Summary Notes - Topic 3: The Earth-Moon-Sun System

3.1 & 3.2 Relative Sizes and Distances

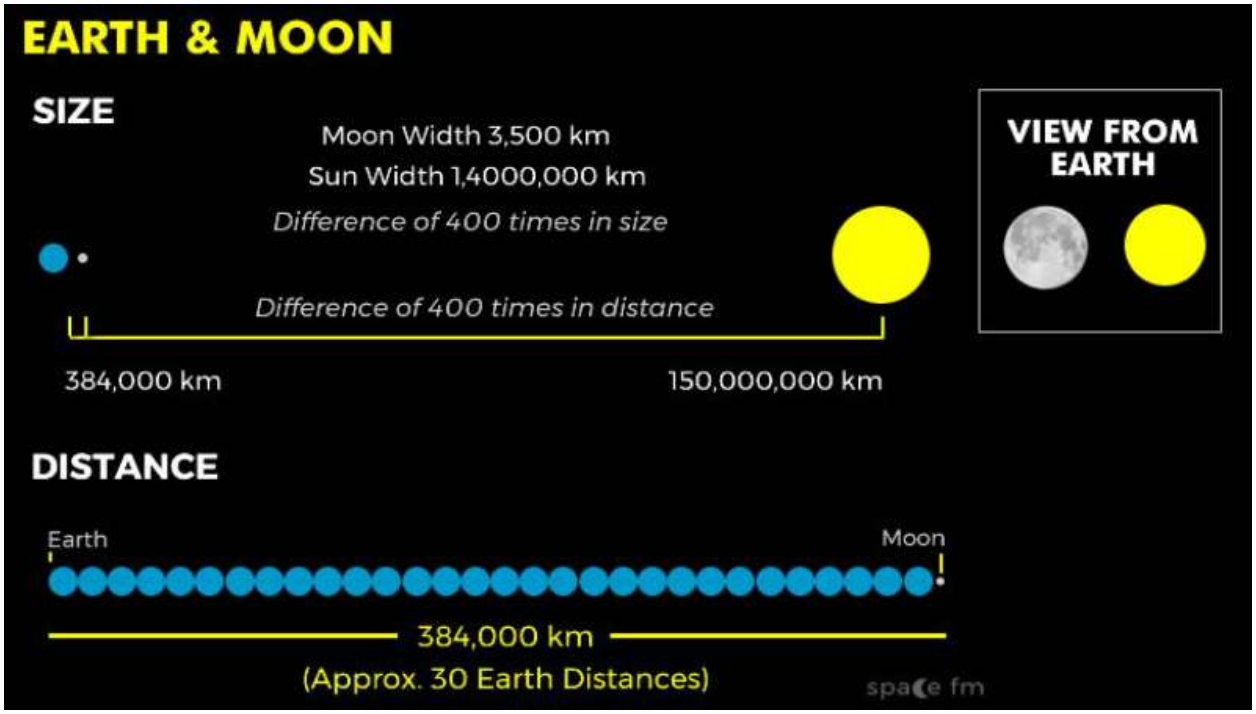
- **Earth's diameter**: ~12,742 km
- **Moon's diameter**: ~3,500 km (~27% of Earth's diameter)
- **Sun's diameter**: ~1.4 × 10^6 km (~109 times Earth's diameter)
- **Earth-Moon distance**: ~384,400 km (~30 Earth diameters)
- **Earth-Sun distance**: ~1 AU (~150 million km)

The Sun is approximately 400 times further away from us than the Moon.

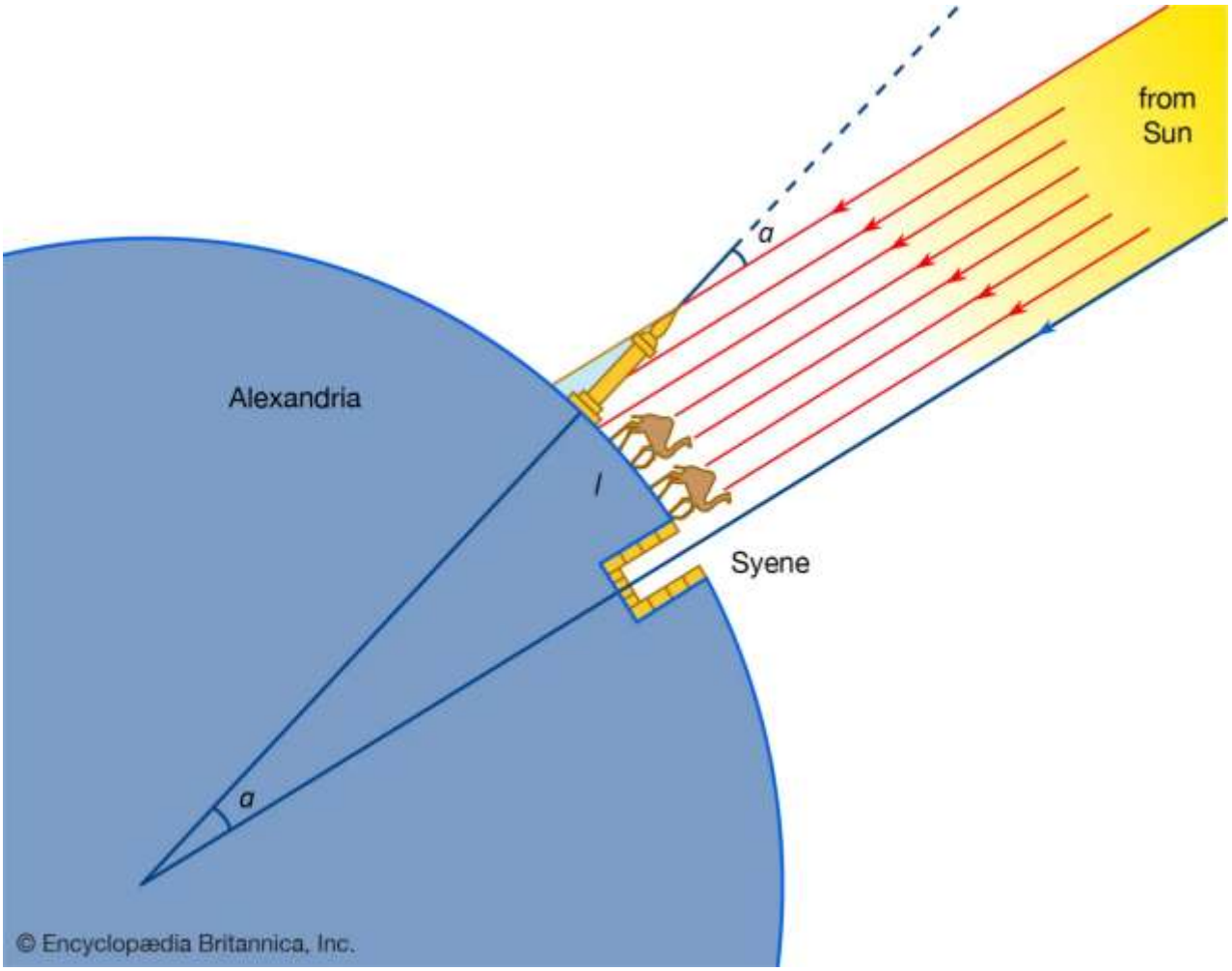
The Moon is 400 times smaller than the Sun.

