6. Theories, Models and Measurements

In this chapter we take a break from presenting more physics but look at some of the underlying ideas relating to the subject. The chapter also takes a look at how some Astronomical measurements can be made. The Greek models of Earth, Moon, Sun, planets and stars form a link between these topics.

What is a Theory?

Eric Rogers in his book "Physics for the Enquiring Mind" describes a discussion you might have with a guy called Faustus who proposes a Demon Theory of Friction.

"How do you know that it is friction that brings a rolling ball to a stop and not demons? Suppose you answer this, while a neighbour, Faustus, argues for demons. The discussion might run thus:

YOU

> I don't believe in demons.

FAUSTUS

> I do.

YOU

> Anyway, I don't see how demons can make friction.

FAUSTUS

> They just stand in front of things and push to stop them from moving.

YOU

> I can't see any demons even on the roughest table.

FAUSTUS

> They are too small, also transparent.

YOU

> But there is more friction on rough surfaces.

FAUSTUS

> More demons.

YOU

> Oil helps.

FAUSTUS

> Oil drowns demons.

YOU

> If I polish the table, there is less friction and the ball rolls further.

FAUSTUS

> You are wiping the demons off; there are fewer to push.

YOU

> A heavier ball experiences more friction.

FAUSTUS

> More demons push it; and it crushes their bones more.

YOU

> If I put a rough brick on the table I can push against friction with more and more force, up to a limit, and the block stays still, with friction just balancing my push.

FAUSTUS

> Of course, the demons push just hard enough to stop you moving the brick; but there is a limit to their strength beyond which they collapse.

YOU

> But when I push hard enough and get the brick moving there is friction that drags the brick as it moves along.

FAUSTUS

> Yes, once they have collapsed the demons are crushed by the brick. It is their crackling bones that oppose the sliding.

YOU

> I cannot feel them.

FAUSTUS

> Rub your finger along the table.

YOU

> Friction follows definite laws. For example, experiment shows that a brick sliding along the table is dragged

by friction with a force independent of velocity.

FAUSTUS

Of course, same number of demons to crush, however fast you run over them.

YOU

If I slide a brick along the table again and again, the friction is the same each time. Demons would be crushed in the first trip.

FAUSTUS

Yes, but they multiply incredibly fast.

YOU

There are other laws of friction: for example, the drag is proportional to the pressure holding the surfaces together.

FAUSTUS

The demons live in the pores of the surface: more pressure makes more of them rush out to push and be crushed. Demons act in just the right way to push and drag with the forces you find in your experiments."

How can you argue against this? For every experimental fact Faustus simply invents a property of demons that explains it. This does not make the demon theory valid as a scientific theory. For something to be called a theory it must make **predictions**. And these predictions must be ones that can be verified by experiment.

Newton's laws together with his law of gravity make such predictions. They allow many practical predictions in the design of most mechanical equipment. They make predictions about the behaviours of gases by analysing the collisions between the molecules. They predict the time periods of vibration of pendulums and springs that we use in clocks. They explain and predict how waves generated at sea by earthquakes will travel and how long they will take to arrive and do their damage. They explain why Saturn has rings and predict how near a moon of planet will have to be to the planet before it starts to break into rings.

So Faustus must put his theory into whatever infernal bin he has at his disposal.

What is a Model?

We will explain this by an example from the ancient Greeks. They made careful observations of the heavens. They noticed that some objects did not remain in the same position in relation to the background of stars. These were called planets, which means wanderers. The common Greek model at this time was that the Earth was at the centre of the universe, and the sun, moon and planets revolved around the Earth each on their own sphere. The stars were just some pinpoints of light that was further away and all these pinpoints were fixed on this "celestial sphere".

