Summary Notes - Topic 7: Early Models of the Solar System

The Importance of Solar and Lunar Cycles in Ancient Civilisations

We have records of the cycles of the Sun, Moon and stars used by our ancestors found throughout the world. Evidence exists of early cave paintings, calendar devices and stone monuments.
For many, the cycles of the heavens would give some stability to their lives and inform important decisions and tracking measures:

Time and Calendar systems

- Early civilisations used the movements of the Sun and Moon to create calendars.
- The **Babylonians** developed a **lunar calendar**, dividing the year into 12 months based on the Moon's cycle.
- Greek, Indian and Persian astronomers have left us names and constellations that we still use today.
- Different cultures used different calendars and time keeping systems until Julius Caesar reformed it and spread the Julian calendar through the Roman Empire.
- The modern **Gregorian calendar**, which we use today, is based on the **solar year (365.25 days).**

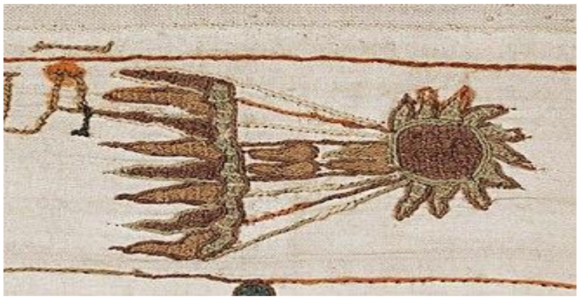
Agriculture

- Knowing the time of year was important as farmers needed to know when the best time was to plant and harvest crops as well as breeding timescales for animals. In Egypt knowing when Sirius first rose in the sky would coincide with when the Nile would annually flood. The **Mayan** civilisation used lunar cycles to predict rainfall patterns.

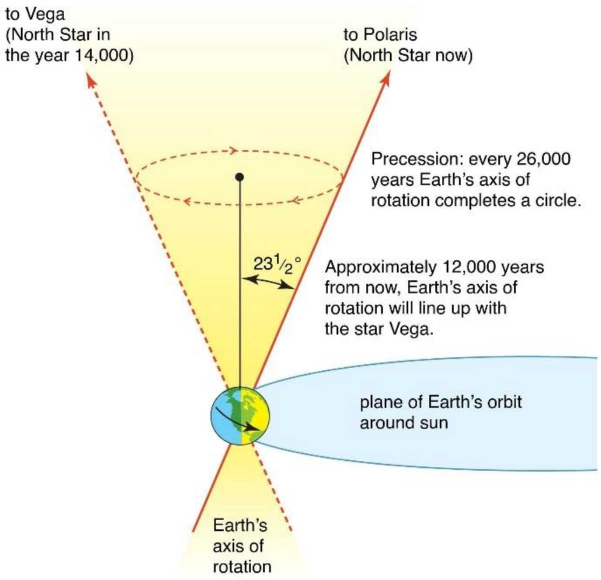
Religious Systems

- Our ancients would have known stories told in their communities about constellations. Some cultures have a history of worshipping Sun or Moon gods. Times of year connected with celestial events such as solstices and equinoxes would be celebrated. As new religions such as Christianity developed these carried on as religious festivals amount the Spring Equinox and Winter Solstice. Judaism and Islam both use lunar calendars to set important religious dates.

- Myths and superstitions would arise so that if a comet was seen this would be a dramatic change in the normally unchanging sky and was thought to herald change. Solar eclipses were feared as the Sun would be blocked by some unseen force. Lunar eclipses would turn the Moon blood red, a sign of the "Witching". Many believe that the appearance of Comet Negra in 1347 rained poisonous gas which brought with it the 'Black Plague'.



7.2 Precession and Changes in Celestial Alignment



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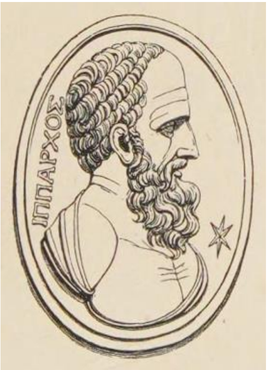
- The Earth's axis **wobbles** in a slow motion known as **precession**.
- This causes the position of stars and constellations to shift over thousands of years.
- The Earth rotates on its axis but has a slight 'wobble' or 'oscillation' to be precise like a spinning top. This wobble takes approximately 26,000 years and has implications for how we view and measure the stars over a (very) long period.
- The process is known as precession of the equinoxes or axial precession.

Main Causes

- Earth is not a perfect sphere and is an **oblate spheroid** (slightly wider at the equator). The Sun and Moon have a gravitational influence on Earth and this combined with the Earth's bulge causes a wobble in the Earth's tilt.

Discovery



● Hipparchus in the 2nd century BC realised that some stars were not where they were meant to be. By studying records from past astronomers, he realised that there was a difference between the time it takes for the sun to return to a star (sidereal year) and then time it takes to return to the same place on an equinox (tropical year).The point of the equinox was therefore moving backwards.

