Lecture 9: Telescopes (part 1)

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

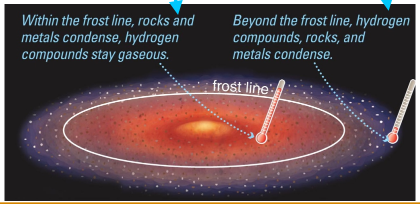
Prof Aline Vidotto

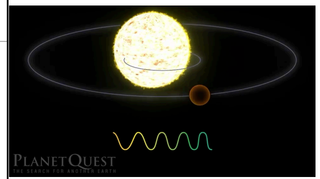
Quick recap of last lecture

Formation of the solar system planets

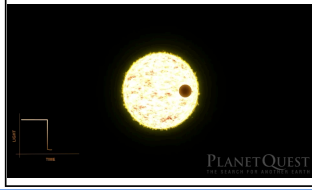
terrestrial planets form

gas giants form



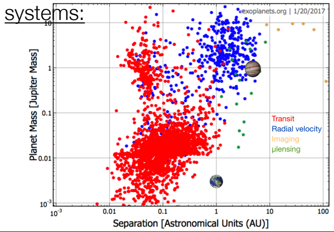


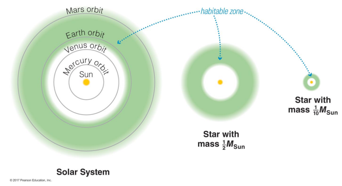
Radial velocity method (derive mass)



Transit method (derive radius)

Diverse architectures of exoplanetary systems:





Habitable zones

region around star where stellar irradiation is enough to allow temperatures required for liquid water.

What we will cover today…

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

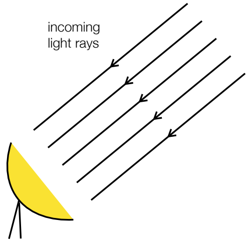
1. What a telescope does
2. Telescope designs

Food for thought:
Physics = experimental science
Astronomy = observational science

• Develop theory & numerical models to explain/predict observations, which sometimes cannot be repeated (contrary to lab experiments)

Some would argue that Astronomy is not a sub-area of Physics!

1. What a telescope does



Telescopes are “light buckets” that collect photons, just as actual buckets collect raindrops falling into them.

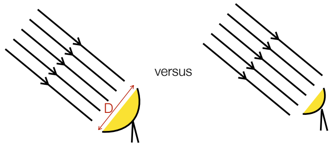
The two most important properties of a telescope:

1. **Light-gathering power:** We can see **fainter** objects with a telescope than with our eyes.
2. **Angular resolution:** We can see greater **detail** with a telescope than without.

1. Light-collecting power (area & exposure time)

- **Light-collecting area:** Telescopes with a larger collecting area can gather a greater amount of light in a shorter time.
  - Light-collecting area of a telescope with diameter D:

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



  - Currently, largest optical telescopes have D=10 metres.

- **Example:** Compare the light-collecting area of the naked eye (pupil diameter = 5mm) to that of a 1m diameter optical telescope

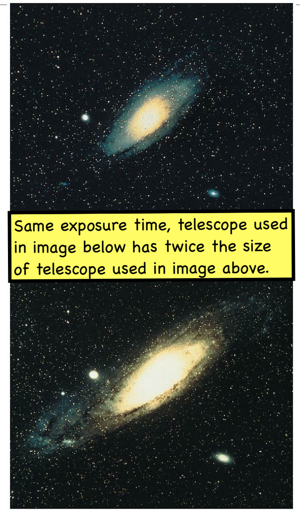
$$\frac{A_{\text{telescope}}}{A_{\text{eye}}} = \left(\frac{D_{\text{telescope}}}{D_{\text{eye}}}\right)^2 = \left(\frac{1\text{m}}{5\times10^{-3}\text{m}}\right)^2 = 4\times10^4$$

- <u>Interpretation:</u> Detected flux (or brightness) of an object is proportional to collecting area: we can see objects that are $4\text{x}10^4$ times fainter with a 1-m telescope than with our eyes.