Because of this, the Sun and Moon appear to look the same size in the Sky.

We can see eclipses of both bodies from Earth. The Sun and Moon are responsible for tides on Earth. Understanding how big and how far away each is from us has been measured over thousands of years.



3.3 Eratosthenes and Aristarchus' Calculations



Eratosthenes (Earth's Size Calculation 3.3a)

Syene (modern Aswan, southern Egypt)

- Close to the Tropic of Cancer.
- On the **summer solstice (21st June)**, the **Sun is directly overhead**.
- Objects cast **no shadow**.
- The Sun's reflection could be seen at the **bottom of deep wells**.

Alexandria (northern Egypt)

- Greek astronomer **Eratosthenes** lived there.
- At noon on midsummer's day, a stick in the ground cast a **7.2° shadow**.
- This showed that the Sun was **not directly overhead** in Alexandria.

Explanation

- Sun is so far away that its rays reach Earth as **parallel lines**.
- The difference between Syene and Alexandria could only be explained if the **Earth's surface is curved**.

Calculating Earth's circumference

- The angular difference between Syene and Alexandria = **7.2°**.
- This is **1/50th of a full circle**
- Therefore, the distance between the two cities represents **1/50th of Earth's circumference**.

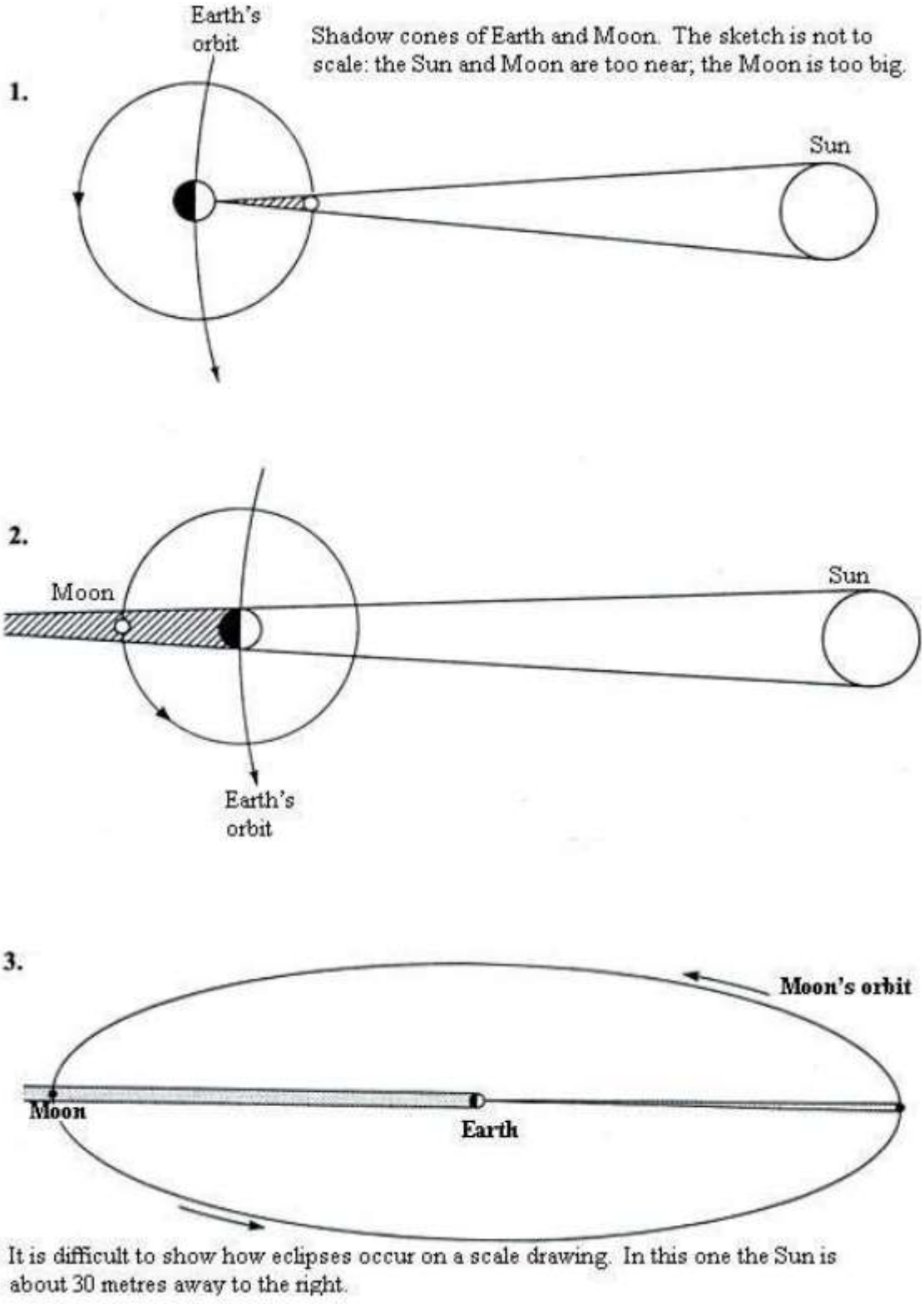
Distance used

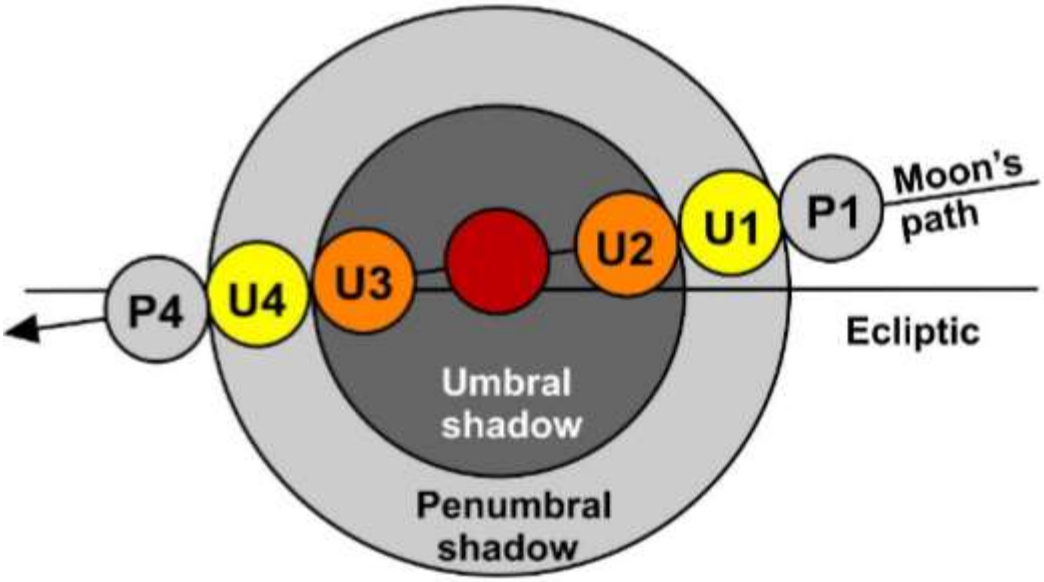
- Eratosthenes estimated Alexandria–Syene = **5000 stadia**.
- Circumference = **50 × 5000 stadia = 250,000 stadia**.

Conversion to modern units

- The length of a stadium varied in ancient times.