This was all Ok until they noticed that the planets did not move in steady direction against the background of the celestial sphere but for a period in their rotation they would actually move backwards, which is called *retrograde motion*. To explain this away while still sticking to the geocentric, Earth centred, model Ptolemy proposed the idea of epicycles. In this model the planets rotated in circles on a "crystal" (i.e. invisible) sphere the centre of which moved steadily around the Earth as in Fig 6.1

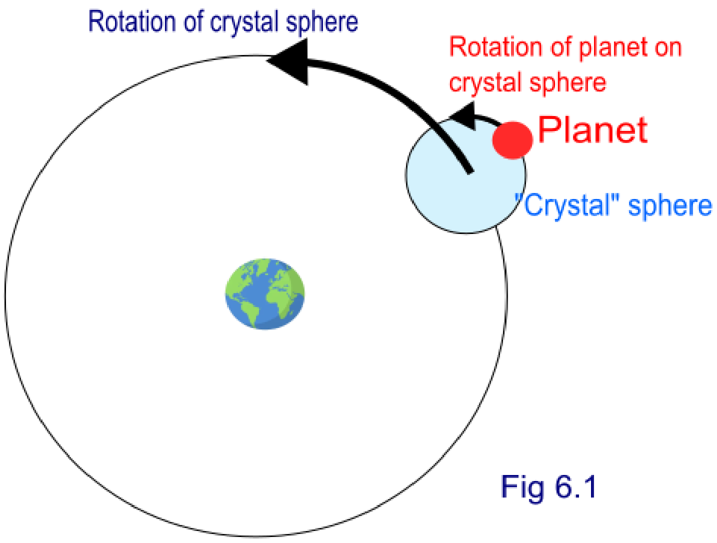


Fig 6.1

You can then see that if the speed of rotation of the epicycle and speed of rotation of this around the Earth are chosen correctly, then sometimes the planet will appear to move backwards. Fig 6.2 (a) and (b) show this.

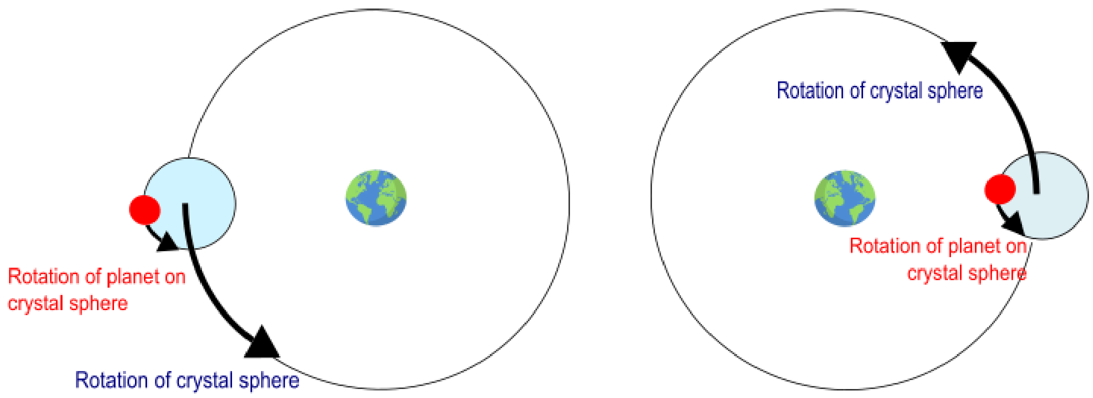


Fig 6.2(a)

Planet appears to move forward

Fig 6.2(b)

Planet appears to move backward

With this correction Ptolemy could make predictions of how the planets will move to some degree of accuracy. So is this model a theory? Well no, but it may be thought of as fair try. The invention of epicycles is a bit like inventing a property of demons to explain friction. But it does make predictions. These predictions, however, are very limited in scope and can only be used for the specific planet. Different data must be used for other planets and they only apply to this branch of heavenly observations. Compare this with the range of applicability of Newton's laws. So it remains a model and not a theory. Range of applicability also matters for an idea to be considered a theory.

(Incidentally Einstein could be guilty in this respect. In his theory of Gravitation he proposed his, now famous, field equation. There was one thing that did not seem to fit so he just invented an arbitrary constant to make things work. He later described this as the worst mistake of his life).

We now know that retrograde motion is simply the result of the Earth rotating more quickly around the sun than the outer planets. While we are "overtaking" them they appear to move backwards against the distant stars.

Astronomical Measurements.

The Greeks were bright cookies. They may have had the wrong model of the Solar System, but they were able to work out the circumference of the Earth, the distance and size of the Moon, and much less accurately, the size and distance of the Sun. Here is how they worked out the values for the Moon. They needed first to know the diameter of the Earth.

