Chapter 2

The Solar System

It may seem strange to have a chapter on the early history of astronomy and the Solar System in a book dedicated to astrophysics, a subject most people would believe applies more to stars and galaxies. However, there is a surprising amount of astrophysics that can be discussed here, as we shall see.

Although a whole book could be written on the subject of Solar System astrophysics, we will limit the discussion mostly to the early history, and to the development of astronomy that led to an understanding of the behavior of planetary orbits and a couple of smaller, but equally important, topics. We will not be covering such areas as planetary geology, planetary atmospheres and the like. There are several books dedicated specifically to those topics listed in the appendices. Naturally, some Bronze Age and Iron Age history will need to be covered, so as to set the scene for the revolution in astronomy that occurred in the Middle Ages.

So without further ado, let us begin our journey…

2.1 Early History of Astronomy

2.1.1 The Geocentric Universe

For most of history, the prevalent view was that Earth was the center of the universe,[1] and that all celestial objects revolved around it. Think about this for a minute; all astronomy was naked-eye astronomy and so was limited to the stars,

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[1] Don't confuse this "universe" with the one we are familiar with today. The universe then was only all that could be seen with the naked eye and was often referred to as "the Heavens."

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planets, comets, meteors, the Moon and the Sun. Moreover, the real nature of the aforementioned objects was unknown, and either given a supernatural, or religious, identity.

This view is known as the geocentric, or Earth-centered, point of view, and can be easily understood, as it really does seem as if the everything revolves around us; the Sun and Moon and planets rise in the east and set in the west, along with the stars. There is no physical sense of movement of Earth whatsoever, and it took quite a while before it was shown that Earth was revolving on its own accord.[2]

The most obvious historical objects of any astronomical significance must be the magnificent stone henges built throughout Europe and Asia, such as Stonehenge and Brodgar, where stone pillars are aligned, so we believe, to indicate the rising and setting of the summer and winter solstice Sun, etc. But the earliest known written astronomical records are clay tablets from Babylonian and Sumerian[3] civilizations, and later Egyptian[4] hieroglyphs. The former two were especially interested in determining the appearance of the new Moon for their calendar, while the latter focused their attention on Sirius, whose appearance seemed to be connected with the flooding of the Nile, a very important event to them.

It is important to note here that these civilizations, and even those that followed, tended to immerse their astronomy within a mystical and religious framework, and it was the action of gods that dictated the events they saw in the sky.

It wasn't until the appearance of the Greeks that things really started to take a more scientific aspect. They, like the Egyptians and Sumerians before them, extended the idea of a domed heaven to that of a giant sphere—the *celestial sphere*—that carried the stars on its inner surface and rotated around a vertical, that is to say, north-south axis.

We still use this idea today, especially when referring to coordinate systems used in astronomy, but we know now of course that the apparent rotation of the celestial sphere is in reality due to the actual rotation of Earth.

The Greeks started to devise some explanations for familiar phenomena that occurred in the sky. For instance, the phases of the Moon were quite familiar to the ancient civilizations, as well as the annual motion of the Sun, but it was the Greeks that realized the position of the Sun and Moon had to coincide for eclipses, whether they be solar or lunar, to occur.

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[2] This is a great question to ask at public star parties—"How do you know that Earth is revolving, and that rather it is the sky (and all it contains) that is revolving instead. Do we feel Earth move? The solution to this problem is to mention Jean Foucault, who, in 1851, with an actual demonstration using a pendulum, showed the effect of the rotation of Earth.

[3] The Sumerians based their calculation on a base 60 format, not the base 10 we use today. We still use a remnant of this system, our angular measurement scheme, 60°, 60 arc minutes, and 60 arc seconds, and the time system.

[4] The Egyptians, like the Babylonians, kept to a lunar cycle but eventually changed to a 12-month, 30-day system. However, in order to make the new year coincide with the appearance of Sirius, they added extra days to the calendar, giving us the 365-day year.