- If 1 stadium = **185 m**, then:
    - 250,000 stadia = **46,250 km**.
- Modern accepted value = **40,075 km**.
- His result was within about **6000 km of the true value** of 40,075 km — remarkably accurate for over 2000 years ago!

Aristarchus (Moon's Size Calculation 3.3b)





Observation

- He studied a lunar eclipse (diagram 2).
- He noticed that the Moon takes several hours to pass through the Earth's shadow (umbra).
- This showed that the Moon is smaller than the Earth, if we assume the umbral shadow has roughly the same diameter as the Earth (a reasonable assumption visible when diagrams are drawn to scale – see diagram 3).

Method

- He compared two times:
    - Time for the Moon to move into Earth's shadow (U1 first contact to U2 second contact) gives an estimate of the Moon's diameter.
    - Time for the Moon to cross the full shadow (U1 first contact to U3 second contact) gives an estimate of Earth's diameter.
- By comparing these times, he could estimate the relative sizes of the Earth and Moon.

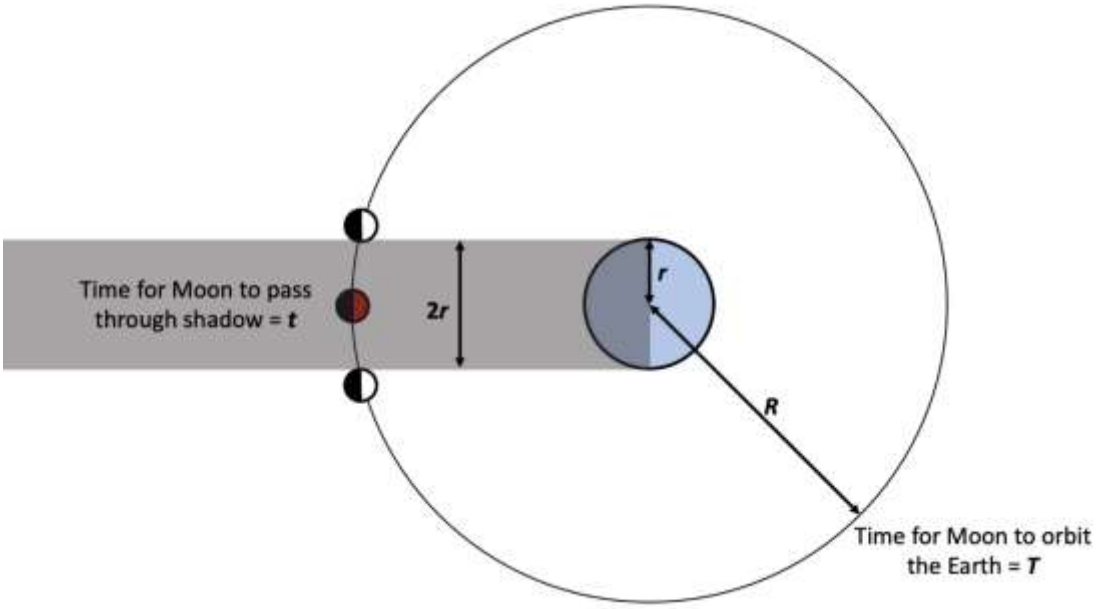
Result

- He estimated that the Moon's diameter was about 2½ times smaller than Earth's diameter.
- In other words, the Moon's diameter ≈ 40% of Earth's diameter (quite close to the modern value of ~27%)

Aristarchus (Moon's Distance Calculation 3.3c)

Assumptions at the time

- The Earth was believed to be at the centre of the Universe (geocentric model).
- The Moon was assumed to move in a circular orbit around the Earth.
- The radius of the Earth's shadow is the same as the Earth's radius.



