Introduction to Science

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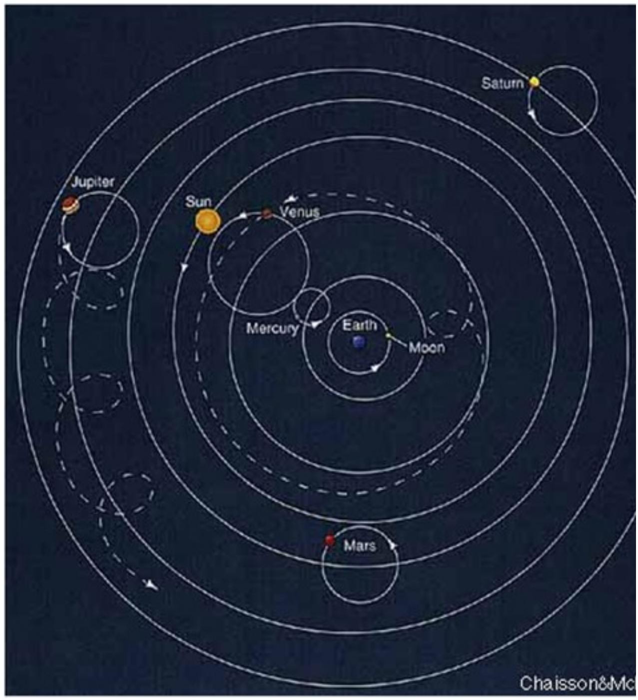
The purpose of this book is to provide a basic understanding of some scientific theories, especially for students who haven't taken much science before. The approach taken here is different from most science textbooks, and you'll likely learn things that are new to you, even on subjects you've studied before. The focus here is on *history*, and on *arguments*.

Rather than simply learning about what scientists presently believe, we're more concerned with the historical processes that got us here. We shall even study some theories that have been entirely discarded, since they contain valuable lessons about how science works.

Also, rather than simply understanding *what* scientists have believed, we aim to understand their *reasons* for believing it, i.e. the evidence and arguments involved. We also consider non-rational forces that are sometimes involved when a theory becomes accepted, at least for a time.

Chapter 1: Ancient Astronomy



Claudius Ptolemy, and his model of the universe

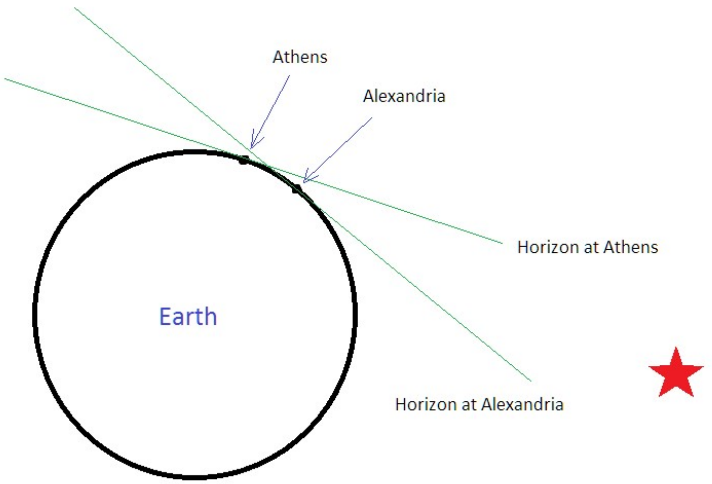
1.1 The spherical earth, and the celestial sphere

Ancient astronomers, at least from the time of Aristotle (384 – 322 BC) believed that the earth was a sphere. Why was this? The main evidence was the fact that travelling south made constellations in the southern sky appear higher above the horizon. (A southern star will increase its 'altitude', or 'elevation', as one travels south.) Indeed, from a southerly location like Alexandria in Egypt, stars could be seen (just above the southern horizon) that were not visible from Athens. How is this observation best explained?