However, there were problems on the horizon. The five planets known at that time—Mercury, Venus, Mars, Jupiter and Saturn—posed problems. They moved independently to the stars, Sun and Moon, along a path called the zodiac, in periods ranging from a quarter of a year for Mercury to 29 years for Saturn. This motion however was not periodic; some objects seemed to slow down, stop, and then reverse their path along the zodiac for a short time, then reverse again and continue in an eastward direction. This *retrograde motion* was even known to the Babylonians.

Furthermore, Mercury and Venus were always found in the vicinity of the Sun, sometimes lagging behind it, and at other times overtaking it. At one time it was even thought that Venus was in fact two stars—the morning star when it rose in the sky before and west of the Sun, and the evening star when it set after and east of the Sun.

2.1.2 The Scientific Method

To present a full and detailed account of the scientific models that were proposed in early history is far beyond the scope of this book, so we shall confine ourselves to just the salient points, events that eventually led to a model of the heavens that was adopted for nearly 1,500 years. Before we do that, however, it is important that we discuss what is known as the *scientific method.*

Basically, the scientific method is the way that science is carried out today, irrespective of what field of science we are talking about, and for any scientific model or theory or idea to be taken seriously, the scientific method must be shown to have been applied. A dictionary describes the method thus: "…the scientific method is a method or procedure that has characterized natural science since the seventeenth century, consisting in systematic observation, measurement, and experiment, and the formulation, testing, and modification of hypotheses."

What it comes down to is this—one tries to describe what is observed, with an idea, or a hypothesis, and then one tests this idea, or hypothesis, along with a prediction of what the result should be. Depending on the results of the test, one either adopts the hypothesis or alters it slightly and does the test, or experiment, again, or completely discards the hypothesis as being utterly wrong.

Once the hypothesis has been tested repeatedly, often by different people in different laboratories (but using the same or similar equipment), and is shown to be successful after many, many repeated experiments, only then can the hypothesis be termed a theory.

There are difficulties, however, in following such a formulaic statement of the method, however. Though the scientific method is sometimes presented as a fixed sequence of steps, it is often more helpful to consider the steps more as general principles. In fact, not all steps take place in every scientific inquiry (or to the same degree), and they are not always in the same order. As the Victorian scientist William Whewell said, “invention, sagacity, genius” are required at every step:

What follows are the basics of the scientific method:

Question—The question can refer to the explanation of a specific observation, as in “Why do things fall down when dropped?” but can also be open-ended. This step also means looking up and evaluating evidence from previous experiments, personal scientific observations or assertions and/or related work of other scientists.

Hypothesis—A hypothesis is a conjecture, based on knowledge obtained while formulating the question that may explain the observed behavior of a part of our universe. The hypothesis might be very specific, e.g., Einstein’s equivalence principle.

Prediction—This step involves determining the logical consequences of the hypothesis. One or more predictions can then be selected for further testing. The more unlikely that a prediction would be correct simply by coincidence, the more convincing it would be if the prediction were fulfilled.

Testing—This is the part where, say, an experiment is performed to see whether the real world behaves as predicted by the hypothesis. The purpose of the experiment is to determine whether observations of the real world agree with or conflict with the predictions derived from the hypothesis. If they agree, confidence in the hypothesis increases; otherwise, it decreases.

Analysis—This involves determining what the results of the experiment show and deciding on the next actions to take. If the results do not support the hypothesis, a new hypothesis is required; if the experiment supports the hypothesis but the results are not strong enough for high confidence, other predictions from the hypothesis must be tested.

There are a few other components to the scientific method that can be done even when all the iterations of the steps mentioned have been completed:

Replication—If an experiment cannot be repeated to produce the same results, no matter who does the experiment, this implies that the original results were in error. Thus, it will be necessary for the experiment to be performed several times.

External review—The process of peer review involves experts, often in the same field of science, evaluating the experiment, who give their opinions anonymously to allow them to give unbiased criticism. If the work passes peer review, which could require new experiments requested by the reviewers, it would often be published in a peer-reviewed scientific journal.

Data recording and sharing—Scientists must record all data very accurately in order to reduce their own bias and aid in replication by others. They must be willing to supply this data to other scientists who wish to replicate any results.

The most successful explanations of the natural world, ones that seek to explain and make accurate predictions in a wide range of circumstances, are called scientific theories.