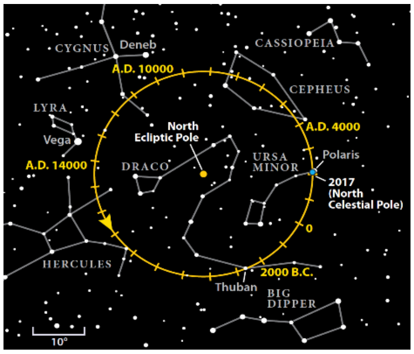
● Isaac Newton later understood that Earth was not a classical sphere and had an equatorial bulge. He understood the Sun and Moon are pulling on the Earth particularly the bulge and this distorts its axial movement.

What it means

- Measurements of a star's longitude are taken from the point where the sun appears to cross the celestial equator at the vernal equinox (spring in the northern hemisphere).
- What happens is that there is a slight shift every year and the point moves westwards. Star positions are republished every 50 years in star catalogues to take this into account.

Celestial Pole Location

- We know Polaris marks the North Celestial Pole although it was not always so.
- Thuban was the nearest pole star thousands of years ago.
- Vega will be the brightest equivalent to Polaris in 14,000 years time.

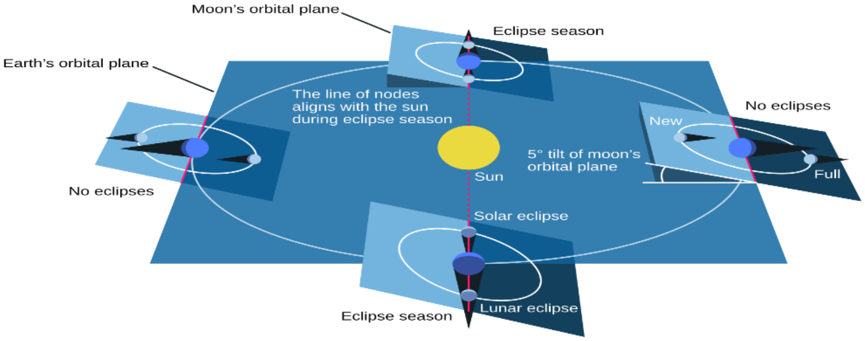


Seeing Procession

- The effects over the course of a precession cycle on observing is that the celestial poles move and all stars therefore shift ever so slightly from one year to the next. This is only noticeable to the casual naked eye observer over millennia.
- If this were possible, we would see that the area of stars from their location that were circumpolar on one date would be different in many years afterwards. And we would see a different range of seasonal stars.
- Fixed monuments (more on this later) aligned to celestial markers will show deviation.

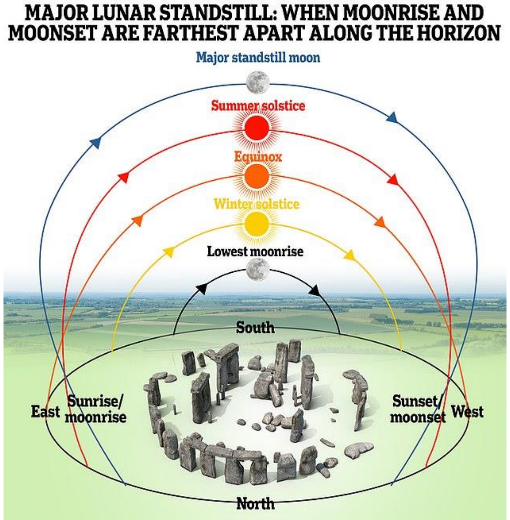
Other Causes and Effects

- There are other factors that astronomers have to take into account when studying precession:
  - The Earth has an elliptical orbit
  - The Moon has its own precession
  - The Moon has an orbit around Earth at a different degree of inclination to the ecliptic (~5 °)
  - Other planets have precession of their own to some degree and their own elliptical orbits which have an effect on the ecliptic itself
  - The Earth's tilt varies from 22.1 to 24.5° every 41,000 years. (Primarily due to gravitational effects from other planets, especially Jupiter and Saturn)

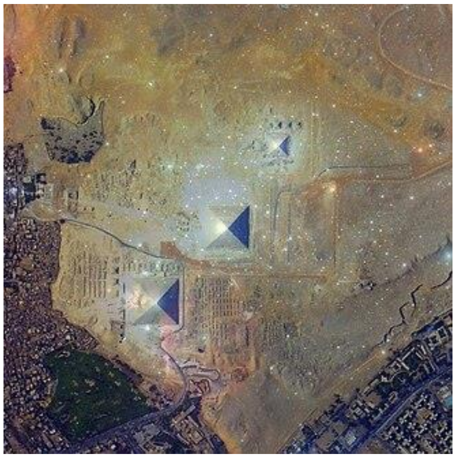


The combined mechanisms behind precession are complex, we only need to know that it happens. If you do further research you will find some of these listed as lunisolar precession, planetary precession and precession of the ecliptic. There are also two other factors regarding Earth's tilt called nutation and polar motion. You can find out about these too. ***Note: When researching take care as many articles are concerned with astrology and not necessarily astronomically accurate.***

7.1 Alignment of Ancient Monuments



- Some cultures erected permanent monuments to assist their observations. Numerous erections acted as astronomical devices. The Aztecs worshipped the Sun god Huitzilopochtli, and their temples were aligned with solar movements.
- Stonehenge is aligned to the summer solstice sunrise and winter solstice sunset.
- The Mayan Temple of Kukulkan at Chichen Itza creates a shadow in the shape of a snake during the equinox.
- Newgrange in Ireland was designed along a long underground passage. Light enters the passage on the winter solstice. Light enters the passage four minutes after sunrise on the winter solstice.