In books called the *Phaedo* and the *Timaeus*, Aristotle's teacher Plato had previously stated that the earth was a sphere, lying at the centre of a spherical universe. In other words, Aristotle was aware of the idea that the earth might be spherical. If the earth *were* spherical, then would the stars change their apparent positions, as one travelled south on the globe? They would indeed, due to the curvature of the earth, as shown on Figure 1 below. Thus, the spherical-earth theory predicts the data that is observed.

Would any other theory predict the same data? Of course. The sphere is not the only solid form with a curved surface. But the sphere has the advantage of being the simplest, and "most perfect", such form (which was at least part of the reason why Plato favoured it). Moreover, at that time, the competing theory of the earth's shape held that it was a flat disc. But the flat-earth theory predicts that the same stars would be visible everywhere. Also, people assumed that the stars were far away, compared with terrestrial distances, in which case the flat-earth theory predicts that the stars shouldn't really look any different at all as one moves south.

Figure 1: **Evidence for a spherical earth**



The star shown (red) will be visible in Alexandria, but not in Athens

Thus, of the two theories then under consideration, the spherical earth theory was the better explanation of the varying altitude of stars when moving north or south.

Another piece of evidence that Aristotle appealed to was the shape of the earth's shadow that is cast on the moon during a lunar eclipse. Figure 2 below shows a series of images taken of the moon, during the night of a lunar eclipse, when the moon passes through the earth's shadow. As the moon enters the shadow you'll see that the edge of the shadow is curved. A few hours later, as the moon exits the shadow, it is curved in the opposite direction. This result is what one would expect, assuming that the earth's shadow is a large circle. What would a flat (disc) earth model predict? If the moon is directly overhead, then it would predict the same thing. But for cases when the moon is near the horizon, the earth's shadow should be a very elongated oval, which isn't what is observed.

A third line of argument from Aristotle was rather different, being based on Aristotle's assumptions about mechanics rather than observations. It was a *theoretical* argument rather than an *empirical* one, based on Aristotle's theory of mechanics. As we'll see in the next chapter, Aristotle thought the earth was formed by the downward gravitation of the heaviest elements (earth, water and air) towards the centre of the universe. Since such gravitation is equal is every direction, the natural shape for the earth to form would be a sphere. This would also mean that the dense matter will remain at the centre of the universe once it gets there, so that the earth must be stationary.

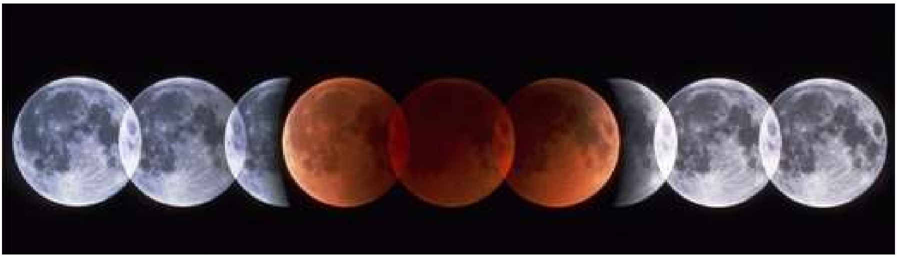


Figure 2. The stages of a lunar eclipse, over several hours

1.2 Ancient Astronomical Data

We have already discussed one astronomical observation from the ancient world, namely the variation in altitude of stars as one changes latitude (travels north or south). In order to understand the arguments of astronomers such as Aristotle, Ptolemy, Copernicus, etc. we must be familiar with a number of other observations, which are described in this section.

1.2.1 The diurnal rotation.

If you watch a star for a few minutes or more you will notice that it moves. Telescopes must be continually turned, or the object being looked at will quickly slide out of view. There is one exception to this rule: the star Polaris, the Pole Star. It's the one thing in the night sky that remains resolutely in place, never moving.

In what way do all stars (other than Polaris) move? They each move in a circle, around Polaris, completing one full circuit in about 24 hours. Thus stars close to Polaris move in a very small circle, and those far from Polaris have to go much faster to get around a very large circle in the same period of time.

