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MOTION ON EARTH AND IN THE HEAVENS

How modern science began when people realized that the same laws of motion applied to the planets as to objects on Earth.

1.1 Galileo's Telescope

In the summer of 1609, Galileo Galilei, professor of mathematics at the University of Padua, began constructing telescopes and using them to look at the Moon and stars. By January the next year he had seen that the Moon is not smooth, that there are far more stars than are visible to the naked eye, that the Milky Way is made of a myriad stars and that the planet Jupiter has faint "Jovian planets" (satellites) revolving about it. Galileo forthwith brought out a short book, *The Starry Messenger* (the Latin title was *Sidereus Nuncius*), to describe his discoveries, which quickly became famous. The English ambassador to the Venetian Republic reported (I quote from Nicolson's *Science and Imagination*):

> I send herewith unto his Majesty the strangeth piece of news . . . ; which is the annexed book of the Mathematical Professor at Padua, who by the help of an optical instrument (which both enlargeth and approximateth the object) invented first in Flanders, and bettered by himself, hath discovered four new planets rolling around the sphere of Jupiter, besides many other unknown fixed stars; likewise the true cause of the *Via Lactae*, so long searched; and, lastly, that the Moon is not spherical but endued with many prominences. . . . So as upon the whole subject he hath overthrown all former astronomy . . . and next all astrology. . . . And he runneth

a fortune to be either exceeding famous or exceeding ridiculous. By the next ship your Lordship shall receive from me one of these instruments, as it is bettered by this man.

Galileo's discoveries proved to be at least as important as they were perceived to be at the time. They are a convenient marker for the beginning of the scientific revolution in Europe. By 1687, Isaac Newton had published his *Mathematical Principles of Natural Philosophy and the System of the World* (often called the *Principia* from the first word of its Latin title), and the first phase of the revolution was complete. The laws of motion and of gravity were known, and they accounted for the movements of the planets as well as objects on Earth.

1.2 The Old Astronomy

Let us review what was known before the seventeenth century about motion and astronomy. I will try to describe what humankind has known for thousands of years, forgetting modern knowledge gained from telescopes, space travel and so on. I will also ignore exceptions and refinements. The basic facts are obvious, qualitatively at least, to anyone. On the Earth, these facts are simple. Solid objects (and liquids) that are free to do so fall down. Otherwise, an effort of some sort is needed to make something move. A stone, once thrown, moves through the air some distance and then falls to the ground. But also a heavy object in motion, like a drifting ship, requires effort to stop it quickly.

The facts about the motion of the stars take longer to tell. I shall describe things as they appear from the Earth, as they would have been perceived say 3,000 years ago.

Thousands of "fixed" stars are visible to the naked eye. These all rotate together through the night sky along parallel circles from east to west. It is as if there were some axis, called the *celestial axis*, about which they all turned. The Pole Star, being very near this axis, hardly moves at all. Stars near the axis appear to move in smaller circles; stars further away in larger ones. The stars that appear to move on the largest circle are said to lie near the *celestial equator* (see Figure 1.1). The time taken to complete one of these

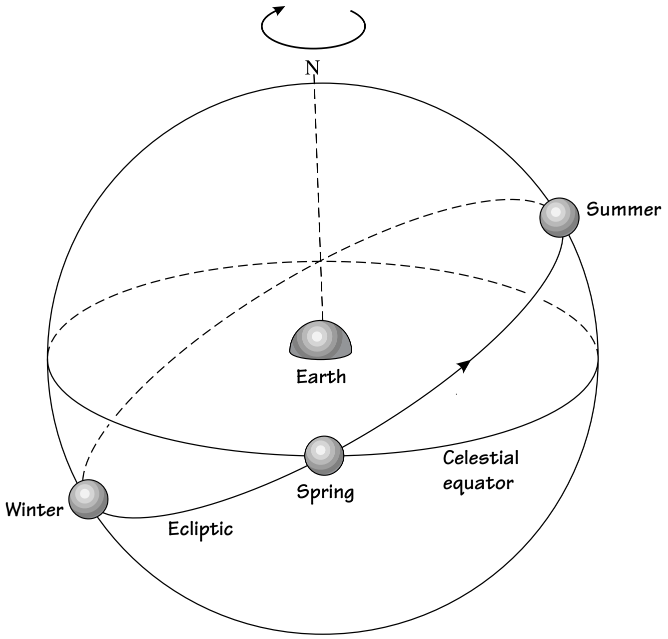

FIGURE 1.1 The "sphere of the fixed stars", which appears to rotate westward daily (as indicated by the arrow at the top). The Sun, relative to the stars, circuits eastward annually along the ecliptic.

apparent revolutions, 23 hours, 56 minutes, 4 seconds, is called a *sidereal day*.