- Circumpolar Stars had a special place in the ancient Egyptian culture as the stars were always in the sky and was a place of heaven and the afterlife. Small shafts ran through the pyramid from the resting place of the Pharoah inside so, it is believed, his spirit could go to the afterlife.
- One shaft would point to the rotation path of Orion. The other shaft pointed to Thuban, the celestial north pole star. (not Polaris)
- The subject of Archeoastronomy is fascinating and it is definitely worth your time to research how our ancestors viewed the heavens.

Note (again): When researching information about Stonehenge or the Pyramids try to view materials written by reputable historians or scientists as a lot on the internet (and a few books as well) is not always well meaning and the historical and scientific accuracy is not always prioritised.

Q.

Many ancient monuments were aligned with the rising and setting of the Sun and the Moon.

An ancient monument was built so that a star in constellation X aligned with two of the stones during the solstice, as shown in Figure 3.

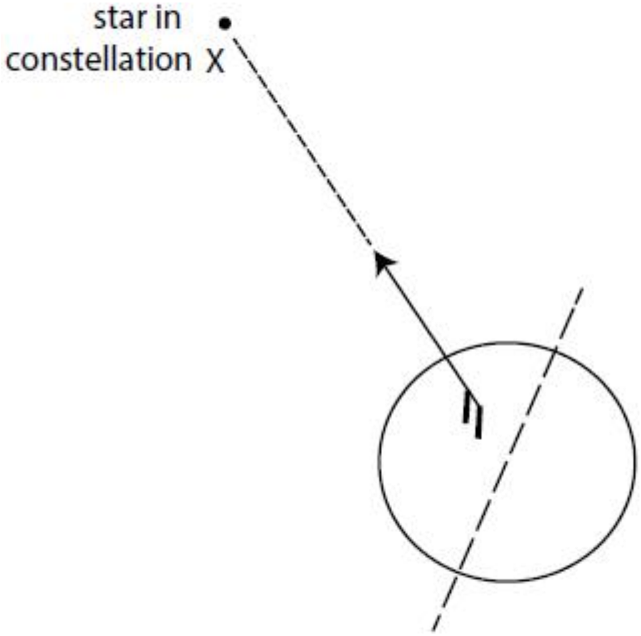


Figure 3

(i) These two stones are currently 35.4° from the star in constellation X.

Explain why precession would cause a star in constellation X to no longer be aligned with the stones during the solstice.

(2)

....

....

....

(ii) The average rate of precession is 1.38° per century.

Calculate an approximate date for the building of this ancient monument.

(2)

date ....

(iii) Today, Polaris is the pole star.

In the past, it was Thuban.
In the future, it will be Alderamin.
Explain why precession causes variation in pole stars.

(3)

....

....

....

....

....

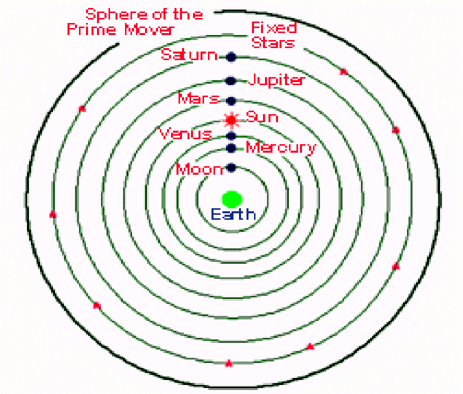
....

(Total for question = 7 marks)

