generally not exactly constant across the image.
  - Units are often arcseconds/mm or arcseconds/pixel.

For $\theta_1 \ll 1$:

$$s = \theta_1 \times F$$

$$\Rightarrow \text{scale} = \frac{\theta_1}{s} = \frac{1}{F}$$

Example: Our 0.5 m telescope has $F = 4.0$ m.

$$\Rightarrow \text{scale} = 0.25 \text{ rad/m}$$

$$= 52 \text{ arcsec/mm}$$

Note 206265 arcsec = 1 rad
Other Telescope Properties

• **Focal ratio**: $f/ = F/d$
  
  – Our telescope has $F/d = (4.0 \text{ m})/(0.5 \text{ m}) \rightarrow f/8$.
  
  • Typical of cassegrain configurations. Large research telescopes are typically $f/2$ at prime focus.

  – **Brightness of extended** images depends only on $f/$.
  
  • Light collected proportional to $d^2$. More light implies a brighter image.

  • Image area proportional to $F^2$. A larger image spreads the light over a bigger area, so the image is fainter.

  – For unresolved objects (like stars), the brightness depends only on collecting area.
Other Telescope Properties

- **Magnification:** Only applies to telescopes used visually. It is the increase in the apparent angular size of objects.

\[
magnification = \frac{\theta_2}{\theta_1} = \frac{F_{\text{telescope}}}{F_{\text{eyepiece}}}\]

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Other Telescope Properties

• The diagram shows the typical use of an eyepiece in an astronomical telescope.
  – Diverging light rays from the image plane are made parallel, accommodating the resting focus of the normal eye (which is at $\infty$).
  – Formula for magnification comes from $\theta_1F_t = s = \theta_2F_e$.
  – Note the the eyepiece forms an image of the entrance aperture of the telescope – the exit pupil.
    • Placing the pupil of the eye at the exit pupil ensures that all of the light from the telescope enters the eye.
    • If the exit pupil is larger than the eye’s pupil, some light is lost. Avoiding this imposes a minimum useful magnification.
Other Telescope Properties

• **Field of View**: The size of the region in the focal plane that is (nearly) fully illuminated and has good image quality.
  
  – Fundamental limit is usually off-axis image aberrations.
  
  – Size of the eyepiece or detector is also important.
Off-Axis Aberrations

- Coma: rays striking different zones of lens or mirror focus at different locations and distances.
Off-Axis Aberrations

- Astigmatism: off-axis rays striking different planes focus at different distances.
Ritchey-Chretien Telescopes

• Have hyperbolic surfaces on the primary and secondary. Additional surface allows a reduction in aberrations.
  – Particularly reduces coma, which causes asymmetric images, relative to astigmatism, which does not.
    • Images better suited for measuring positions – astrometry.
  – Do have *field curvature* (a curved focal plane).

• Most large professional telescopes use the R-C design.
Schmidt telescope designs use a spherical primary mirror to get a wide field of view, but suffer from spherical aberration – which must be corrected.
THE FOUCAULT-SCHMIDT PHOTOGRAPHIC TELESCOPE

5 degree fov
Off-Axis Aberrations

• Vignetting: not all off-axis rays make it to the focal plane – generally hit baffles or stops.

Image of uniformly illuminated field taken with the CCD camera on the 0.5m telescope. Plots of image intensity along central row and column show reduction in signal <10%. 
Light enters Hubble's **aperture** and travels down the **main baffle**. A baffle is a surface which eliminates stray light.

Light is reflected by the **primary mirror** which measures about 8 feet (2.4 meters) in diameter. Because of the concave shape, the primary mirror converges the light to the secondary mirror through a **secondary baffle**.

The **secondary mirror**, measuring about 1 foot (0.3 m) in diameter receives the light. It in turn reflects the still-converging light back toward the primary mirror through a **central baffle**.

**The light travels through a** the primary mirror, to reach the **focal plane**, where the science instruments examine the light.
Other Telescope Properties

• Field of View: The size of the region in the focal plane that is (nearly) fully illuminated and has good image quality.
  – Usually determined by off-axis image aberrations.
  • 0.5 degrees for our telescope’s Ritchey-Chretien optics

  ![Small field of view](image1.jpg) ![Large field of view](image2.jpg)

  – Other limits:
  • Baffles inserted to eliminate scattered light.
Other Telescope Properties

• Field of View: The size of the region in the focal plane that is (nearly) fully illuminated and has good image quality.
  – Usually determined by off-axis image aberrations.
    • 0.5 degrees for our telescope’s Ritchey-Chretien optics
  – Other limits:
    • Baffles inserted to eliminate scattered light.
    • Size of the detector (the cameras on our telescope and on the Hubble Space Telescope).
HST focal plane is about 0.5 degree across. But the individual cameras cover only a small fraction of it.
FOV of the Kepler space telescope: about 10 degrees across. Is an 0.95m diameter telescope.

Detector pixels are so large on the sky that defocus the telescope so that stars are sampled by a few pixels.
Large Synoptic Survey Telescope (LSST): 8.4 m primary mirror; the 3-mirror design gives a $3.5^\circ$ fov. Survey to begin in 2022 (first light late 2020?).
Other Telescope Properties

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  - Other limits:
    - Baffles inserted to eliminate scattered light.
    - Size of the detector (the cameras on our telescope and on the Hubble Space Telescope).
- With an eyepiece: \((\text{apparent eyepiece fov})/\text{mag}\)
  - For most of our eyepieces apparent fov = 70 degrees.