1. Light-collecting power (area & exposure time)

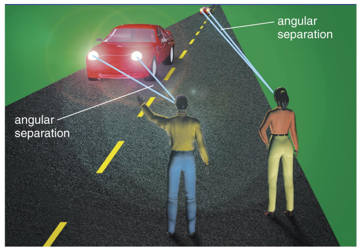
- **Exposure time:** time spent gathering light from a source.
  - With modern detectors, exposures of several hours are possible.
  - "Exposure" of the eye is limited at 1/20s

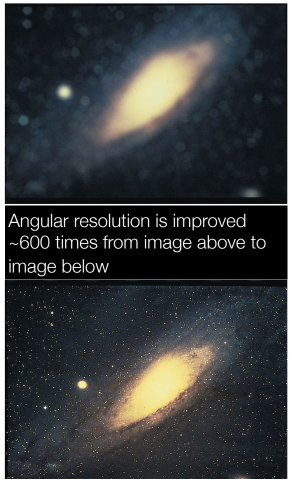
- <u>Equivalence of area & exposure time</u>:
  - <u>Area:</u> a 5-m telescope produces an image that is 5^2=25 times brighter than a 1-m telescope, with same exposure time
  - <u>Time:</u> A 5-m telescope produces an image 5^2=25 times faster than a 1-m telescope because it gathers energy at a rate that is 25 times grater
    - ➡ **Example:** 1h exposure with 1-m telescope is equivalent to 1/25h (2.4 min) exposure with a 5-m telescope



2. Angular resolution

- **Angular resolution:** The minimum angular separation that the telescope can distinguish

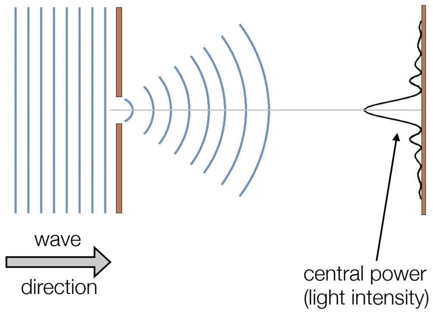


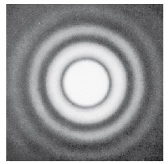


- Telescopes that are larger are capable of taking images with greater detail.

Q: What is the minimum angular separation that the telescope can distinguish?
A: the limit is set by diffraction

Diffraction affects the limit of angular resolution





Fuzzy shadow

In the absence of any diffraction, the shadow would be perfectly sharp. But this never happens in reality!

- The amount of diffraction (the amount of *fuzziness*) depends on the angular width of the central power

$$\Delta\theta[\text{rad}] = \frac{\text{wavelength}}{\text{diameter of aperture}} = \frac{\lambda}{\text{D}}$$

Diffraction affects the limit of angular resolution

$$\Delta\theta[\text{rad}] = \frac{\text{wavelength}}{\text{diameter of aperture}} = \frac{\lambda}{\text{D}}$$

- Diffraction results in images of stars being smeared out because by Δθ
  - if two stars are closer together than Δθ → their images will blend!
- For circular aperture, we should use $\boxed{\Delta\theta[\text{rad}] = 1.22\frac{\lambda}{\text{D}}}$ known as Rayleigh limit

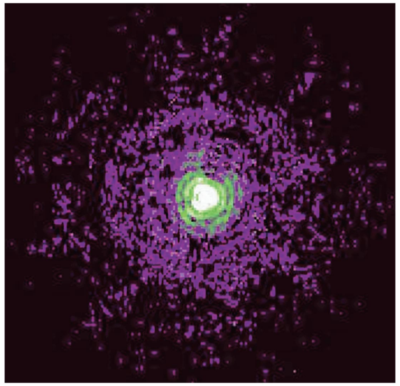
- **Example**: what is the angular resolution of the pupil (diameter = 5mm) for light of wavelength 550nm?

$$\Delta\theta = 1.22\frac{550\times10^{-9}\text{m}}{5\times10^{-3}\text{m}} = 1.3\times10^{-4}\ \text{rad}$$
$$= 1.3\times10^{-4}\frac{180\times60\times60}{\pi} \simeq 28\ \text{arcsec}$$

Diffraction affects the limit of angular resolution

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

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



Close-up of a star from the Hubble Space Telescope

- larger telescope (larger D) gives us better resolution (smaller Δθ)
- larger wavelengths gives us worse resolution (larger Δθ)
  - observations in the infrared or radio range are often limited by the effects of diffraction → we need bigger radio telescopes to improve the resolution at radio wavelengths
- This limit on angular resolution is known as the diffraction limit.