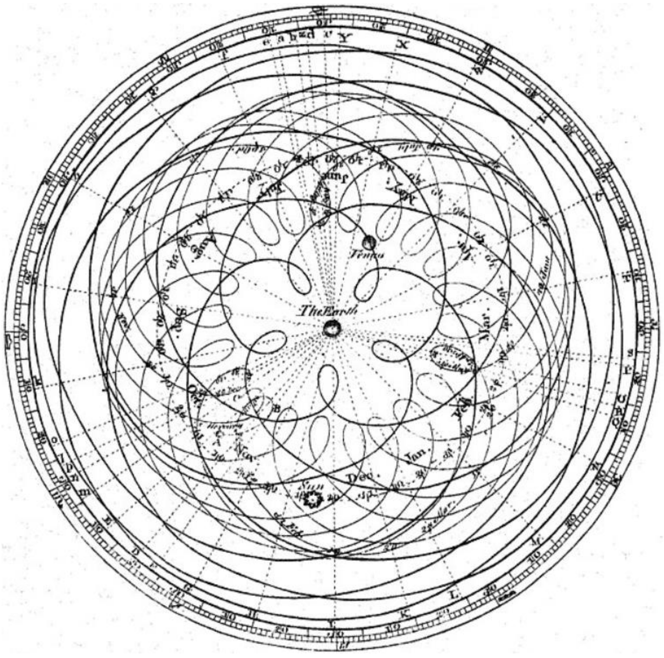
7.3 Early Models of the Solar System

- You already know as a fact that the Earth and all solar system bodies orbit the Sun but for centuries astronomers believed that the Sun and planets orbited the Earth.
- To us it looks natural. Celestial bodies appear to orbit us.
- Some ancient astronomers such as Aristarchus of Samos and Seleucus of Seleucia proposed that Earth orbits the Sun. No-one listened to them as the observational evidence did not support their argument.
    - If the Earth did spin then why don't we fly off it?
    - Why would birds be able to fly from one position to another without flying backwards?
    - Why did the stars not move from one half of a year to another?
- This was before any understanding of the forces of gravity and celestial motion.

- The pre-eminent model – proposed by Aristotle was the **GEOCENTRIC SOLAR SYSTEM**.
- Despite being the accepted idea for many years, some felt there was something not quite right about this model. The orbits of inner planets seemed very elaborate - see the apparent orbit of the inner bodies image. The outer planets sometimes seemed to wobble and move backwards. (we will come onto retrograde motion in a future session)



Aristotle's Universe



7.4 The Role of Epicycles in Ptolemy’s Model

- Ptolemy introduced **epicycles** to explain the unusual movements of planets.
- An epicycle is a **small circular orbit** that moves along a larger circular path (deferent).
- This helped explain some of the odd motions noted in Aristotle’s model (such as where planets appear to move backward for a short time).
- Even though the model was incorrect, it was accepted for over **1,400 years** with Ptolemy’s adjustments. It was the best fit for available observations.
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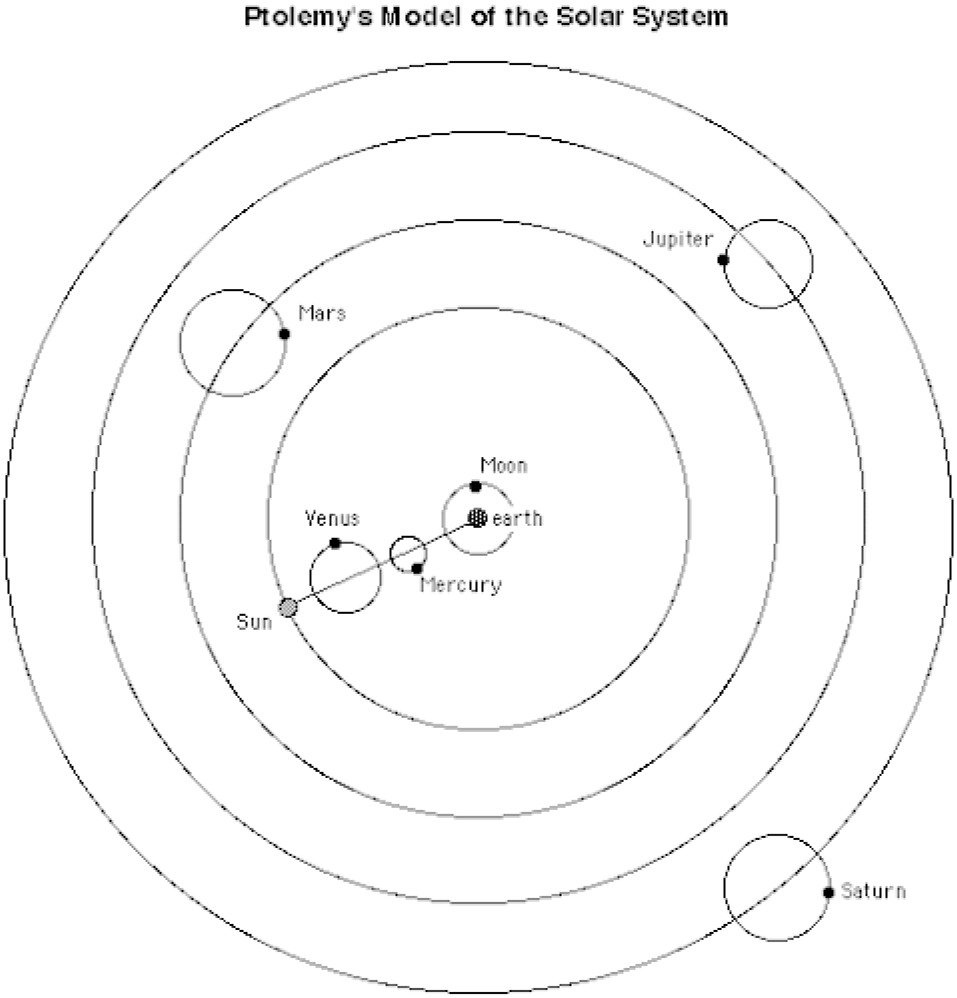