Circumference of the Earth

This was done by Eratosthenes who lived 276-195 BC and his answer was fairly accurate On a certain day in the year the sun would shine down a vertical well in Syene showing that the Sun was vertically overhead. He arranged that at the same time someone measured the angle of the sun at Alexandria by measuring the length of the shadow cast by a vertical pole whose length was also measured. The ratio of the length of the shadow to the length of the pole enabled them to work out the angle. They had measured the distance between Alexandria and Syrene previously. The angle at Alexandria was at 7 degrees to the vertical. This is illustrated in Fig 6.3.

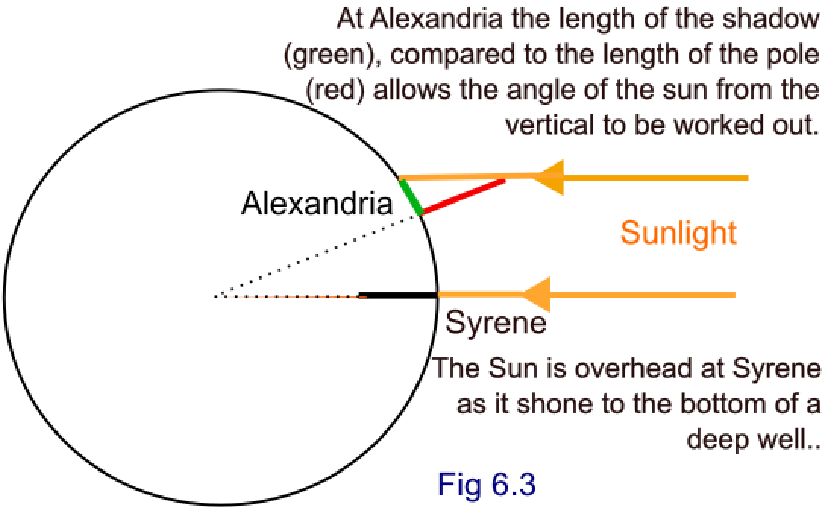


Fig 6.3

Fig 6.3 shows that the curvature of the Earth has caused the 7 degree difference. The Greek measurement of distance was different from our units, but in km the distance northwards of Alexandria from Syrene is about 800 km. This means that 7 degree is caused by a curvature round the Earth of 800 km. So 360 degrees would need 360/7 = 51.4 times this distance. This is just over 41,000 km which is near the correct answer of just over 40,000 km.

There is no need to do this experiment on a specific day. If you had a pole in London and one in Edinburgh, which is about 530 km due North, you could measure the angle at each location. The difference in the angles would then represent the curvature caused by the 530 km. You could then work out the answer in the same way. If we know the circumference of the Earth we can find the diameter – just divide by π. The answer for the diameter is 12,800 km. (The approximate value of π was first found by the Egyptians in 1650 BC.)

Distance and Diameter of the Moon.

The method that is explained below was used by Hipparchus who lived from 190 – 120 BC. It relies on observations during a lunar eclipse.

To explain how the method works there are a few facts that need to be known. If you look upwards into the sky at 30° to the horizontal and the moon were low in the sky you could make a guess as to how many moons would fit in top of one another to get to 30°. The answer is 60. *The moon is just 0.5° across*. In an eclipse of the Sun where the moon passes in front of the Sun then the Sun is almost exactly covered. So the Sun looks just 0.5° across also – (it is a lot further away, of course, but is also correspondingly bigger).

The 0.5° that the Sun is across means that the shadow cast by the Earth into space tapers like a cone with 0.5° at the apex of the cone. Fig 6.4 shows the idea where the sun is shining from the left. In this diagram the Earth is a centimetre or so across. If we drew the diagram properly to scale the apex of the cone would be way off the paper over a metre to the right. In real figures the shadow is a cone whose base has a diameter equal to the diameter of the Earth (12,800 km) and the apex of the cone has an angle of 0.5°. This enables the length of the cone to be worked out and it comes to 1,500,000 km approximately.