Nowadays, we understand the diurnal rotation to be the result of the earth's rotation about its own axis, but I want you to forget about that, at least for now. Get your mind into the ancient world, and think about it from Aristotle's perspective. Why should the earth rotate? Is there any evidence that it does (rather than the stars themselves rotating)? The earth is made from dense elements (earth, water and air) which, according to our observations, naturally move downwards if space permits. They do not naturally move in a circle – an external force is required to make them do that. And what force could possibly turn a body the size of the earth at such a fantastic speed? Such a crazy idea would need a lot of supporting evidence, but there is none at all. The rational thing to believe, then, is that the earth is stationary but the stars are turning.

Time lapse photograph of Polaris and neighbouring stars

As stated above, the stars all move in circles about Polaris, completing one orbit in just under 24 hours. In other words, the stars behave as if they're embedded in a huge sphere that rotates about the earth. This sphere is known as the *celestial sphere*. In ancient times the celestial sphere was assumed to be very large in comparison to the earth's diameter, yet much smaller than even the Solar System is believed to be today.

Polaris is apparently located at one end of the axis of rotation, a point called the 'north celestial pole', which explains its lack of movement. There's also a south celestial pole, although it cannot be seen from the northern hemisphere, and there are no bright stars near it. Directly above the earth's equator, half way between the celestial poles, is an enormous circle called the celestial equator. Stars lying on the celestial equator (such as the constellation Virgo – see Figure 3 below) are moving very fast indeed, as the celestial sphere rotates westward.

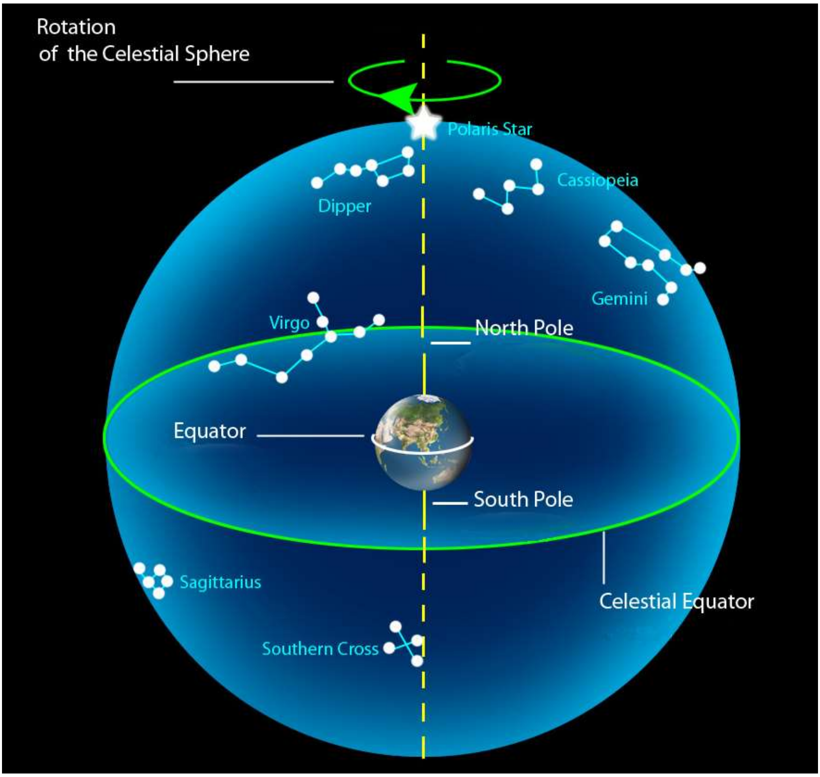


Figure 3: The Celestial Sphere, and its axis, poles, and equator.

1.2.2 The Wanderers (Planets)

All the stars (celestial bodies) move along with the rotation of the celestial sphere. But seven stars are special. For, while they *do* share in the diurnal rotation, they have a much smaller motion of their own that is added to it. Imagine, for example, a crowd of people standing on a ‘moving walkway’ at an airport. Everyone is gliding along at the same speed of 4 feet per second. Then you notice that one person is moving slightly faster, say at 5 feet per second. That’s because they’re shuffling along the belt instead of just standing on it. Their own motion is added to that of the walkway itself.