Examples: diffraction limit

- What is the diffraction limit of the 2.4-m Hubble Space telescope for visible light with a wavelength of 500nm? Give your answer in arcsec (”).

$$\Delta\theta[\text{rad}] = 1.22\frac{\lambda}{\text{D}} \quad \times\frac{180\times60\times60}{\pi}$$
$$\Delta\theta[\text{arcsec}] = 2.5\times10^5\frac{\lambda}{\text{D}}$$

$$\Delta\theta = 2.5\times10^5\frac{500\times10^{-9}\text{m}}{2.4\text{m}}$$
$$= 0.05''$$ arcsec symbol

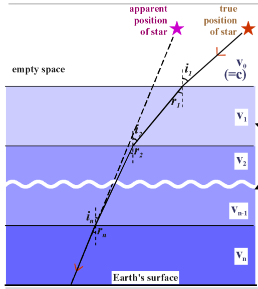
<u>Interpretation</u>: Hubble can resolve objects separated by more than 0.05”, while objects separated by less will be blurred together.

- How large a telescope would you need to achieve a diffraction limit of 0.001” for visible light (wavelength of 500nm)?

$$\Delta\theta = 0.001''$$

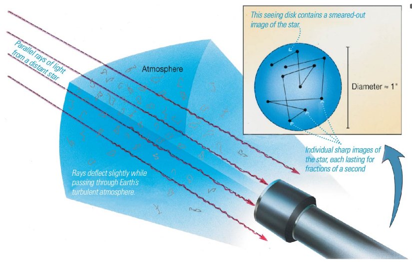
$$D = 2.5\times10^5\frac{\lambda}{\Delta\theta[\text{arcsec}]} = 2.5\times10^5\frac{500\times10^{-9}\text{m}}{0.001''} = 125\text{m}\quad(!!)$$

Earth’s atmosphere affects angular resolution



different indexes of refraction

- light passes through increasingly dense air
- larger density → larger refraction index
- as light passes through one layer of the atmosphere to the next, it is slightly bents towards the vertical
  - Star appears to be at higher position above the horizon as it actually is



- Not a problem if atmosphere is stable. However, turbulence in the atmosphere cause changes in the index of refraction
  - Image moves around and we see a blurred image
  - Effect is called *seeing* and it limits resolution to a few arcsec

Effects of seeing

- On the ground, seeing is typically worse than 1”. At a good observatory site, on a good night, seeing can be as good as 0.3”.
- Building larger telescopes does not help us overcome seeing limitation on resolution (but it improves light-gathering power!)

- Three possible solutions:
  1. Put telescopes in space (no atmospheric turbulence).
     - ➡ On the ground: a 1-m telescope observing at λ=550nm has diffraction limit of 0.11”
     - ➡ In space: a 1-m telescope can improve resolution by a factor of ~5. See previous example: Hubble (2.4m) has a resolution of 0.05”
  2. Put telescopes on mountaintops, especially in deserts.
  3. Use adaptive optics: control mirrors by bending them slightly to correct for atmospheric distortion.

Best ground-based sites for astronomical observations

- calm (not too windy)
- high (less atmosphere to see through)
- dry (few cloudy nights)
- dark (far from city lights)

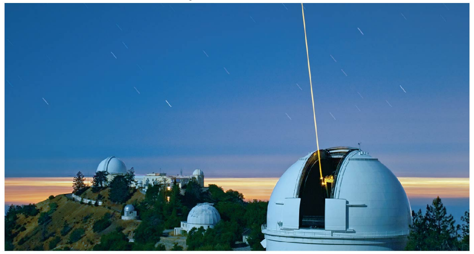
Mauna Kea, Hawaii

Best observing sites are atop remote mountains

Light pollution: Scattering of human-made light in the atmosphere is a growing problem for astronomy.

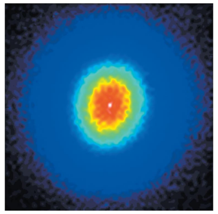
Adaptive optics

- Rapidly changing the shape of a telescope’s mirror compensates for some of the effects of atmospheric turbulence.