Setting up the problem

- Let R = radius of the Moon's orbit.
- Let T = time taken for the Moon to orbit Earth once (~1 month).
- In one orbit, the Moon covers a distance of $2\pi R$.

During a lunar eclipse

- The Moon passes through Earth's shadow when opposite the Sun (when we are seeing a full moon)
- The width of the Earth's shadow $\approx 2r$, where r = Earth's radius.
- Let t = time taken for the Moon to cross Earth's shadow (~3 hours in the longest eclipses).

Constant speed assumption

- The Moon moves at a steady speed around Earth.
- Speed of Moon = Distance ÷ Time, so: $(2\pi R / T) = (2r / t)$.

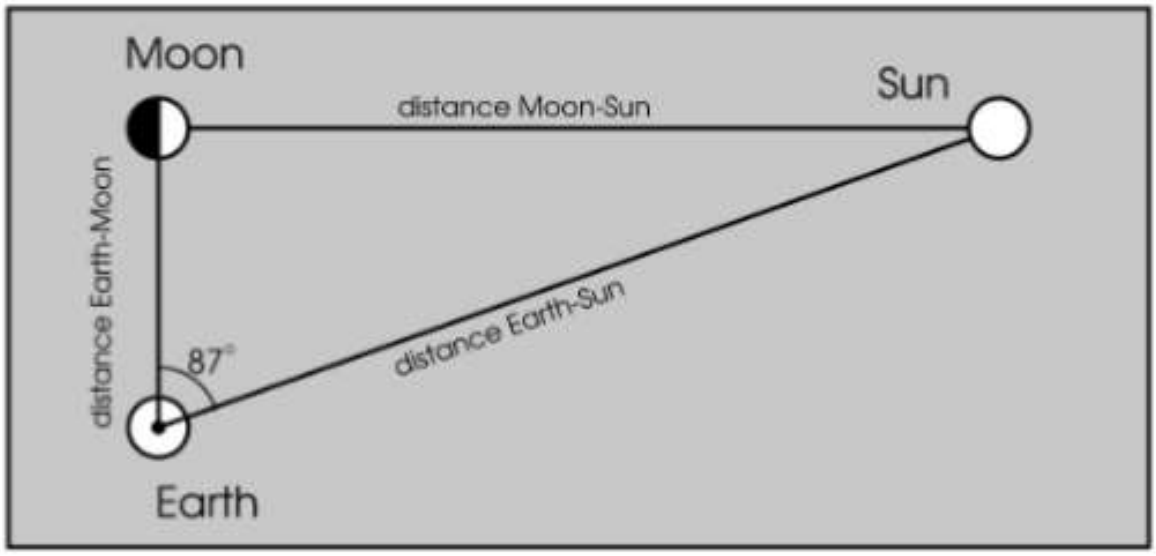
Simplified ratio

- Rearranging gives: $(\pi R / r) \approx (T / t)$.
- Substituting values gave $R/r \approx 60$.

Result

- Aristarchus concluded the Moon is about 60 Earth radii away. Modern value: the average Earth–Moon distance = 60.3 Earth radii (remarkably accurate!).

Aristarchus (Sun's Distance Calculation 3.3d)



Observation of the Moon

- Aristarchus looked at the Moon when it was exactly half illuminated (a first or last quarter Moon).
- At this moment, the Earth, Moon and Sun form a right-angled triangle.

Method

- He measured the angle between the Sun and Moon from Earth at this time.
- If the Moon is exactly half lit, then the angle between Earth–Moon and Earth–Sun lines should be slightly less than 90° (Aristarchus estimated 87, but in reality it is 89.8°)
- Using geometry (as this method preceded our modern trigonometry), he could calculate the relative distances to the Sun and Moon.

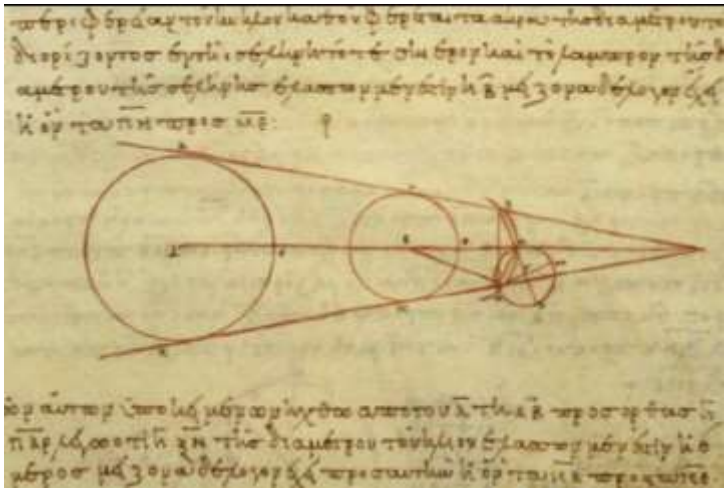
Result

- Aristarchus estimated that the Sun was about 19 times further away than the Moon.
- This was an underestimate, because the angle is very difficult to measure accurately with the naked eye.
- Modern value: the Sun is about 400 times further away than the Moon.

Importance

- Even though his result was wrong, Aristarchus was the first known astronomer to attempt a geometric calculation of the Sun's distance.
- He also suggested that the Sun, not Earth, was at the centre of the Solar System (a heliocentric idea that was ignored until Copernicus, ~1800 years later).

Aristarchus (Sun's Diameter Calculation 3.3e)



Background

- After estimating the distance to the Sun, Aristarchus also attempted to calculate its diameter.
- He compared the apparent angular sizes of the Sun and Moon.

Key idea

- The Sun and Moon appear to be about the same size in the sky (~0.5°).
- If two objects appear the same size but are at different distances, the further one must be physically larger.

Method

- Aristarchus already had an (underestimated) value for the Sun's distance compared to the Moon.
- He reasoned:
    - Apparent diameter of Moon ≈ apparent diameter of Sun.
    - Therefore, the ratio of their true diameters = ratio of their distances.