7.3 Early Models of the Solar System

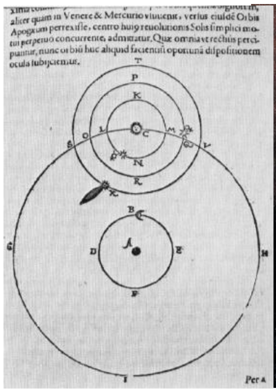
MOVEMENT TO HELIOCENTRIC THEORY

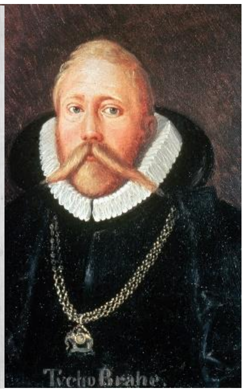
Copernicus

- Copernicus put forward a theory called the **HELIOCENTRIC** theory which put the Sun at the centre of the solar system.
- In 'Dē revolutionibus orbium coelestium' (On the revolutions of heavenly spheres) he claimed all bodies moved around the Sun (with the exception of the Moon orbiting Earth) and had circular orbits. Emerging mathematical observations of the movements of the planets supported this, especially the odd retrograde motion of outer planets.
- Authorities and the public were careful to accept it as it turned against perceived wisdom.
- There were verses in the Bible which mentioned the Sun's movement and the Earth's lack of movement and a challenge to them may not be popular.
- His book was published after his death and the idea spread among scientists including Brahe, Kepler and Galileo.

Tycho Brahe

- Tycho Brahe had issues with the Copernican model and proposed a Geo-Heliocentric Model where the Moon and Sun orbited Earth but everything else orbited the Sun.
- This system removed the epicycles of Ptolemy. He believed Earth was too 'lazy' a body to move and his arguments were both religious and based on observation.
- Brahe made thousands of naked eye observations over many years. He said that no movement or change in the stars was visible (indeed it would be difficult with the naked eye to measure any).





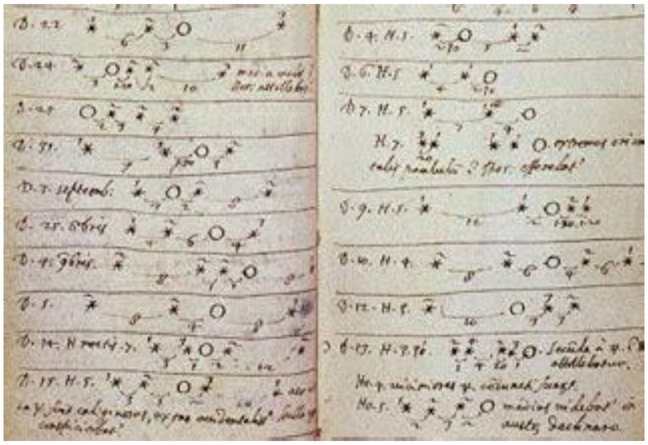
Kepler

- Kepler was Tycho Brahe's assistant in Prague. Despite this he was influenced by Copernicus's writings.
- He refined the heliocentric theory.
- Armed with Tycho's observations he noticed planets did not follow circular orbits but were elliptical (much more on Kepler in Topic 8)

Galileo

- Copernicus and Kepler's ideas were all well and good but even with Brahe’s recordings, there was nowhere near enough observational evidence to force a change in the scientific community.
- Galileo was the first telescopic observer to make **published astronomical observations**. He found two discoveries to provide evidence to support the heliocentric theory including:

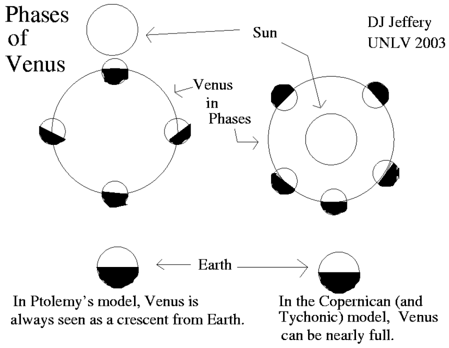
Jupiter had moons



- The discovery of celestial bodies orbiting something other than Earth dealt a serious blow to the then-accepted geocentric model.
- How could these bodies obviously orbit Jupiter?

Venus had phases (see Topic 5)

- How could this occur if it orbited Earth rather than the Sun?
- In geocentric model, Venus would only show new and crescent phases. This is because, in this model, Venus is always positioned between the Earth and the Sun, meaning it would never be seen as half-lit or full from Earth's perspective.
- Galileo’s observations challenged this.



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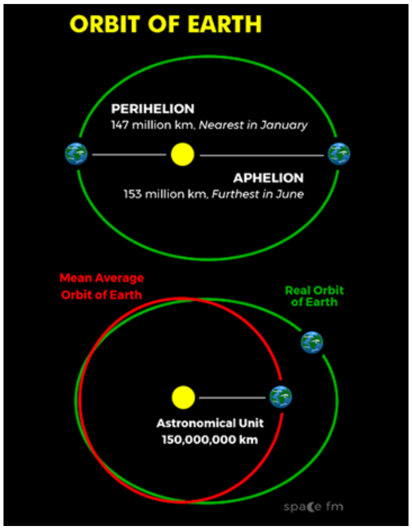
In Ptolemy’s model, Venus is always seen as a crescent from Earth.