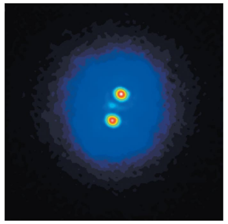
Lasers probe the atmosphere above the telescope, returning information about atmospheric turbulence.

A computer then uses this information to “undo” the effects of turbulence



without adaptive optics

with adaptive optics



now the two stars can be distinguished!

Conceptual question

Resolution is improved by using

(a) larger telescopes and longer wavelengths.
(b) infrared light.
(c) larger telescopes and shorter wavelengths.
(d) lower frequency light.
(e) visible light.

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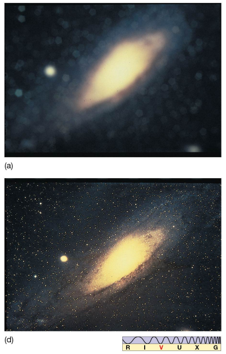
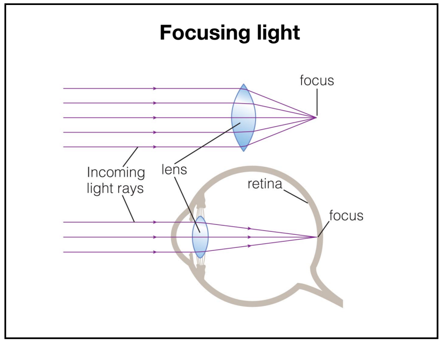


Explanation: Diffraction limits resolution; larger telescopes and shorter wave light produces sharper images.

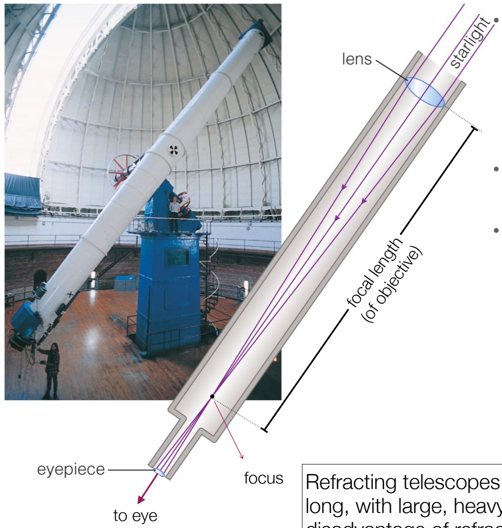
$$\Delta\theta[\text{rad}] = 1.22\frac{\lambda}{D}$$

2. Telescope designs

Refracting telescope: focuses light with lenses
Reflecting telescope: focuses light with mirrors



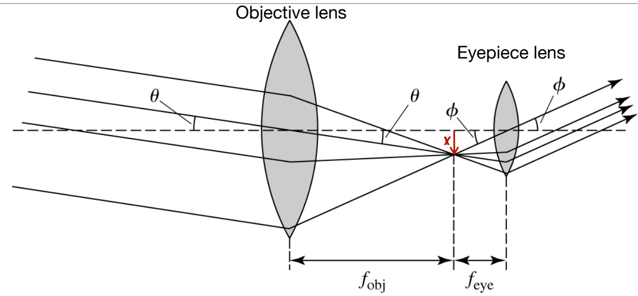
Refracting telescopes (lens)



- Light first passes through a large lens: objective lens
  - larger objectives → greater light-gathering power
- Image is formed at the focus
- Light is then concentrated in the eyepiece
  - image formed can be viewed by the eye or by a camera
  - The eyepiece acts as a magnifying glass of the image formed at focus

Refracting telescopes need to be very long, with large, heavy lenses → one disadvantage of refracting telescopes

Angular magnification of a refracting telescope



small angles:
tan θ ≈ θ

$$\tan\theta = \frac{x}{f_{obj}} \qquad \tan\phi = \frac{x}{f_{eye}}$$

$$x = \theta f_{obj} \qquad x = \phi f_{eye}$$

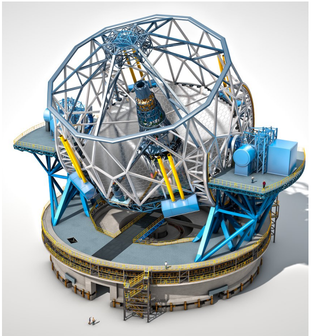
angular magnification: $m = \dfrac{\phi}{\theta} = \dfrac{f_{obj}}{f_{eye}}$

- Different focal lengths of the eye piece can produce different angular magnifications
- Viewing a large image requires long objective focal length + short focal length of the eyepiece.