In a similar way, these seven ‘wandering’ stars are not glued down to the celestial sphere like the others. Instead they ‘walk around’ on it, so that a (very small) motion of their own is added to the motion of the sphere itself.

The wandering stars are called *planets*. What are their names? In order of their distance from the earth, in Aristotle’s theory, they are: the moon, Mercury, Venus, the sun, Mars, Jupiter, and Saturn. You may not think of the moon and sun as planets, but they do meet the ancient definition of a planet, since they are celestial bodies that move relative to the celestial sphere. Of course, the term ‘planet’ now means something else, so that the earth is now a planet (it wasn’t back then) and the sun and moon are not planets any more. Be aware that science often keeps the same *words* for many centuries, even though the *meanings* of those words may change now and then!

1.2.3 The Ecliptic

If you observe the movements of the seven planets on the celestial sphere, you’ll see that they’re confined to a fairly narrow strip called the ecliptic. The planets all (roughly) follow this path. The ecliptic is a huge circular band, that goes right around the celestial sphere. This circle is angled at 23 ½° relative to the celestial equator.

The stars along the ecliptic have been grouped into twelve constellations, known as the ‘signs of the zodiac’. Their names are familiar from astrology: Ares, Taurus, Gemini, Cancer, etc. In one year (by definition), the sun completes a full tour of the ecliptic, passing through all twelve signs of the zodiac. All the other planets follow roughly the same path, although the time taken to complete one circuit varies:

Orbital Periods of the Planets	
Moon	28 days
Mercury	1 year (approx)
Venus	1 year (approx)
Sun	1 year (by definition)
Mars	2 years (approx)
Jupiter	12 years (approx)
Saturn	29 years (approx)

The sun is a very special planet, being the largest of all, as well as the universe's light source. So it is natural to divide the planets into upper and lower (or 'superior' and 'inferior') according to whether they are above or below the sun. The moon, Mercury and Venus are inferior planets. Mars, Jupiter and Saturn are superior. Notice that the ancient universe has an absolute centre, which defines an objective *up* and *down*. We, standing on earth, are very near the centre (i.e. bottom) of the universe, so that everything in the heavens is *above* us. Also, the further away a heavenly body is, the higher it is. For example, Saturn is *above* the sun, not just further away from us.

You may notice that Mercury and Venus also take 1 year to orbit the earth, on average. If you observe these planets over a period of months, you'll see that they remain close to the sun at all times. Each planet sometimes runs ahead of the sun, then slows down, gets caught and overtaken by the sun and falls behind it. Then the planet speeds up and overtakes the sun again, and so the pattern repeats. The sun appears to have Venus on a short leash, and Mercury on an even shorter one.

The two motions of each planet (i.e. the diurnal motion, plus its own motion) are usually in opposite directions. The celestial sphere itself rotates westward, so that (for example) each day the sun rises in the east and sets in the west. The planets' own motions, however, are generally *eastward* through the heavenly sphere, i.e. relative to the "fixed stars". For this reason, the sun's rotation around the earth (for example) takes a little longer than the rotation of the celestial sphere itself. The sun revolves around the earth once every 24 hours (by definition), but the diurnal rotation takes about 4 minutes less.

(One can easily calculate the fact that the "solar day" is about 4 minutes longer than the diurnal period. We know that the diurnal rotation is *approximately* 24 hours, which is 1440 minutes. The sun takes 365 days to complete the same circuit, so it is moving 365 times slower than the sphere itself. Dividing 1440 minutes by 365 gives 3.95 minutes.)

1.2.4 Retrograde motions

I said above that each planet *generally* moves to the east through the celestial sphere. This qualification is needed, since 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. the diagram below shows Mars in retrograde motion for a couple of months.