Calculation

- He believed the Sun was about 19 times further away than the Moon.
- So, he concluded the Sun's diameter was about 19 times the Moon's diameter.
- Since the Moon's diameter had been estimated as about ⅓ of Earth's diameter, he calculated:
    - Sun's diameter ≈ 6–7 times Earth's diameter.

Modern value

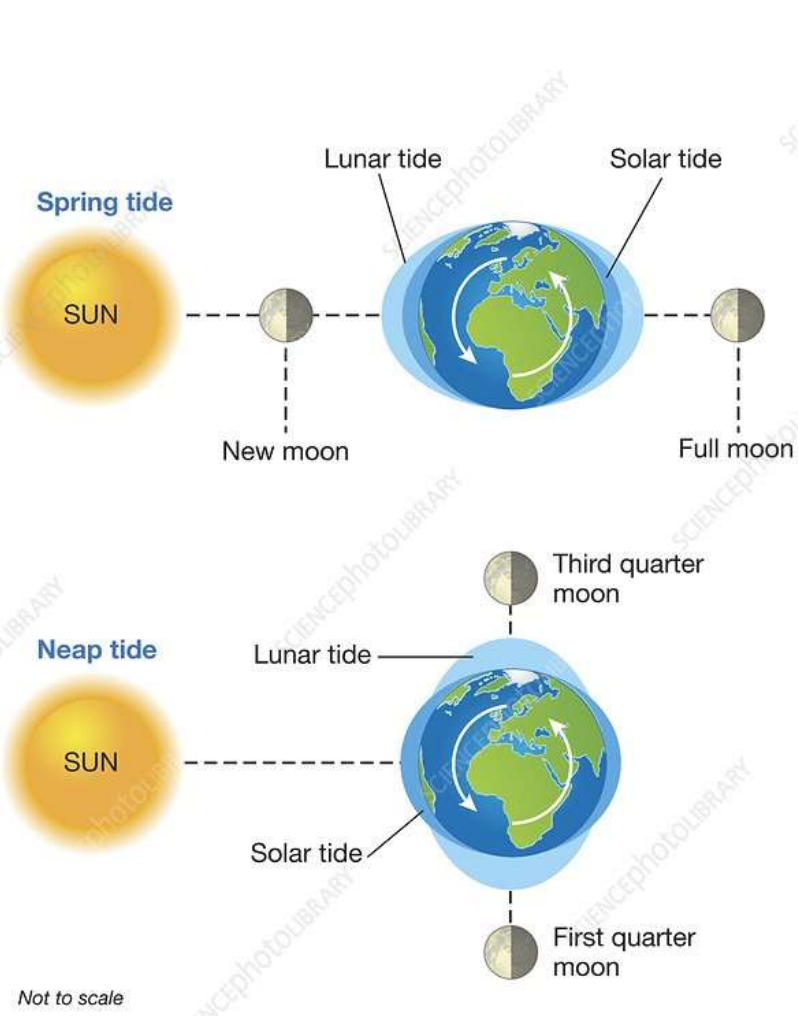
- Actual ratio: the Sun is about 400 times further away than the Moon, and about 109 times wider than Earth.
- Aristarchus underestimated the Sun's size, but his method was logical and pioneering.

3.4 The Sun’s Diameter

- The Sun’s mean diameter is **1.4×10^6 km**.
- Modern methods of measurement including measurement of angular diameter and radar location using the inner planets to find the distance to the Sun.

3.5 Tidal Effects of the Sun and Moon

- **Moon’s gravity**: Primary cause of tides.
- **Sun’s gravity**: Secondary influence on tides.
- **Spring tides**: Occur when the Sun, Moon, and Earth align (new/full Moon) – higher high tides.
- **Neap tides**: Occur when the Sun and Moon are at right angles – lower high tides.



Type	Feature	Timing
Spring Tides	Higher HIGH tides Lower LOW tides	Full & New
Neap Tides	Lower HIGH tides Higher LOW tides	First & Third Quarters

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3.6 & 3.7 Precession of Earth's Axis

What It Is

- The Earth spins on its axis but the axis itself wobbles like a spinning top.
- This wobble takes about 26,000 years to complete one cycle.
- It slowly changes the direction in which Earth's axis points in space.

Main Cause

- The Earth is not a perfect sphere – it is slightly wider at the equator.
- The complex gravitational pull of the Sun and the Moon acts on this bulge.
- This pull gradually shifts Earth's axis, producing the wobble.

Discovery

- In the 2nd century BC, the Greek astronomer Hipparchus noticed that some stars were not in the same position as earlier records showed.
- He realised this was because the point of the equinox was drifting slowly backwards over time.
- Later, Isaac Newton explained the cause: the Sun and Moon pulling on Earth's equatorial bulge.

