Ancient Astronomy

The world of Ptolemy

## "The Greatest"

- The universe described here, based on a central, stationary, spherical earth, was first developed by Aristotle (384-322 BC).
- But Aristotle's model was qualitative. A mathematically precise version, that could be used to predict the motions of the planets, was developed by Ptolemy ( $83-168$ AD). Ptolemy's work of astronomy is known by its Arabic name, Almagest, meaning "the greatest".


## A Layered Universe

- The universe is made of 5 different elements, which are (in order of weight):
- Earth
- Water
- Air
- Fire
- Aether
- The heaviest element, earth, naturally descends to the bottom (centre) of the universe. The other elements layer on top, in order of weight.


## c.f. Soil composition



Water

Clay layer (after water is clear) Silt layer (formed after about 2 h )

Sand layers
(formed within minutes)

## A layered universe (not to scale)



## Higher and lower

- In the ancient universe, there is an objective up and down. We, standing on earth, are very near the centre (i.e. bottom) of the universe.
- Everything in the heavens is above us.
- The further away a heavenly body is from earth, the higher it is. For example, Saturn is above the sun.
- The centre is the lowest, not the best, place to be. (The Devil is right at the centre!)


## Dante’s Inferno (1314)



## Ancient terminology

- A star is a heavenly body that appears (from the earth) as a small point of light in the night sky.
- So the 'stars' include the 'fixed stars' like Polaris and Sirius, as well as planets (wandering stars) like Venus and Jupiter.
- The sun and moon appear large, from the earth, so they aren't considered stars.
- The heavenly bodies are the sun, moon and stars.


## The Two Spheres

- The ancient universe consists of two spheres, one inside the other.
- The smaller, inner sphere is the earth.
- The outer, much larger sphere is the celestial sphere.


## Rotation

of the Celestial Sphere


## The diurnal rotation.

- The celestial sphere rotates (west) about its axis, roughly once per day. There is one complete revolution in just under 24 hours
( 23 hours, 56 minutes, 4 seconds).
- Most stars are fixed in the surface of the celestial sphere, and so rotate with it.
- The earth is stationary, and does not rotate.


## The Wanderers (Planets)

- Seven stars are special. Instead of being fixed in the celestial sphere, they constantly move relative to it. These are the planets (in ascending order):

1. Moon
2. Mercury
3. Venus
4. Sun
5. Mars
6. Jupiter
7. Saturn

## Ancient meanings of 'star' and 'planet'



- Each planet, or "wanderer", has 2 motions:

1. It shares in the (rapid) diurnal rotation, i.e. the daily rotation of the whole heavenly sphere. This is a westward motion.
2. It moves slowly to the east through the heavenly sphere, i.e. relative to the "fixed stars". The planet moves through the celestial sphere close to a line called the ecliptic. (We will focus on this motion from now on.)

## The Plane of the Ecliptic



## The Ecliptic

- The sun's path through the celestial sphere is called the ecliptic. The planets all (roughly) follow this path.
- The ecliptic is a huge circle, that goes right around the celestial sphere. This circle is angled at $231 /{ }^{\circ}$ relative to the celestial equator.
- The sun completes a full tour of the ecliptic in one year, by definition.


## The 12 signs of the zodiac

- The familiar constellations of the zodiac all lie on the ecliptic. One's "star sign" is determined by the position of the sun on one's date of birth.



## The Solar Day

- You may be puzzled why the diurnal rotation of the celestial sphere takes slightly less than one day. (About 4 minutes less.)
- The reason is that the sun moves slowly east through the celestial sphere, against the westerly motion of the sphere itself. So the sun moves slightly slower than the fixed stars.
- Thus the "solar day" is slightly longer than the diurnal period. (The sun moves $360^{\circ}$ in 365 days, so roughly 1 degree per day. The diurnal rotation is $360^{\circ}$ in about 24 hours, so that $1^{\circ}$ of motion adds about 4 minutes.)


## Speeds of the planets

- Each planet goes east through the heavens, roughly along the line of the ecliptic, i.e. through all the 12 signs of the zodiac. But the time taken to complete one circuit varies:
- Moon- 28 days
- Mercury - $\approx 1$ year
- Venus - $\approx 1$ year
- Sun-1 year
- Mars - 2 years
- Jupiter - 12 years
- Saturn - 29 years


## Retrograde motions

- Generally each planet moves to the east through the celestial sphere. But occasionally a planet (other than the sun and moon) will stop, turn around, and go west for a little while, before going east again.
- This is called a retrograde motion.