Disadvantages of refracting telescopes

- Light traveling through lens is refracted differently depending on wavelength.
- Some light traveling through lens is absorbed.
- A large lens can be very heavy and can only be supported at the edge (so that light can pass through).
- A lens needs two optically acceptable surfaces, but a mirror needs only one.

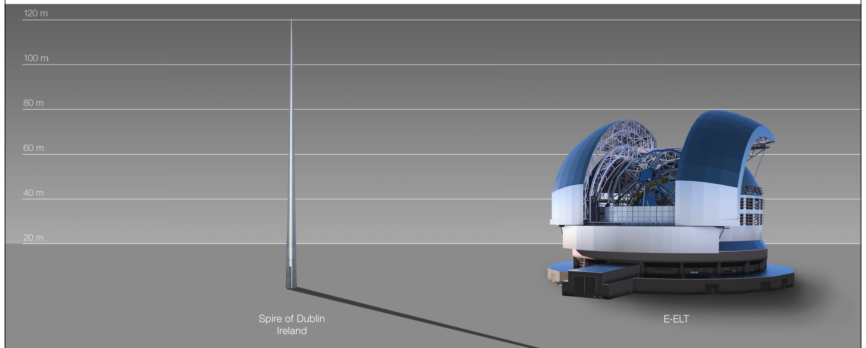
- Modern telescopes are all reflectors (with mirrors)
  - Reflecting telescopes can have much greater diameters, as the mirrors can be supported from behind



The European Extremely Large Telescope is currently being built (will be located in Chile). It is a 39-m telescope and will be the world's biggest eye on the sky when it becomes operational early in the next decade

The European Extremely Large Telescope

European Southern Observatory



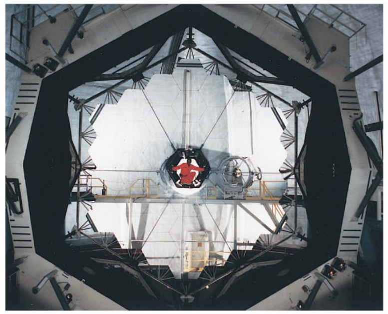
How are mirrors made?

- Mirrors are made by shaping and polishing a large piece of glass + adding a thin layer of reflecting material (eg, aluminium)

- Surface of mirror must be perfect to within approximately $\lambda/20$ (λ: wavelength of light being observed). For $\lambda \approx 500$nm, surface must be accurate to within 25nm (≈250 atoms!)

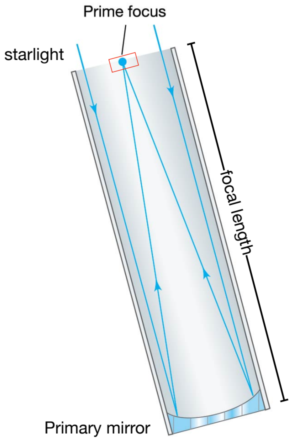
Mirrors in Reflecting Telescopes

Twin Keck telescopes on Mauna Kea in Hawaii



Segmented 10-meter mirror of a Keck telescope

Reflecting telescopes (mirrors)



Above: a prime focus arrangement. There are other types of telescopes

- To observe the image, the eyepiece (and observer) should be placed between the stars and the primary mirror
  - this blocks some of the incoming light

- **Example:** consider a 5-m telescope, with a 1-m diameter prime focus cage. What fraction of the incoming light is blocked by the cage?

$$\text{fraction blocked} = \text{ratio of areas}$$

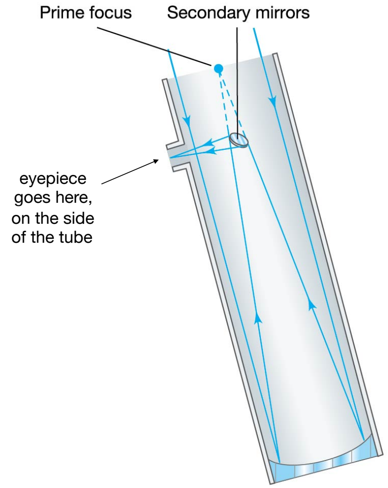
$$= \left(\frac{1\text{m}}{5\text{m}}\right)^2 = 0.04 = 4\,\%$$