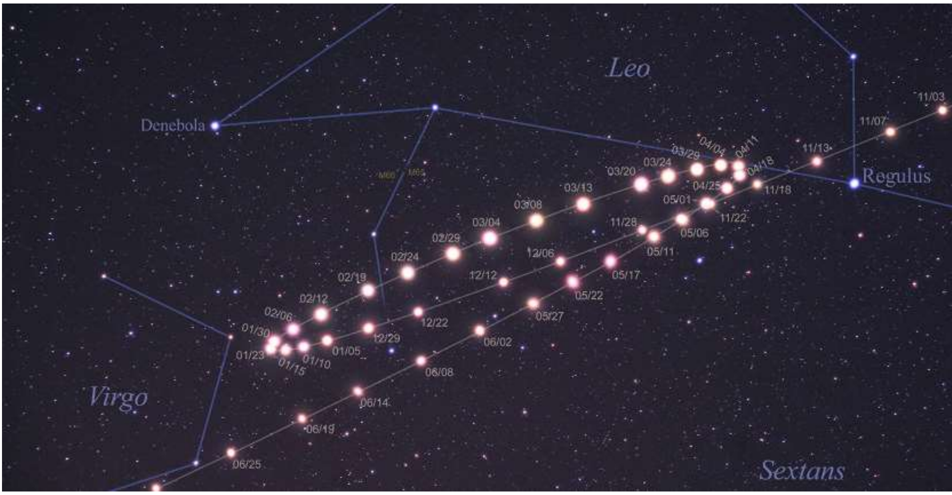


Figure 4: Mars undergoing retrograde motion

1.2.5 Elongations of the Planets,

As mentioned above, the inferior planets Mercury and Venus have the same average period as the sun (1 year), and seem to each be held by the sun on a leash.

The superior planets (Mars, Jupiter, Saturn) are not tied to the sun in this way, and so they can have much longer orbital periods (2, 12 and 29 years). Incidentally, it is due to these longer orbital periods that ancient astronomers *assumed* these planets to be above the sun, as it difficult to know the distance of a planet merely by observation. Clearly, the higher a planet is above the earth, the further it has to travel to complete one orbit. Then, if the planets have roughly the same speed, the higher planets will take longer to go once around the earth. By this reasoning Saturn is the highest planet, then Jupiter, then Mars.

In observational terms, the “distance” between the sun and another planet is an angle, known as the *elongation* of the planet. For example, the elongation of Jupiter at a given time is the angle between the two straight lines: earth-sun and earth-Jupiter.

On this definition, the elongation of the sun itself is always zero, of course. Most of the other planets (moon, Mars, Jupiter, Saturn) can have any elongation, from 0° to the maximum 180°. But Mercury and Venus have limited elongations. Venus has a maximum elongation of 47°, and Mercury of 28°.

When the elongation of a planet is (roughly) zero degrees, it is in *conjunction* (with the sun). When the elongation is close to 180°, the planet is *in opposition* (to the sun). In other words, when a planet appears to be close to the sun, it is in conjunction. When it is opposite the sun in the celestial sphere, it is in opposition.

1.2.6 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). This observational fact was included in Ptolemy's model of the universe, but he could give no real explanation of it. Copernicus showed, however, that this fact must be true in any heliocentric (sun-centred) model of the universe – and Copernicus argued for his model on this basis.

1.2.7 Absence of an Annual Stellar Parallax

There is no annual *stellar parallax* observable with the naked eye. That is, the constellations do not change their apparent sizes between (e.g.) summer and winter. This observational fact was used by Aristotle to argue that the earth is stationary, contrary to the speculations of some ancient thinkers (e.g. Philolaus, and Aristarchus of Samos). These early heliocentrists imagined that the sun was stationary, at the centre of the universe, and the earth orbited the sun. In that case, as these philosophers pointed out, the sun would *appear* to orbit the celestial sphere, as from the earth's perspective the constellation behind the sun would continually be changing.

Aristotle had to grant that they were right that the sun would appear to move through the celestial sphere, along the ecliptic, if the heliocentric model were correct. But if the earth were truly in orbit around the sun then a given constellation would sometimes be closer to the earth, and sometimes further away, according to the season. For example, in early August the sun appears to be in Leo. That means, on the heliocentric view, that the earth is really in Aquarius, on the opposite side of the celestial sphere. In that case, however, the nearby Aquarius should appear larger than usual, and distant Leo should appear shrunken. Careful observations, however, reveal no such seasonal changes, even though celestial angular distances could be measured very accurately, with errors of only perhaps 5 arc-minutes (5/60, or 8%, of one degree). Indeed, with the later use of a telescope by Galileo there was still no observable stellar parallax, even though Galileo could measure to an accuracy of just a few arc-*seconds*. (One arc-second = 1/3600 degrees = 0.00027 degrees.)