Celestial Poles

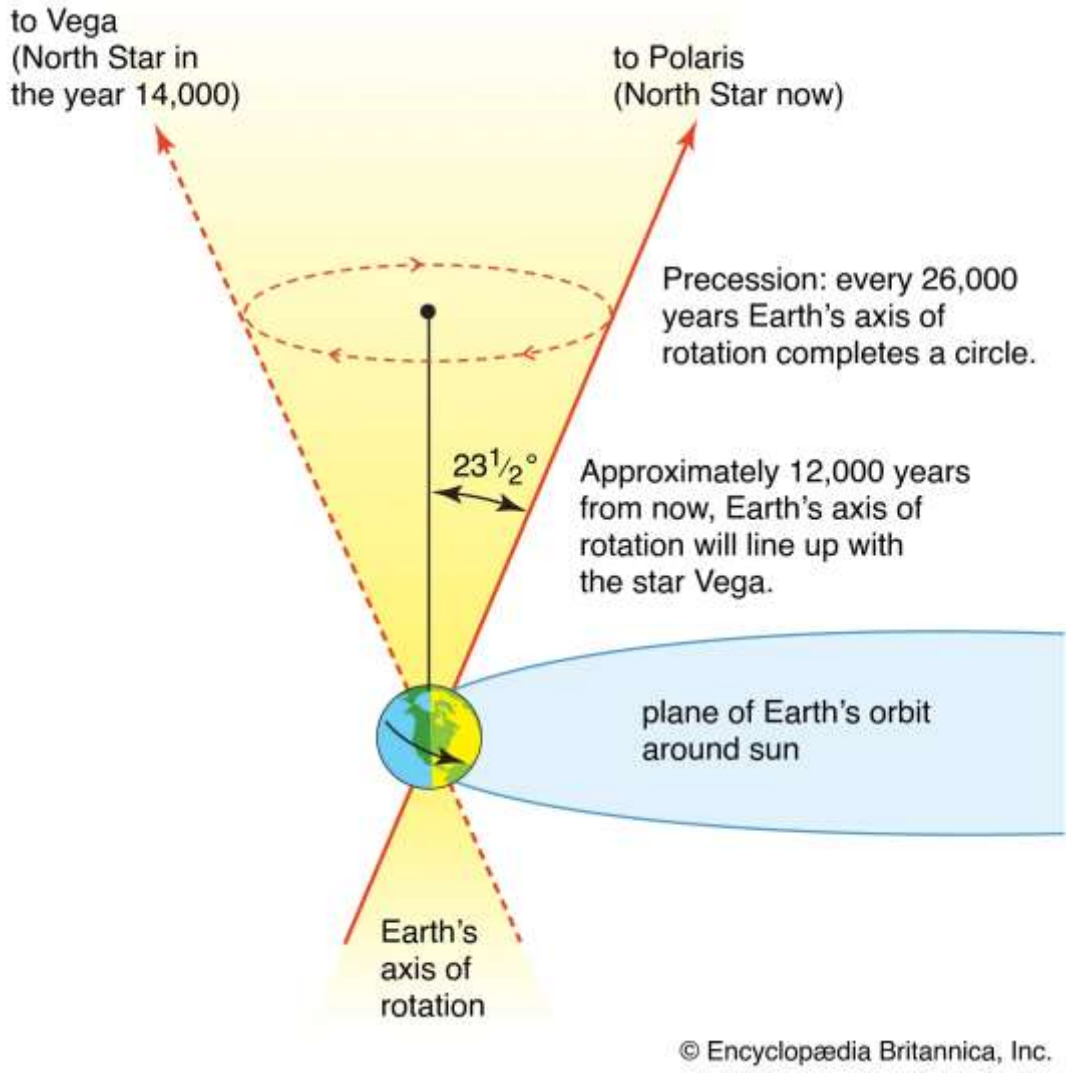
- The North Celestial Pole does not always point to the same star.
- Now: it points close to Polaris.
- In the past: it pointed near Thuban (a star in Draco).
- In the future: it will point near Vega (in about 14,000 years).
- The South Celestial Pole does not currently have a bright star nearby.

Effects on Observing
Over thousands of years:

- The position of the celestial poles changes.
- The stars that are circumpolar (always visible from a location) also change.
- The stars visible in each season shift very slowly.
- Ancient monuments aligned to certain stars or the rising Sun no longer line up exactly today.

Key idea to remember

- Axial precession is a 26,000-year wobble of Earth's axis, caused by the Sun and Moon pulling on Earth's equatorial bulge. It changes which star is the Pole Star and alters the stars visible in different seasons over long timescales.



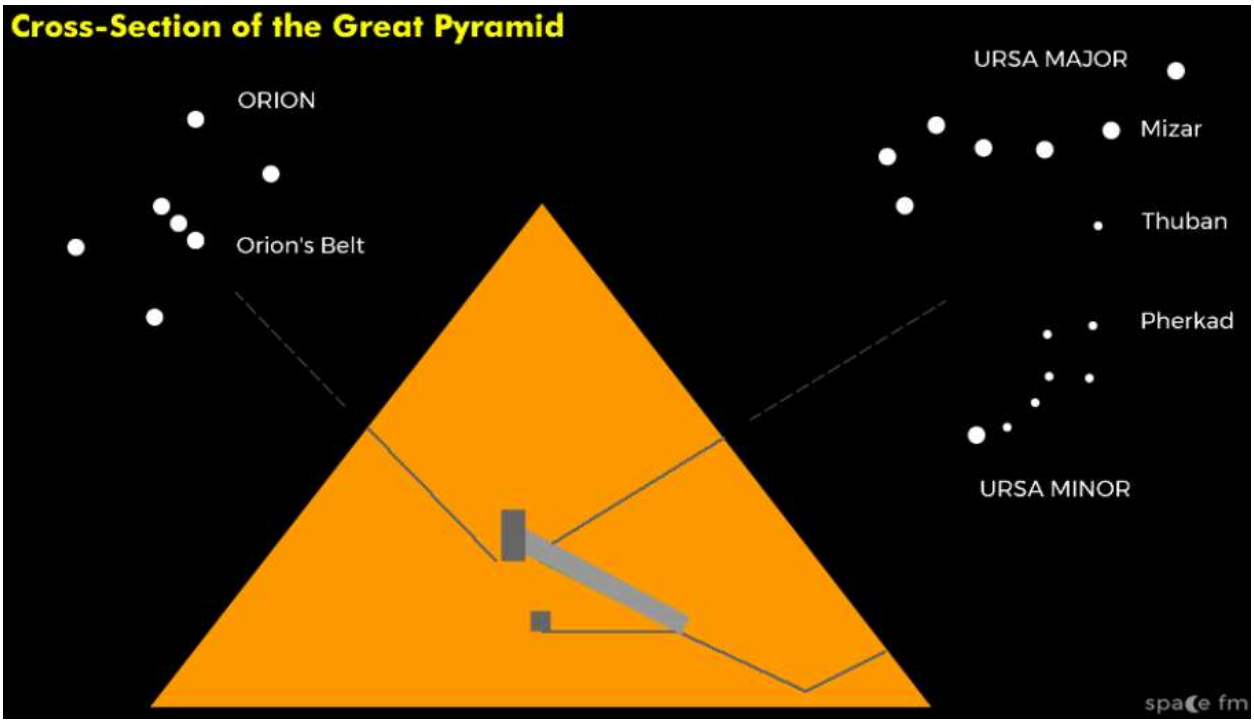
3.6 & 3.7 Archeoastronomy

Studying precession is important for archeoastronomy

- Archeoastronomy is the study of how ancient people built monuments to make astronomical observations.
- Precession changes the appearance of the Sun, Moon and stars over thousands of years.
- This means ancient alignments of monuments no longer match exactly with the sky today.
- Over thousands of years:
    - The position of the celestial poles changes.
    - The stars that are circumpolar (always visible from a location) also change.
    - The stars visible in each season shift very slowly.
    - Ancient monuments aligned to certain stars or the rising Sun no longer line up exactly today.