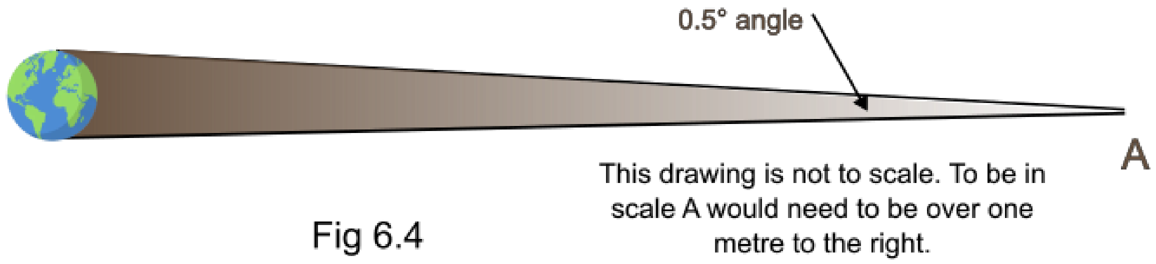


Fig 6.4

A lunar eclipse is caused when the Moon passes through the Earth's shadow. Fig 6.5 shows what happens during an eclipse of the Moon. Clearly from what we have just said just this a very squashed up picture! But it shows the ideas more clearly than something more spread out. At the distance of the Moon the Earth's shadow has a diameter larger than the Moon. So in a total eclipse of the Moon the Moon can spend some time in complete shadow. Fig 6.5 may help to make this clearer.

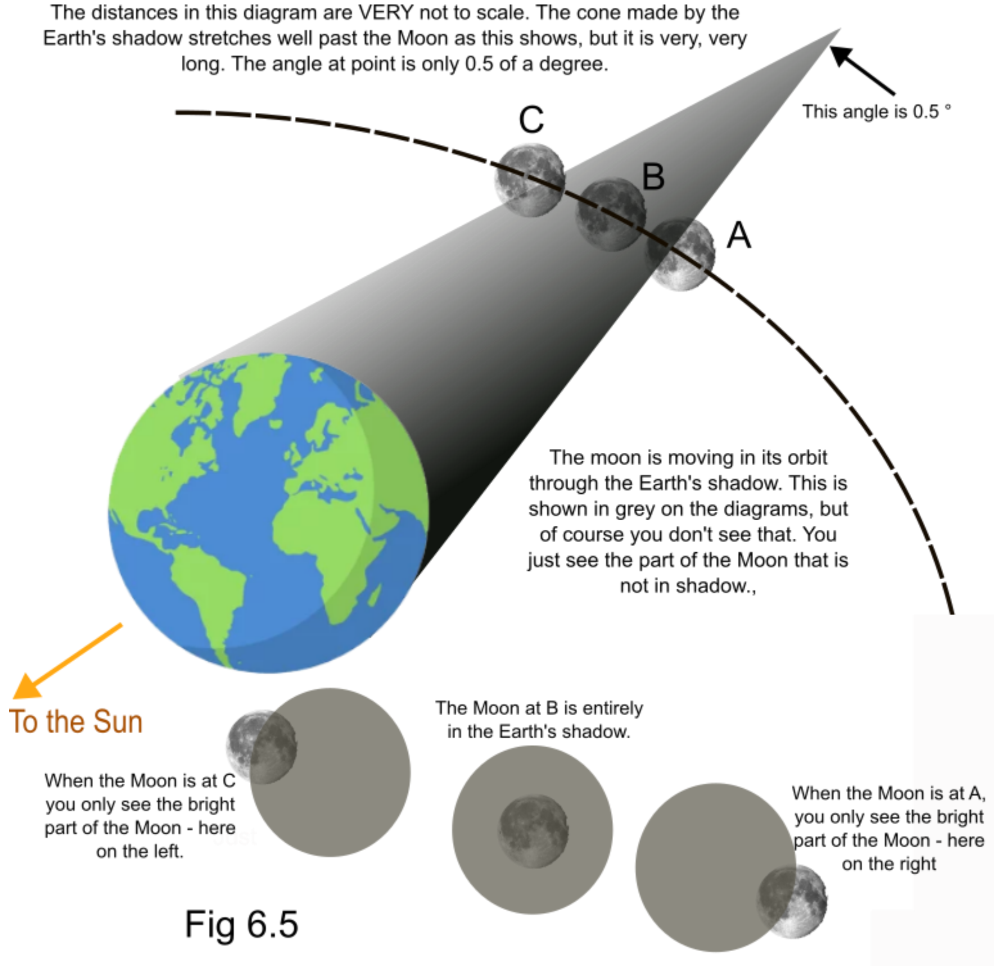


Fig 6.5

The gist of the method to find the distance of the Moon is as follows.