If we make the telescope smaller, but keep the cage the same size, the blockage worsens

Types of reflecting telescopes: Newtonian focus

- Newton realised the problem with the blockage of light and proposed a different mirror arrangement: Newtonian focus

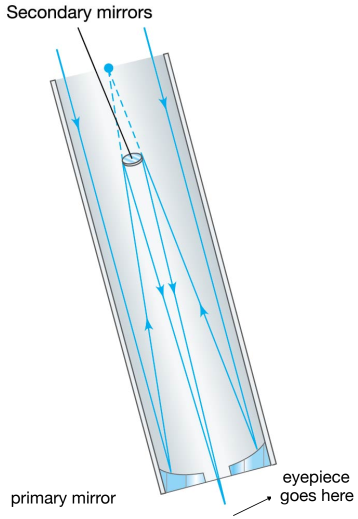
- Arrangement is difficult to use in a large telescope, as the eyepiece goes at the top of the telescope



Types of reflecting telescopes: Cassegrain focus

- Cassegrain focus is an alternative solution
- a secondary mirror directs the rays back through a hole in the centre of the primary mirror (not much light is lost as the hole in the centre of mirror is already blocked by the secondary mirror or prime focus cage)

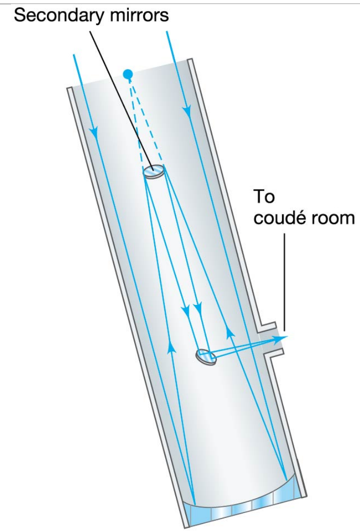
- Advantage: if you want to place a lot of equipment at the eyepiece position, this is not too far from the point of support of the telescope



Types of reflecting telescopes: Coudé focus

- If astronomers want to use an equipment that cannot be conveniently mounted on the telescope (example: too large, or need a room with temperature control), the best is to use a coudé focus

- Disadvantage: large number of mirrors → some light is lost at each reflection



Birr Castle Great Telescope: The Leviathan

- Resolved the spiral arms of galaxies for the first time.
- Earl of Rosse named nebula "The Whirlpool Nebula". Later shown to be a galaxy (M51).

Drawing by Earl of Rosse

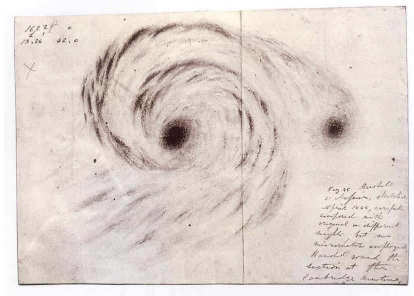


Image from Hubble Space Telescope

Conceptual question

Modern telescopes use mirrors rather than lenses for all of these reasons EXCEPT

(a) light passing through lenses can be absorbed or scattered.
(b) large lenses can be very heavy.
(c) large lenses are more difficult to make.
(d) mirrors can be computer controlled to improve resolution.
(e) reflecting telescopes aren't affected by the atmosphere as much.

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Explanation: Reflecting telescopes can be made larger, and more effective, than refractors.

Conceptual question

A telescope's sensitivity (light gathering power) is determined primarily by its

(a) objective diameter
(b) objective area
(c) magnification
(d) objective focal length

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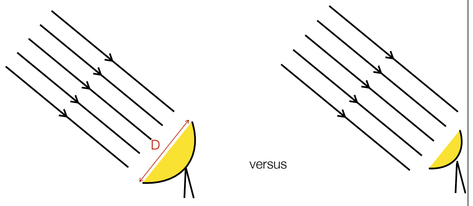

$$A = \pi \left(\frac{D}{2}\right)^2$$

Conceptual question

A telescope's spatial resolution is determined primarily by its

(a) objective diameter
(b) objective area
(c) magnification
(d) objective focal length

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