Egyptian Pyramids

- Ancient Egyptians gave special importance to circumpolar stars, which never set below the horizon.
- They were linked with heaven and the afterlife.
- Small shafts inside the pyramids were aligned so that the Pharaoh's spirit could travel to the afterlife.
- One shaft pointed towards Orion's path of rotation.
- Another pointed towards Thuban, which was the North Pole Star at that time (not Polaris).



Newgrange (Ireland)

- Built around 5,000 years ago as a burial mound with a long passage.
- On the winter solstice, sunlight shines into the passage.
- Today, sunlight enters about four minutes after sunrise, but when it was built it aligned exactly with sunrise.
- This change is due to precession.

Newgrange is a 5,200 year old passage tomb located in the Boyne Valley in Ireland's Ancient East

Effects of Precession

- The position of the celestial pole star has changed.
- Thuban was once the North Pole Star, now it is Polaris, and in about 14,000 years Vega will be the bright Pole Star.
- At Newgrange, the Sun still rises on the solstice, but at a slightly different direction and later time than when it was first built.

Key idea to remember

- Precession causes the sky to change slowly over thousands of years. Monuments built by ancient cultures that were aligned to the Sun, Moon or stars no longer line up exactly with the sky as they once did.

3.8 - 3.10 Solar and Lunar Eclipses

Solar Eclipses

- A solar eclipse only takes place during a new Moon when the Moon is on the side of the Earth nearest the Sun.
- They happen because the Moon's disc totally covers the disc of the Sun.
- The Sun is about 400 times further away than the Moon but also 400 times larger, so they appear the same size in the sky.
- Total solar eclipses can last a maximum of 7 minutes 30 seconds because of the Moon’s motion, Earth’s rotation, and the size of the Moon’s shadow.
- The eclipse begins at sunrise somewhere on Earth and ends at sunset somewhere else.
- Totality happens only along a narrow path called the 'line of totality'.
- Observers outside this path see only a partial eclipse.

Total Solar Eclipse
Best explained through stages called contact points, assuming the observer is on the line of totality.

- **First Contact**
  - The penumbra reaches the observer's location, producing a partial eclipse.
  - The Moon's edge (limb) begins to move in front of the Sun.
  - A small black arc appears on the Sun's disc.
  - Before first contact the sky darkens, the temperature drops, and unusual effects may occur (shadow bands, animals reacting as if it were night).

- **Second Contact**
  - The last rays of sunlight shine through lunar craters, creating the diamond ring effect known as Baily's beads.
  - The umbra reaches the observer's location and totality begins.
  - The sky becomes dark, stars and planets become visible.
  - The Sun's corona can be seen, along with prominences.

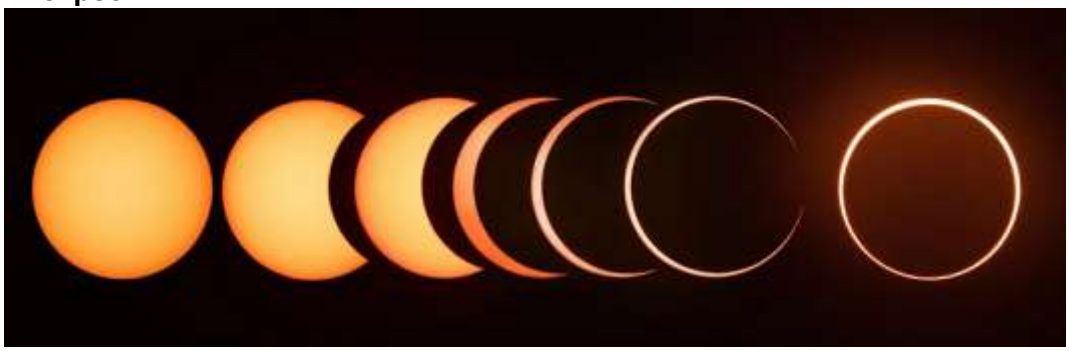
- **Third Contact**
  - The Moon begins to move away, revealing the Sun's disc.
  - Baily's beads are seen again but the corona disappears.
  - The umbra continues along the line of totality.

- **Fourth Contact**
  - The Moon completely leaves the Sun's disc.
  - The penumbra moves away and the eclipse ends.