The motions of the Sun, Moon and planets are more complicated. I shall describe their apparent motions *relative* to the fixed stars, because this is slower and somewhat simpler than the motion relative to Earth. The positions of the Moon and planets can easily be compared with those of the stars. The Sun is not usually visible at the same time as the stars, but we can work out what stars the Sun *would* be near, if only we could see them.

Relative to the stars, then, the Sun moves from west to east round a circle, called the *ecliptic*, taking $365\frac{1}{4}$ days to complete a circuit. Since

$$365\tfrac{1}{4} \times (24 \text{ hours}) = 366\tfrac{1}{4} \times (23 \text{ hours } \ 36 \text{ minutes } \ 4 \text{ seconds}),$$

this means that the Sun appears to circle the Earth in 24 hours. In a year the Sun appears to rise and set $365\frac{1}{4}$ times, but the stars rise and set $366\frac{1}{4}$ times.

The ecliptic (the path of the Sun) is tilted at $23\frac{1}{2}$ degrees to the celestial equator, so that the Sun moves to the north of the celestial equator in summer (the summer of the northern hemisphere) and to the south in winter. (See Figure 1.1.) The ecliptic crosses the celestial equator at two points, and the Sun is at one of these points at the spring equinox and at the other at the autumn equinox.

The Moon too appears to move round from east to west, near the ecliptic, and, of course, it waxes and wanes. The interval between two new moons (when the Sun and Moon are nearly in the same direction) is $27\frac{1}{3}$ days.

Lastly there are the planets, five of which were known up to 1781: Mercury, Venus, Mars, Jupiter and Saturn. They are often brighter than the fixed stars, and they move in much more complicated ways. Like the Sun and Moon, they appear to move relative to the fixed stars in large circles. These circles are tilted relative to the ecliptic by small angles, which vary from planet to planet. But, unlike the Sun, the planets do not move at a constant rate, nor even always in the same direction. Most of the time, they appear to move, like the Sun, west to east relative to the stars, but at rates that vary greatly from time to time and from planet to planet. Sometimes they appear to slow down and stop and go east to west temporarily. As examples, as seen from Earth, Venus completes a circuit relative to the stars in 485 days and Mars in 683 days. (This apparent motion comes about from a combination of the planet's true motion with the Earth's. The true periods of Venus and Mars are 225 and 687 days.)

What was made of all this before modern times? Ancient civilizations, like the Babylonian, the Chinese and the Mayan, had officials who kept very accurate records of the movements of the heavenly bodies. They noticed regularities from which, by extrapolating to the future, they were able to predict events like eclipses. One practical motive for their interest was to construct an accurate calendar. This is a complicated matter, because there are not a whole number of days in a year or in a month, nor a whole number of months in a year. Navigation was another application of astronomy. Astrology was yet another.

Yet these peoples did not try to *explain* their astronomical observations, except in terms of what we would call myth. The first people known to have looked for an explanation were from the Greek cities bordering the Aegean in the sixth and fifth centuries B.C. The problem of decoding the (Sir Thomas Browne quoted in Nicolson's book)

> Strange cryptography of his [God's] starre Book of Heaven

occupied some peoples' minds for about 2,200 years before it was solved. It needs an effort of our imagination to appreciate how difficult the problem was.

Some things were understood quite early, for example, that the Earth is round, and that the Moon shines by the reflected light of the Sun, the waxing and waning being due to the fraction of the illuminated side of the Moon that is visible from the Earth. For example, the full Moon occurs when the Earth is nearly between the Moon and the Sun, so that the whole of the illuminated side of the Moon is facing the Earth. In the fifth century B.C., Anaxagoras (who was expelled from Periclean Athens for teaching that the Sun was a red-hot rock) understood the cause of eclipses. An eclipse of the Sun is seen from a place on Earth when the Moon comes between the Earth and Sun and casts its shadow at that place. (Because the Moon is small compared to the Sun, the region in shadow on the Earth is small.) The Moon's path is tilted with respect to the ecliptic (the Sun's path), so an eclipse does not happen every month. The two paths cross each other at two points called *nodes*. An eclipse of the Sun occurs only when the Sun and Moon happen to be both simultaneously in the direction of one of these nodes. An eclipse of the Moon occurs when the Moon comes into the Earth's shadow. This happens only when, simultaneously, the Moon is in the direction of one node and the Sun in the direction of the other.

1.3 Aristotle and Ptolemy: Models and Mathematics

I will now move on to the ideas of Aristotle in the fourth century B.C. He had amongst other things a full theory of motion and of astronomy, which was (with some amendments) enormously influential for some 2,000 years. The story of the Scientific Revolution in the seventeenth century is in some ways the story of the escape from the influence of Aristotle's physics.