2.1.3 *Ancient Greek Science*

The reason the scientific method was discussed at this point is because the Greeks were the first people that tried to explain what they saw, using mathematics models and not relying on mystical reasons and religious explanations, and thus were using, sort of, the scientific method.

Admittedly, they got it wrong quite a few times, but nevertheless they started the process. To describe in detail the main ideas and introduce all the people that developed them would literally fill up several books, so we shall just give the salient points and end up with the model that was the basis of astronomy for over 1,500 years.

Many Greek and Egyptian mathematicians and philosophers developed models that were added to or refined over a period of 500 years, among them Leucippus, Democritus, Pythagoras, Heraclides, Philolaus, Plato, Eudoxus, Aristotle, Hipparchus, and, last but not least, the man who gathered together all these ideas and formed a working model, Claudius Ptolemaeus.[5]

Basically, the explanation, or model, goes something like this.

To begin with, Earth is at the center of the universe and is surrounded by 56 concentric, transparent crystal spheres, rather like the Russian dolls one can buy, where you take the outer one off and inside is a smaller doll, and you take that one off and inside there is a smaller doll…you get the idea.

The outermost sphere is the "celestial sphere," upon which the stars reside. The motion of this outermost sphere was transmitted to an outer sphere of Jupiter; and between the inner sphere of Jupiter and the outer sphere of Saturn lie three additional spheres, and so on and so on with Mars, Venus and Mercury, as well as spheres for the Moon and the Sun. and all these spheres were connected by various linkages. As you can see, it is complicated!

In addition, there were a few other ideas that were adhered to and proved quite difficult to get rid of. One of these was of such appeal that it took a very long time for it to be discarded and replaced. It was this:

> "The universe is perfect and unchanging, and thus its constituents are perfect and must move along perfect orbits. Since the circle is the perfect curve and the sphere a perfect solid, it follows naturally that the heavenly bodies, including Earth, are spheres".

Although the model seemed, initially, to correctly describe what was observed, it did have a few problems, as was mentioned earlier, in that Mercury and Venus are always close to the Sun, the retrograde motion of Mars, as well as the changing brightnesses of the planets, and so on. To explain these anomalies, corrections and additions were made to the model such that it became very complicated.[6]

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[5] There were, of course, many more people who contributed ideas, but those listed were, more or less, the main players.

[6] Don't think that everything they did was wrong however, Greek mathematicians managed to work out the distance and size of the Moon and Earth, as well as the precession of the equinoxes, to name but a few.

Another idea that must be mentioned here is that, surprisingly, the Greeks were aware of the phenomena of parallax—the apparent displacement of an object owing to the motion of the observer, in this case the motion of Earth.[7] They believed that the apparent shift of the stars due to the motion of Earth around the Sun (!) would be visible and measurable. They didn't find any, not surprisingly, as the distances to the stars are so immense that the crude instruments of the Greeks could not detect the parallax shift. However, Aristarchus[8] guessed the reason and pointed out that the orbit of Earth was very small compared to the size of the celestial sphere, so that it was like the center of a sphere of infinite radius and thus immeasurable.

However, not even Archimedes would accept this explanation, as the Greeks could not grasp such concepts as infinity. Thus the idea that Earth revolved around the Sun was discarded, and rather the reverse scenario was the true one—the Sun revolved around a stationary Earth, a concept that was adhered to for a very long time.

2.1.4 The Ptolemaic System

The man who collected all these ideas and placed them within a coherent model was Claudius Ptolemaeus, also known as Ptolemy of Alexandra. He is the author of the *Almagest*,[9] a book that contained a full description of all astronomical knowledge of his time as well as his own contributions. It became the astronomical Bible and formed the basis of western astronomy throughout the Middle Ages.

Of particular interest are the introductory chapters that deal with what can be called the postulates of Ptolemaeic astronomy. In them, he provides convincing arguments as to why Earth is spherical, dismisses the idea of a spinning Earth and instead assumes Earth to be immovable at the center of the universe, "a point compared with the surrounding star-sphere."