In the Copernican (and Tychonic) model, Venus can be nearly full.

- His publications meant he got into trouble with the Church at the time but his work ensured the heliocentric became widely accepted after. By the time of Isaac Newton the theory was accepted as the correct model of the solar system.

7.6 Really Big Distances….



The Astronomical Unit (AU)

- Thanks to Newton and Kepler, we know that Earth rotates around the Sun in an elliptical orbit. This means it orbits in a slight oval shape.

- At some point in the year it is nearer the Sun, at another point it is further away. So we take a mean....

- The mean average distance from Earth to the Sun is 149,600,000 km. (150,000,000 km)

- This is called 1 Astronomical Unit, or AU. This figure is a standard number in astronomy. Many distances to planets and stars are calculated using this number.

The Lightyear (ly)

- Light travels at approximately 300,000 km/s. The Moon is 380,000 km away so we see light from the Moon as it was just over a second ago (Hence the slight lag in the Moon Landing videos).

- In distance terms we might say that the Sun is 8 light minutes away and Neptune is 4 light hours away.

- The length is time it takes light to travel in an Earth Year is called a light year. (Just over 9 trillion kilometres or 63,241 AU)

- When we view the Andromeda Galaxy we are seeing light that left there 2 million years ago. Writing the distance to an object like this in kilometres, or even astronomical units, would be impractical so we use light years instead.

The parsec (pc)

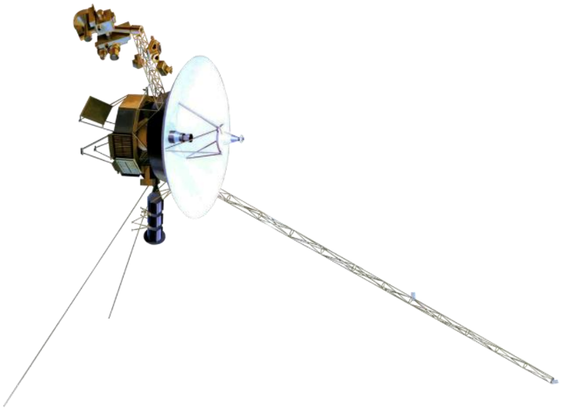
- A parsec is another measurement used in astronomy. It is used to determine the distances to stars. It is the distance that a star would have to move that would cover an arc second in the sky as viewed from Earth. (More on this in Topic 13)

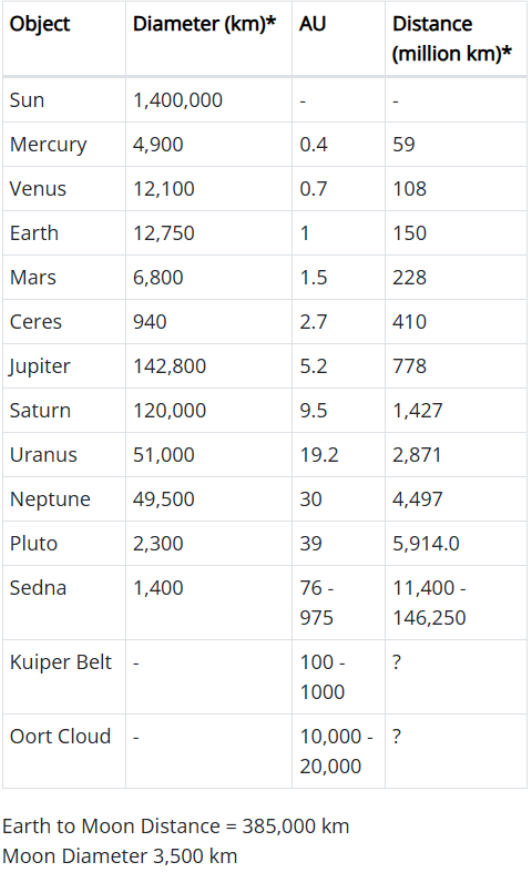
- **1 parsec is 3.26 light years.**

7.5 Understanding the Scale of the Solar System

- The **Astronomical Unit (AU)** is the average distance from **Earth to the Sun** (1 AU = **1.5 × 10⁸ km**).