Aristotle contrasted "natural" motion and "forced" motion. On Earth, the natural motion of heavy bodies (made of the elements earth and water) was towards the centre of the Earth (which was considered also to be the centre of the universe). In the heavens, the natural motion was motion in a circle at constant speed. On Earth, there were also forced departures from natural motion, caused by efforts like pushing, pulling and throwing. In the heavens, only the natural circular motion could occur, lasting eternally unchanged. Thus the heavens were perfect and the "sublunary" regions were not. Stones fall, but stars do not.

To explain the complicated motions of the heavenly bodies, Aristotle invoked a system of great invisible spheres, nested inside each other, and each with its centre at the Earth. The spheres were made of a fifth element ("quintessential") different from the four "elements" (earth, water, air and fire), which he supposed to make up everything sublunary. Each sphere was pivoted to the one just outside it at an axis, about which it spun at a constant rate. The axes were not all in the same direction. The fixed stars were attached to the outermost sphere. Next inside was a system of four spheres designed to get right the motion of Saturn, the planet attached to the innermost of these four spheres. Aristotle, careful to be consistent, then put three spheres inside just to cancel out Saturn's motion. Then more spheres gave successively the motion of Jupiter, Mars, the Sun, Venus, Mercury and the Moon. He ended up with a total of 55 spheres. With this wonderful machinery, Aristotle could get the observed motions roughly right.

This theory may seem far-fetched to us. We do not find it easy to visualize these great, transparent, unalterable spheres. However the ancients thought about this cosmology, by the middle ages people had begun to envisage the celestial spheres as solid things. One then had an example of what we may call a *mechanical model*. We shall meet several such in the course of this book. It is an explanation based upon imagining a system built like a machine or a mechanical toy. It does nearly all that such a machine would do, except that some properties are pushed to extremes. The fifth element is a bit different from anything we know on Earth: more transparent than glass, and no doubt perfectly rigid.

Aristotle's model of planetary motion did not fit all the observations, and, by the second century A.D., it had been superseded by a synthesis due to Ptolemy of Alexandria. The Earth was still fixed at the centre, and motion in circles was still assumed to be the right thing in the heavens. But, to get the motions right, Ptolemy (following Apollonius and Hipparchus) took the planets to revolve in small circles ("epicycles") whose centres were themselves rotating about the Earth in bigger circles. (It is easy to see how, for example, a planet could sometimes reverse the direction of its apparent motion when the motion in the small circle was taking it backwards with respect to the motion in the large one.) There were other complications. The centres of the larger circles were not quite at the position of the Earth, and the circles were not traversed at quite constant speed (as viewed from their centres, at any rate). With a sufficient number of such devices, Ptolemy was able to fit the observed motions very accurately. Even his system did not get everything right at the same time. For example, the Moon's epicycle would make the apparent *size* of the Moon vary much too much, because its distance from the Earth varied too much.

Ptolemy provided no mechanical mechanism for the motions. His was more of a *mathematical* (specifically, geometrical) theory than a mechanical model. This too is something we will meet again. When people despair of imagining a physical model, they fall back on mathematics, saying: "Well the mathematics fits the facts, and maybe it is not possible to do better. Maybe we are not capable of understanding more than that".

Before leaving the ancient world, we should note one more piece of knowledge that had been gained. This was some idea of size. In the third century B.C., Eratosthenes, librarian at Alexandria, had determined the radius of the Earth from a measurement of the direction of the Sun at Alexandria at noon on midsummer day. It was $7\frac{1}{2}$ degrees from being vertically overhead. On the Tropic, 500 miles south, the Sun would be overhead at the same time. From this it follows that the circumference of the Earth is

$$\frac{360}{7.5} \times (500 \text{ miles}) = 24{,}000 \text{ miles}.$$

Ptolemy later made an estimate of the distance of the Moon, using its different apparent positions (parallax) as viewed from different places on the Earth. The distance of the Sun could be inferred from the extent of the Sun's shadow at a solar eclipse and the extent of the Earth's shadow at a lunar eclipse, but the ancient estimates were badly out.

Aristotle and Ptolemy had these beliefs in common: that the Earth was at rest, that the motion of the heavenly bodies had to be constructed out of unchanging *circular motion* but that the motion of bodies on Earth was of a quite different nature. These beliefs dominated scientific thought, first in Arab lands from the eighth to the twelfth century, then in medieval Europe until the sixteenth century.

The ancient world became aware that the Moon had weight, like objects on Earth, and there had to be a reason why it did not fall out of the sky. For example, Plutarch wrote,

> Yet the Moon is saved from falling by its very motion and the rapidity of its revolution, just as missiles placed in slings are kept from falling by being whirled around in a circle.