Since the heliocentric model implies a stellar parallax, which does not exist, Aristotle concluded that the earth is stationary, at the centre of the universe. This view is called *geocentrism*.

1.3 Ptolemy's Universe

A mathematically precise version of Aristotle's geocentric model, one 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 medieval Arabic name, *Almagest*, meaning "the greatest", giving a clue to its importance at that time. (N.B. Ptolemy himself didn't give his book this name, but titled it rather more modestly as *Syntaxis Mathematica*, meaning 'mathematical treatise'.)

1.3.1 Deferent and Epicycle

In Ptolemy's model the earth is stationary, and (roughly) at the centre of the sun's circular orbit. The moon, Mercury and Venus orbit the earth below the sun, and Mars, Jupiter and Saturn orbit above the sun.

The sun is observed to move fairly uniformly through the heavens, and never undergoes retrograde motion, so Ptolemy was able to give it (more or less) a simple circular orbit. The other planets have more complex motions, however, so Ptolemy was forced to combine two or more circular motions to account for them.

The moon, although it never moves retrograde, has a curious "hopping" motion that is extremely difficult to model. (Even the great Isaac Newton could not fully explain the moon's orbit.) Ptolemy combined three circular motions to approximate the lunar orbit. The remaining five planets (Mercury, Venus, Mars, Jupiter and Saturn) all required two circles each, known as the epicycle and the deferent.

The deferent was a large circle, centred at the earth (at least approximately). The deferent accounts for the general movement of the planet through the celestial sphere. The epicycle is a much smaller circle that the planet follows as it travels around its deferent. The epicycle is needed to account for the occasional retrograde motions of these planets. At times, the planet will be moving around its epicycle in a direction that is opposite to its general motion around the deferent. At those times, it will slow down and even stop or go backwards.

In the diagram below, the red line shows the path of a planet that has an epicycle and deferent. The loops are the retrograde motions.

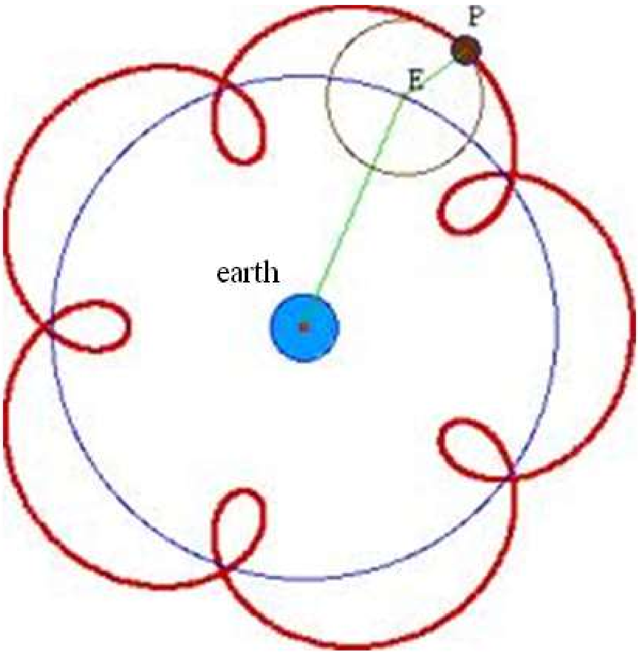


Figure 5: Combining two circular motions, to account for retrograde motions. The deferent is the large blue circle, the epicycle is the small black circle. The actual path of the planet P is shown in red.

1.3.2 Complications

Ptolemy's basic model described the motions of the planets using 1 + 3 + (5 x 2) = 14 circles. Unfortunately this basic model wasn't too accurate, and to improve the fit between theory and data it was usually modified by adding "minor epicycles", i.e. additional circles that were much smaller than the main epicycles used to explain retrograde motion. Typically around 6-12 minor epicycles were used.