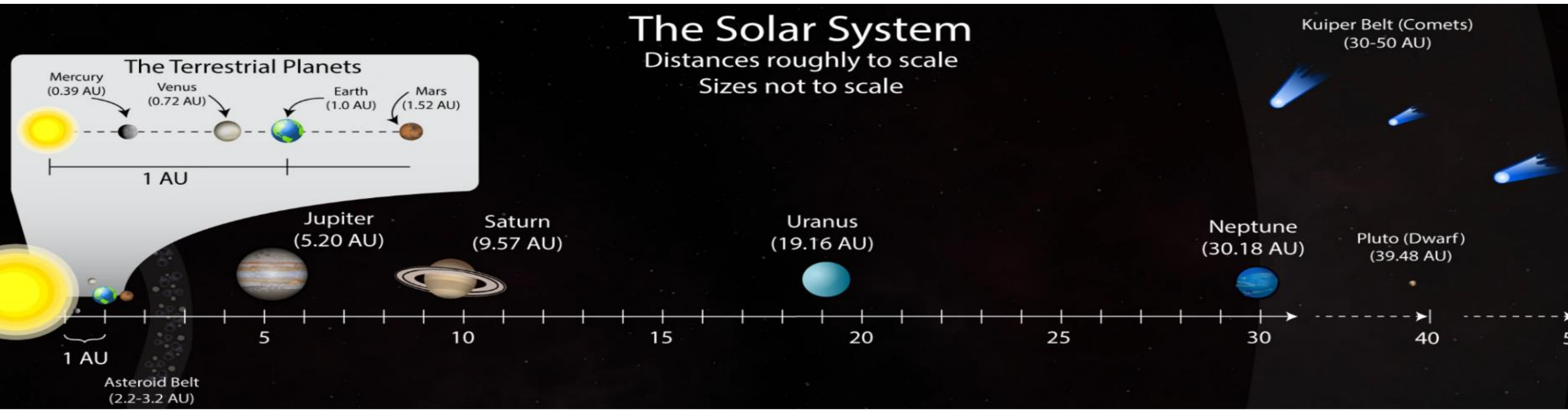
- Other key distances:
  - **Earth to Moon**: ~0.0026 AU (~384,400 km)
  - **Earth to Neptune**: ~30 AU
  - **Oort Cloud (outer edge of Solar System)**: ~100,000 AU
  - **(Voyager 1** is the most distant man-made object from Earth at 168.9 AU)



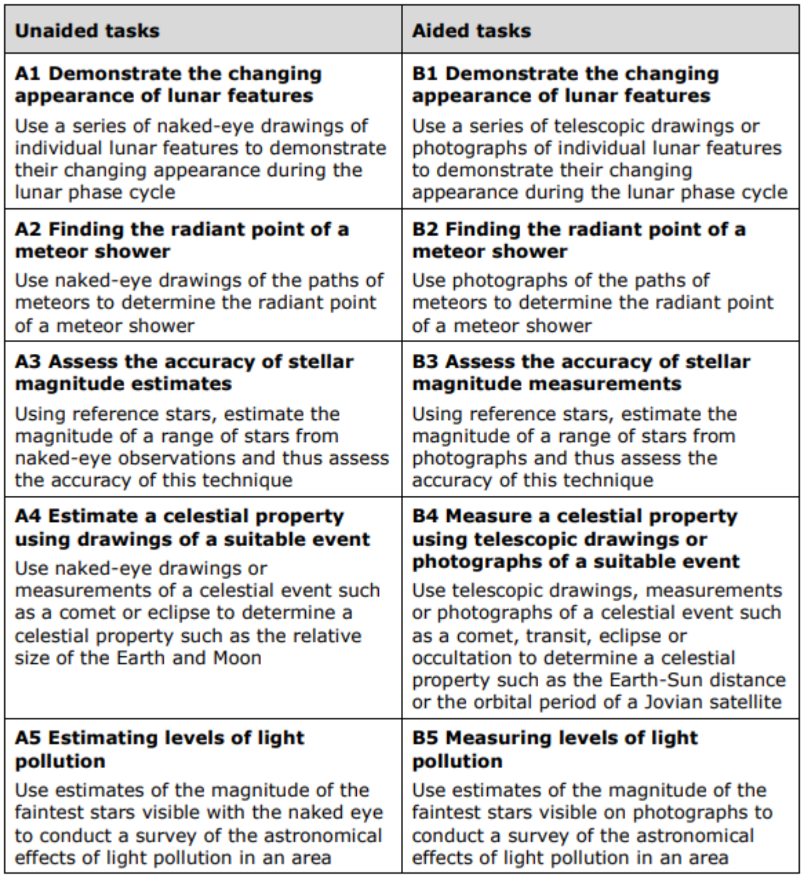


Object	Diameter (km)*	AU	Distance (million km)*
Sun	1,400,000	-	-
Mercury	4,900	0.4	59
Venus	12,100	0.7	108
Earth	12,750	1	150
Mars	6,800	1.5	228
Ceres	940	2.7	410
Jupiter	142,800	5.2	778
Saturn	120,000	9.5	1,427
Uranus	51,000	19.2	2,871
Neptune	49,500	30	4,497
Pluto	2,300	39	5,914.0
Sedna	1,400	76 - 975	11,400 - 146,250
Kuiper Belt	-	100 - 1000	?
Oort Cloud	-	10,000 - 20,000	?