## E.g. retrograde motion of Mars


(There are about 5 days between observations)

## Superior and inferior planets

- Looking at the table of speeds, you'll see that two of the planets (Mercury and Venus) have the same period as the sun (1 year).
- Actually these planets seem to follow the sun on its path through the heavens. They move back and forth, sometimes ahead of the sun and sometimes behind it.
- Mercury is apparently on a "shorter leash" than Venus.
- These sun-bound planets are termed inferior (lower).


## Superior and inferior planets

- The superior (above the sun) planets (Mars, Jupiter, Saturn) are not tied to the sun, as they have much longer orbital periods ( 2,12 and 29 years).
- The superior planets are assumed to be above the sun due to their longer period. On this basis Saturn is the highest planet, then Jupiter, then Mars.


## Retrograde motion and opposition

- It is observed that the superior planets undergo retrograde motion when (and only when) they are in opposition (to the sun). Why? They just do.
- Two celestial bodies are in opposition when they are on opposite sides of the celestial sphere.
- When two planets are close together in the celestial sphere, they are in conjunction.


Mars in opposition (to the sun)


Mars in conjunction (with the sun)

## Proof that the earth is stationary

- There is no annual stellar parallax observable with the naked eye.
(That is, the constellations do not change their appearance between (e.g.) summer and winter.)
- Suppose the earth were in orbit around the sun, as suggested in the ancient world by Philolaus and Aristarchus of Samos. Would the stars change their appearance in some way, over the course of a year?

These two stars shown would appear closer together in February, and further apart in June, if the earth moved.

# Ptolemy explains retrograde motion: combine 2 circular motions 



The small circle is called the "epicycle", and the large circle is the "deferent".

## The theory of epicycles

- Apart from the sun and moon, every planet moves around two circles at once.
- It moves around a small circle, called its epicycle. And the centre of the epicycle also moves around a larger circle called the deferent.
- The combination of these two circular motions creates a looping motion, that includes retrograde sections.


## Lots of free parameters ...

- In his model, Ptolemy adjusted the sizes of the epicycle and deferent of each planet to fit the data.
- E.g. for Saturn, the observed retrograde motion is small, so Ptolemy made the epicycle much smaller than the deferent.
- He also chose the two speeds of each planet, around its epicycle and deferent.


## Odd coincidences concerning the sun

- Inferior planets


- Superior planets




## Odd coincidences concerning the sun

- In Ptolemy's model the sun's orbit (around the earth) is rather special.
- The sun has no epicycle, just a deferent
- The epicycles of the superior planets (Mars, Jupiter, Saturn) each exactly duplicate the sun's orbit.
- The deferents of the inferior planets (Mercury, Venus) exactly duplicate the solar orbit.

The sun's orbit, as well as every orbit that duplicates it, is shown in yellow (not to scale).


## "ad hoc" adjustment

- Ptolemy could give no theoretical reason why the solar orbit should be duplicated in five other places in the universe.
- The following data simply forced him to put this into his model:
- The inferior planets are always close to the sun.
- The superior planets undergo retrograde motion when (and only when) in opposition to the sun.


## Ptolemy makes his model complicated!

- In order to fit the data better, Ptolemy made his model more complicated, including minor (smaller) epicycles, eccentric orbits and equants.
- E.g. the sun's orbit is eccentric, in the sense that the earth is not at the centre of the circle.
- And the angular speed of the sun, about the centre of the circle, isn't constant. Rather, the angular speed is constant about another point, called the equant.
- He also used "minor" (much smaller) epicycles to make small adjustments to the orbits.


## Eccentric Orbit: The earth isn't (quite) at the centre of the planet's deferent!



Equant: The planet sweeps out equal angles (about the equant) in equal times.



- Ptolemy's actual model of (e.g.) Mercury was quite complicated.


## The "Alice's restaurant" problem with epicycles

- With enough epicycles, any conceivable orbit can be modelled accurately in this way. The framework is incredibly flexible.
- As in Alice's restaurant, "you can get anything you want".
- Is such flexibility in a scientific theory a good or a bad thing?
- It's considered a very bad thing! (Why?)