People were certainly aware of the shortcomings of the Aristotelian and Ptolomaic views. There were some strange coincidences in Ptolemy's theory. The periods of revolution were about one year in the *large* circles of the inner planets (Mercury and Venus) and also about one year in the *small* circles of the outer planets. Aristarchus in the third century (quoted by Archimedes) had suggested that everything would be simpler if the Sun, not the Earth, was at rest.

As regards motion on Earth, Aristotle's doctrine had great difficulties with something as simple as the flight of an arrow. This was not a "natural" motion towards the centre of the Earth (except perhaps at the end of its flight), so what was the effort keeping it in motion after it had left the bow? Aristotle said that a circulation of the air followed it along and kept it going. It is not hard to think of objections to this idea. In the sixth century, the Christian Philoponus of Alexandria made a particularly effective critique of Aristotle's physics. (See Lloyd's book *Greek Science after Aristotle*.)

In the middle ages, several attempts were made to improve on Aristotle's account of motion. Nevertheless, in the thirteenth century

Thomas Aquinas argued that Aristotelian physics was compatible with Christian theology, and the two systems of thought got locked together. When Galileo published his dialogues in the 1630s, it was still the Aristotelian viewpoint he was combating (represented in the dialogues by one of the disputants, Simplicio).

1.4 Copernicus: Getting Behind Appearances

Nicolas Copernicus, born in 1473, was a Polish canon who worked at the University of Cracow and later in Italy. He developed a Sun-centred theory of the Solar System, in which the Earth was just another planet, circulating the Sun yearly between Venus and Mars. (Actually, the centre of the planetary motions was taken to be slightly displaced from the Sun.) He assumed that the planetary motions had to be built up out of circular motions, and so he had a system of epicycles and so on, not much less complicated than Ptolemy's. Copernicus also assumed that the "fixed" stars were indeed fixed, their apparent daily motion being due to the Earth's spinning on its axis. He nursed his ideas for some 40 years and published his complete theory (in *De Revolionibus Orbium Coelesium*) only in the year of his death, 1543. Copernicus dedicated his book to Pope Paul III, but a colleague, Andreas Osiander, added a cautious preface saying that the Sun-centred system was not to be taken as the literal physical truth, but only as a geometrical device for fitting the observations.

In a Sun-centred system, many things fall into place. The reason that planets sometimes appear to reverse their motion relative to the stars and move "backwards" (that is, east to west instead of west to east) is that the forward motion of the Earth can, at certain times, make a planet appear, by contrast, to go backwards. In Ptolemy's system, the order of planets from the Earth was to some extent arbitrary, but in Copernicus' system there is a natural order of planets from the Sun, with the periods of revolution increasing with distance: Mercury (88 days), Venus (225 days), Earth (1 year, i.e., 365 days), Mars (1.9 years), Jupiter (11.9 years) Saturn (29.5 years). The fact that Mercury and Venus never appear far from the Sun is explained because they really *are* nearer the Sun than the Earth and other planets.

But what were the drawbacks of the Copernican system, given that it seems (to us) so much more natural than Ptolemy's picture? There were two objections, each of which might be thought to be fatal. Since the Earth moves (roughly) in a circle of radius 150,000,000 kilometres, we ought to be seeing the fixed stars from a different standpoint at different times of the year, and this should be evident. This effect is called *annual parallax*. The only way to avoid it is to assume, as Copernicus did, that the stars are at distances very large compared to this 150,000,000 kilometres, so that the annual parallax was too small to be seen. This seems a rather weak excuse: the effect is there, but unfortunately it is too small for you to see it. But it turned out to be true. The nearest star has an annual parallax of only a few hundred thousandths of a degree (i.e., its apparent direction varies by this amount at different times of the year). This is much too small to see without a good telescope. As we shall see in later chapters, very large numbers *do* turn up in nature, and as a result some things are very nearly hidden.

In fact, people had already used a weaker version of this argument, also concerned with a parallax effect. The view of the stars ought to be slightly different at different places on the Earth. For this effect to be unobservable, one must assume that the stars are very far away compared to the Earth's radius (6,378 kilometres).

The second argument against the Copernican system is this. The rotation of the Earth about the Sun gives it a speed of about 100,000 kilometres per hour, and the daily spin of the Earth gives a point on the equator a speed of 1,670 kilometres per hour. Why do we not feel these speeds? Why is the atmosphere not left behind? Why is a projectile not "left behind"? It appears to us obvious that the Earth is at rest. Copernicus of course recognized the difficulties with his theory:

> Though these views of mine are difficult and counter to expectation and certainly to common sense . . .

Galileo was the first to understand fairly clearly the fallacy underlying the second objection to Copernicanism.

It happened that some natural events occurred in the latter half of the sixteenth century that challenged the Aristotelian view. In 1572 there appeared a supernova, that is, a "new" star, which