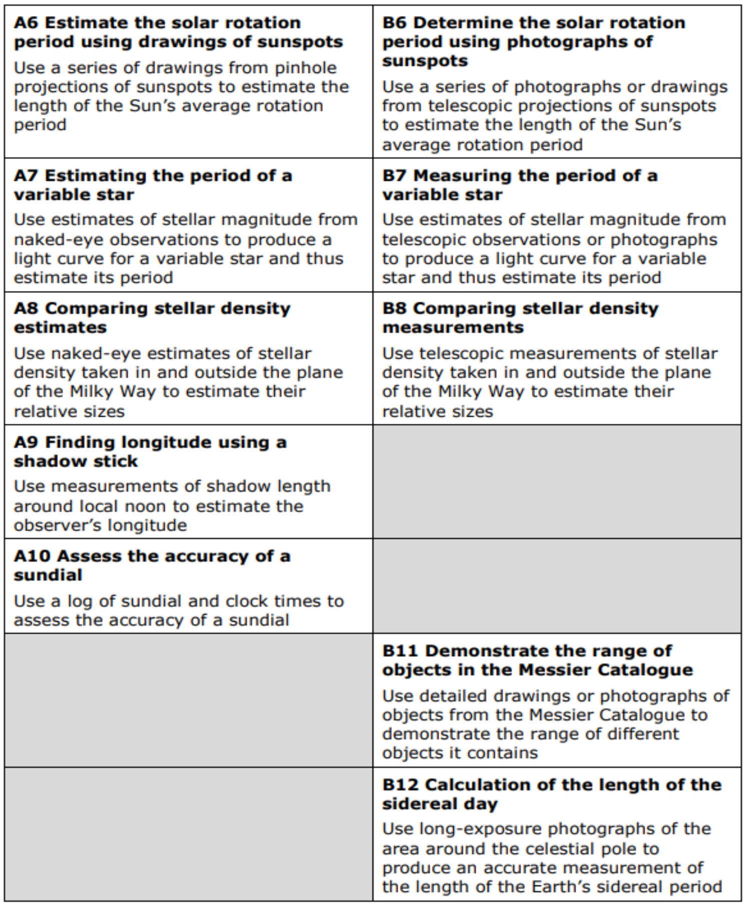
Earth to Moon Distance = 385,000 km
Moon Diameter 3,500 km



Observation options- an early look



Unaided tasks	Aided tasks
A1 Demonstrate the changing appearance of lunar features Use a series of naked-eye drawings of individual lunar features to demonstrate their changing appearance during the lunar phase cycle	**B1 Demonstrate the changing appearance of lunar features** Use a series of telescopic drawings or photographs of individual lunar features to demonstrate their changing appearance during the lunar phase cycle
A2 Finding the radiant point of a meteor shower Use naked-eye drawings of the paths of meteors to determine the radiant point of a meteor shower	**B2 Finding the radiant point of a meteor shower** Use photographs of the paths of meteors to determine the radiant point of a meteor shower
A3 Assess the accuracy of stellar magnitude estimates Using reference stars, estimate the magnitude of a range of stars from naked-eye observations and thus assess the accuracy of this technique	**B3 Assess the accuracy of stellar magnitude measurements** Using reference stars, estimate the magnitude of a range of stars from photographs and thus assess the accuracy of this technique
A4 Estimate a celestial property using drawings of a suitable event Use naked-eye drawings or measurements of a celestial event such as a comet or eclipse to determine a celestial property such as the relative size of the Earth and Moon	**B4 Measure a celestial property using telescopic drawings or photographs of a suitable event** Use telescopic drawings, measurements or photographs of a celestial event such as a comet, transit, eclipse or occultation to determine a celestial property such as the Earth-Sun distance or the orbital period of a Jovian satellite
A5 Estimating levels of light pollution Use estimates of the magnitude of the faintest stars visible with the naked eye to conduct a survey of the astronomical effects of light pollution in an area	**B5 Measuring levels of light pollution** Use estimates of the magnitude of the faintest stars visible on photographs to conduct a survey of the astronomical effects of light pollution in an area



A6 Estimate the solar rotation period using drawings of sunspots Use a series of drawings from pinhole projections of sunspots to estimate the length of the Sun's average rotation period	**B6 Determine the solar rotation period using photographs of sunspots** Use a series of photographs or drawings from telescopic projections of sunspots to estimate the length of the Sun's average rotation period
A7 Estimating the period of a variable star Use estimates of stellar magnitude from naked-eye observations to produce a light curve for a variable star and thus estimate its period	**B7 Measuring the period of a variable star** Use estimates of stellar magnitude from telescopic observations or photographs to produce a light curve for a variable star and thus estimate its period
A8 Comparing stellar density estimates Use naked-eye estimates of stellar density taken in and outside the plane of the Milky Way to estimate their relative sizes	**B8 Comparing stellar density measurements** Use telescopic measurements of stellar density taken in and outside the plane of the Milky Way to estimate their relative sizes
A9 Finding longitude using a shadow stick Use measurements of shadow length around local noon to estimate the observer's longitude	
A10 Assess the accuracy of a sundial Use a log of sundial and clock times to assess the accuracy of a sundial	
	B11 Demonstrate the range of objects in the Messier Catalogue Use detailed drawings or photographs of objects from the Messier Catalogue to demonstrate the range of different objects it contains
	B12 Calculation of the length of the sidereal day Use long-exposure photographs of the area around the celestial pole to produce an accurate measurement of the length of the Earth's sidereal period