In the Ptolemaic system, each planet moves uniformly inside a small circle, called an *epicycle*, the center of which moves along the circumference of a larger circle, the *deferent*, with the center of the deferent situated a short distance from the center of Earth, at a different point for each planet. The following diagram, Fig. 2.1, will illustrate this.

The whole system was then assumed to rotate slowly around its common axis, thus accounting for the precession of the equinoxes. In this way, it was possible to account for the irregular motions of the planets quite accurately but at the same time preserve the basic idea of motion along circles with constant radii and constant speed.

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[7] This topic was covered in detail in Chap. 1.

[8] Aristarchus was a lone voice at this time, as he did propose that the Earth, Moon and five planets revolved around a motionless sun. The work in which he put forward this remarkable idea is alas, lost to us, but is reported by such authorities as Archimedes and Plutarch. There can be no doubt that Aristarchus was indeed the first to propose a sun-centered universe.

[9] This is the name given it by its Arabic translators.

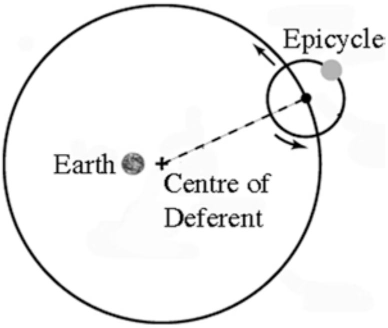

Fig. 2.1 Epicycles and deferents

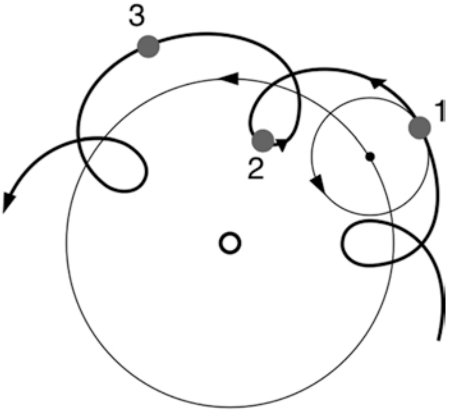

Fig. 2.2 Retrograde motion illustrated

In this system it was easy to see how the retrograde motion of Mars arose. As the planet moved along its epicycle, it would, at one time be moving, say, in a left direction, Position 1, but at a later time it would be moving towards the right, Position 2, seemingly moving backwards, and at Position 3, it would continue its leftward motion (see Fig. 2.2).

The Moon had a similar setup, but its epicycle revolved in an opposite direction to those epicycles of Mars, Jupiter and Saturn, to account for its differing speed at full and new phase, compared to the other phases.

Mercury and Venus, too, were treated differently from the other planets to account for the fact that they were always seen in close proximity to the Sun. For this reason, the centers of their epicycles had to remain on the same line as that of the Sun from Earth, and their periods on the deferents had to be the same as that of the Sun, namely 1 year (see Fig. 2.3).

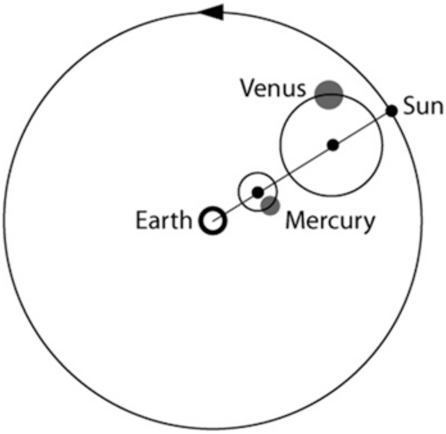

Fig. 2.3 The Earth-Sun line

In this way, Ptolemy built up his system, adding further epicycles and deferents whenever the data warranted it, until at the end, he had 40 epicycles, including the celestial sphere. This, now very complicated, model remained unchallenged for centuries, with the idea of Earth at the center of the universe.

What followed can be considered the Dark Ages in the development of astronomy in Europe, and even though some enlightened people attempted to continue the work of the Greek mathematicians and philosophers, such as Thomas Aquinas (1225?–1274) and Roger Bacon (1214?–1294), much was lost. Indeed Roger Bacon, who advocated the study of science, was accused of witchcraft by the Church, thrown into prison for 10 years and his work forgotten. It was 400 years before his work was published.