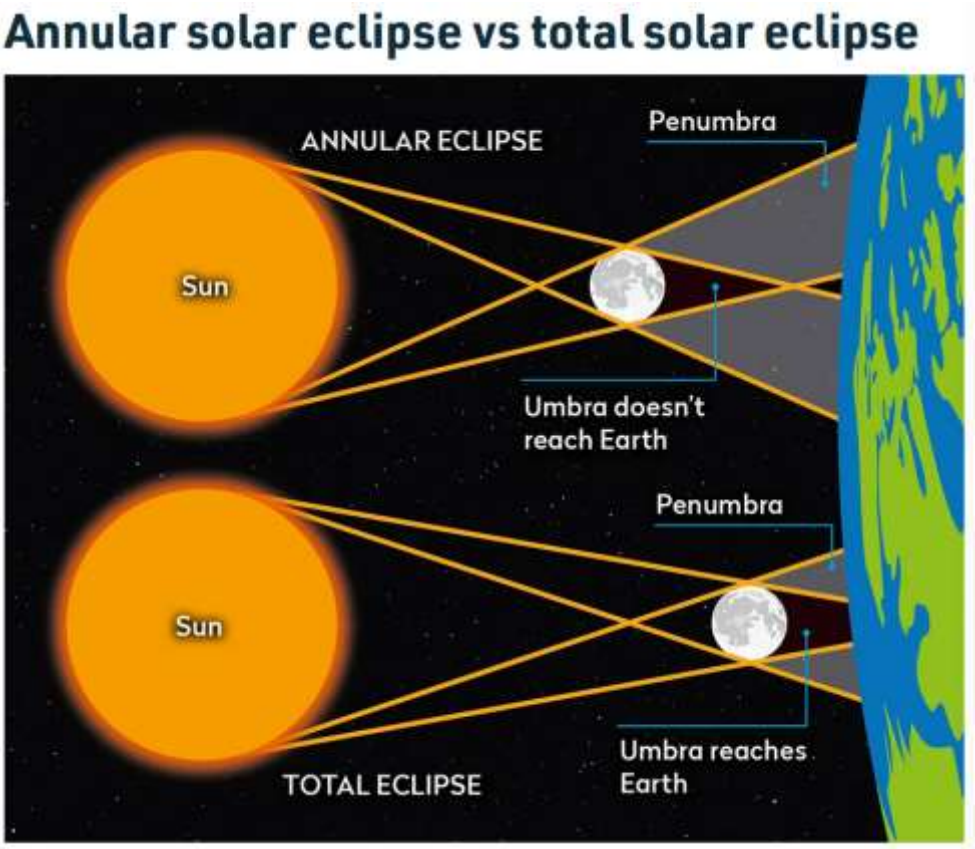
Partial Eclipse

- Occurs when the Moon covers only part of the Sun's disc. The distance between the Moon and the Earth varies as the Moon's orbit is elliptical.
- Only two contacts: when the Moon starts and ends its path across the Sun.

Annular Eclipse



- Called 'annular' from Latin 'annulus' meaning ring.
- The Moon is farther from Earth (at apogee) and appears too small to cover the Sun completely.
- The result is a bright ring of sunlight, sometimes called a 'ring of fire'.
- The corona and prominences cannot be seen clearly.



Hybrid Eclipse

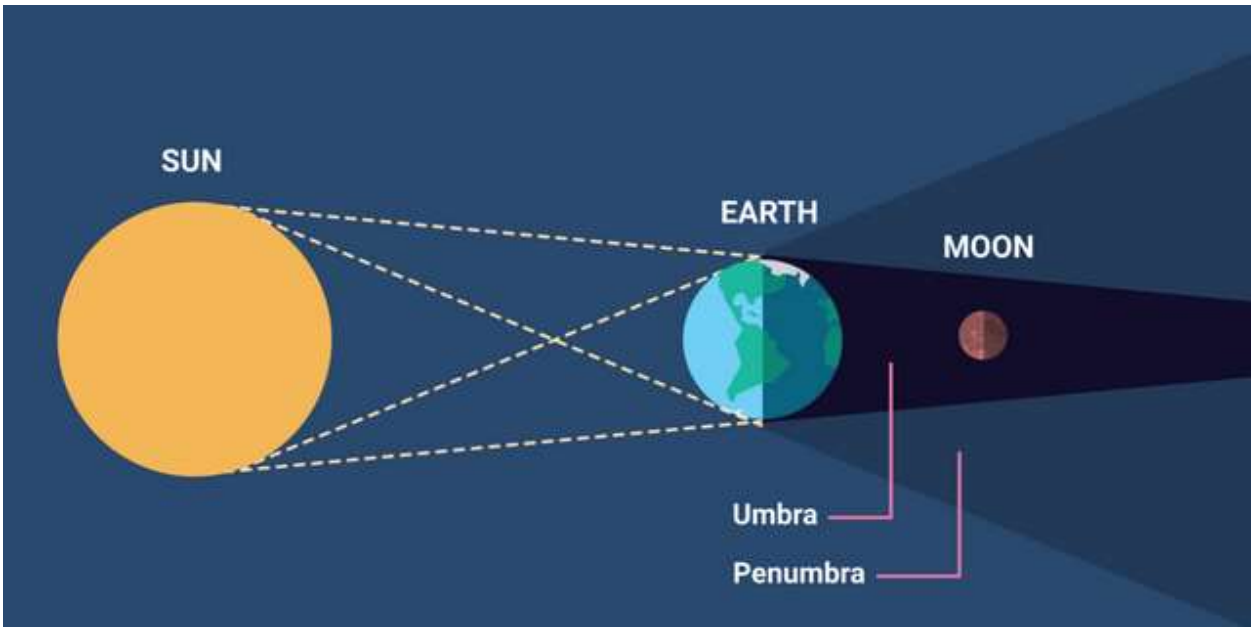
- A rare type that is annular in some places along the line of totality and total in others.
- Caused by Earth's curvature and the changing distance of the Moon's shadow.
- At some locations (usually near noon) it is total, but at sunrise and sunset it may appear annular.

Lunar Eclipses

Key Facts

- A lunar eclipse happens when the Moon enters the Earth's shadow.
- They only occur during a full Moon when the Moon is opposite the Sun.
- From first to last contact, a lunar eclipse can last several hours.
- Totality can last up to 1 hour 42 minutes – longer than a solar eclipse because Earth is larger than the Moon.
- Unlike solar eclipses, totality can be seen by most observers on the night side of Earth, not just along a narrow path.

Total Lunar Eclipse Stages



- First Contact – The Moon enters Earth's penumbra. It may appear darker or greyer.
- Second Contact – The Moon moves into Earth's umbra. Red light refracts through Earth's atmosphere and colours the Moon red, copper, orange, or burgundy.
- Third Contact – The Moon begins moving out of the Earth's umbra.
- Fourth Contact – The Moon leaves the penumbra.

Partial Lunar Eclipse

- Happens when Earth's shadow covers only part of the Moon.
- Sometimes occurs alongside total lunar eclipses, appearing partial to some observers depending on the time of moonrise or moonset.

Solar vs Lunar Diagrams