Also, Ptolemy used devices called *eccentric* orbits and *equants*. For example, in Ptolemy's model the sun's orbit is 'eccentric' in the sense that the earth is not quite 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 yet another point, also close to the earth, called the *equant*.

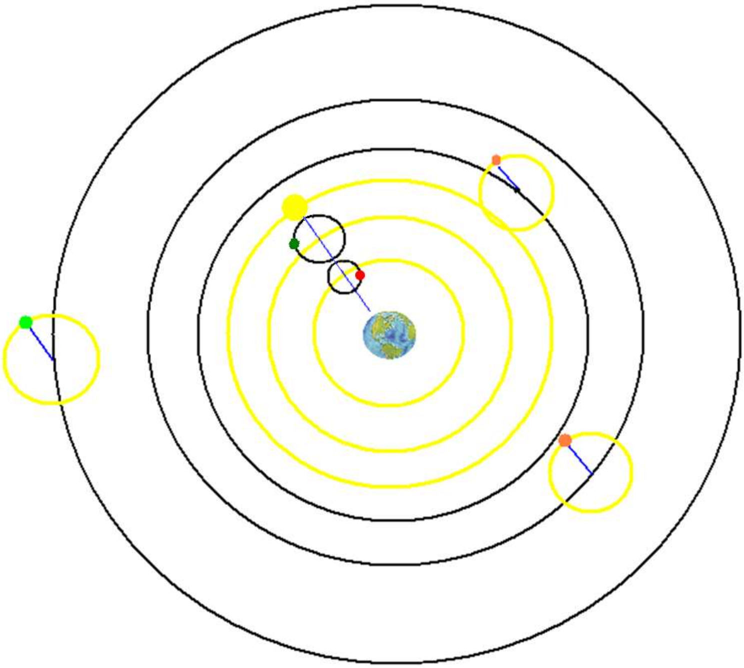
1.3.4 "Ad hoc" Adjustment of the Epicycles

In Ptolemy's model five of the planets each have an epicycle and a deferent. Each of these circles has a radius of course, and the planet orbits each circle with a certain speed and phase. How did Ptolemy choose all of these quantities?

Ptolemy chose them *as needed to make his model fit the data*. Scientists call this method of setting up a model *ad hoc*. An 'ad hoc' feature of a model is one that is chosen for the purpose of fitting the data, rather than for any theoretical necessity.

For example, recall that the inferior planets Mercury and Venus are always close to the sun, with maximum elongations of 28° and 47°. To make his model fit this observation, Ptolemy fixed the centre of Venus's epicycle so that it always lay on the straight line connecting the earth and the sun. He did exactly the same with Mercury (see Figure 6 below). He also adjusted the size of Venus's epicycle, in relation to its deferent, so that the maximum elongation would be 47°.

Figure 6: The sun's orbit, as well as every orbit that duplicates it, is shown in yellow. (Not to scale)



Also, you may remember that the superior planets undergo retrograde motion when (and only when) in opposition to the sun. There is no particular reason, within the epicycle framework, why this should be so, but it can easily be put in by hand (ad hoc). It's easy to see that the superior planets will undergo retrograde motion when they're on the lowest part of their epicycle (i.e. closest to the earth), for that's when the epicycle motion is opposite to the deferent motion. For the planet to be in opposition to the sun at this time, the radius of the planet's epicycle just has to be parallel to the earth-sun line. So that's exactly what Ptolemy specified in his model. (This is also shown in Fig. 6, where all the blue lines are parallel at all times.) Since these lines are always parallel, each superior planet must also take exactly one year to go around its epicycle.

Chapter 1 Glossary

Altitude (or *elevation*) of a star – the angle between a line pointing at the star and a line pointing at the horizon.

Celestial – concerned with the heavens

Diurnal Rotation – the rapid (once per 23 hours, 56 minutes) rotation of the celestial sphere around the earth

Ecliptic – a circular band around the celestial sphere that the sun and other planets travel around

Terrestrial – concerned with the earth

Theoretical – concerned with theories, or models, or hypotheses

Empirical – concerned with observation and data