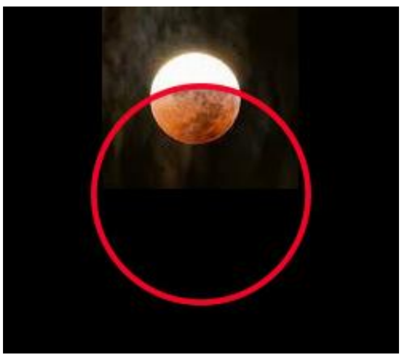
(a) We use what we see during an eclipse to work out the angle the shadow would offer to our eyes if we could see it. We can do this because we can see the curvature of the shadow on the surface of the Moon.

(b) If we know this angle and we know the geometry of the cone then we can work out how far away that particular bit of the cone is. This is at the distance of the Moon.

Here is more explanation of each of these.

(a) The dense shadow of the Earth is called the umbra. When the Moon is moving *into* the umbra the appearance is as in Fig 6.6(a). This is a real photograph – it is when the moon is entering the shadow, similar to the moon at A in Fig 6.5.

6.6(a)



6.6(b)

You can imagine the curve of the umbra completed to form a circle as in Fig 6.5(b). The diameter of the umbra can be measured against the diameter of the moon (0.5°) and turns out to be about 2.7 times larger – the red circle is 2.7 times larger than the moon. So the shadow at this distance looks to be about 1.33° (2.7 x 0.5°) .

(b) With the known diameter of the Earth we now have all we need to calculate the distance of the Moon and its size. Fig 6.7 shows how this can be done.

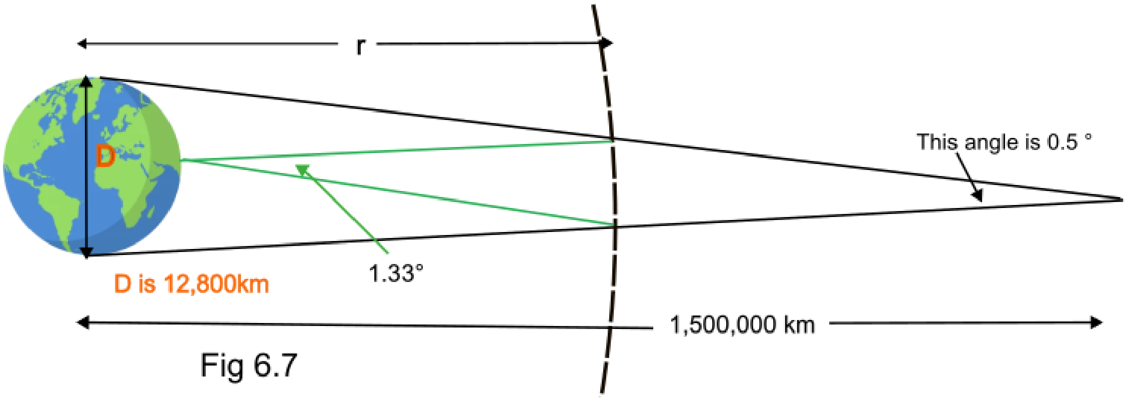


Fig 6.7

From the geometry of Fig 6.7 it is possible to work out the distance, r, at which the cone of the Earth's shadow, has a size as seen from Earth of 1.33°. We won't go through the maths but it comes out to be around 390,000 km. The diameter of the moon can also be worked out from the geometry of Fig 6.7 and comes out to be about 3,500 km.

So the Moon is 390,000 km away and has a diameter of 3,500 km and these figures come from observations of an eclipse of the Moon – together with the known diameter of the Earth.

Modern methods use laser ranging, by measuring the time taken for a laser fired at the surface of the moon to be seen reflected back.