Although the study of astronomy and science languished in Europe, it flourished in the Arabic world. Arab scientists kept the knowledge gathered by the Greeks alive, developed mathematics, especially algebra, translated much of the Greek work into Arabic (which fortunately was later translated into European languages), and it was probably about this time that the first custom-built astronomical observatories were erected. In fact, it can be said, with some justification, that without the flourishing world of Arabic science, and astronomy in particular, much would have been lost, and the further development of astronomy would have taken place at a much later date.[10]

We now move on to when astronomy was resurrected in Europe, and the true development of science in the western world begins.

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[10] Just think of some star names—Rigel, Vega, Betelgeuse, to name but a few—that have Arabic roots.

2.1.5 The Copernican Revolution

We begin our story in the sixteenth century, in Poland, where a man called Niklas Koppernigk, but more famously known as Copernicus, put forward several new ideas, that, although not accepted initially, really did cause a revolution in deposing the then accepted view of the Earth-centered universe.

Copernicus was a canon in the Church, working in the small, sleepy town of Fraunberg, having acquired a well-rounded education, and was proficient in medicine, jurisprudence and astronomy, although there was no indication that he was about to set the scientific world on fire.

He sent a short manuscript, in Latin—*Commentariolus*—to some friends, summing up his ideas in seven propositions, or assumptions, and they are listed here:

- There is no one center of all the celestial circles or sphere.
- The center of Earth is not the center of the universe, but only of gravity and of the lunar sphere.
- All the spheres revolve around the Sun as their midpoint, and therefore the Sun is at the center of the universe.
- The ratio of Earth's distance from the Sun to the height of the firmament is so much smaller than the ratio of Earth's radius to its distance from the Sun that the distance from Earth to the Sun, in comparison with the height of the firmament, is imperceptible.
- Whatever motion appears in the firmament arises not from any motion of the firmament but from Earth's motion.
- What appears to us as motions of the Sun arise not from its motion but from the motion of Earth and our sphere, with which we revolve around the Sun, like any other planet. Earth has, then, more than one motion.
- The apparent retrograde and direct motion of the planets arises not from their motion but from Earth's. The motion of Earth alone, therefore, suffices to explain so many apparent inequalities in the heavens.

As you can see, this is all quite revolutionary. Note that the two most fundamental innovations in the list are,[11] of course, that the Sun and not Earth is at the center of the universe—the *heliocentric system*, and that it is the motion of Earth that accounts for the apparent daily rotation of the celestial sphere, as well as other "apparent inequalities in the heavens."

However, don't make the mistake in thinking that he got it all correct—he didn't. For instance, he still believed that everything moved in circles, that there was a sphere of fixed stars beyond the planets, and in fact, to account for the varying velocities of the planets in their orbits, he had no choice but to revert to the epicycles of the Ptolemaic system, since circular motion (or a combination of circular motions) was the only possible one. In the end he had a system of 36 (some histori-

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[11] But recall that Aristarchus had proposed these ideas over 1,000 years earlier!

cal researchers suggest 38) circles that would completely explain the entire structure of the universe.[12]

Initially, there wasn't much reaction, but over time word slowly spread. He continued, over many years, to refine his measurements, and eventually published a six-volume work entitled *De Revolutionibus*, containing all of his ideas along with expositions of mathematical astronomy, spherical trigonometry, star catalogs, descriptions of planetary orbits, etc.

However, this wonderful endeavor hasn't got a happy ending. Although Copernicus was recognized as a great astronomer, his ideas were ignored, even ridiculed.[13] All the previous classical arguments against an Earth that moved were resurrected and passages from the Bible were cited to refute him. It is said that he died, on May 24, 1543, only a few hours after he had received one of the first copies of his book. It took some time for Copernicus and his ideas to gain acceptance. The real significance of the heliocentric, or Sun-centered, system lies in the immensity of its conception, rather than in the discovery itself. With his concept of a moving Earth, Copernicus laid the cornerstone for modern astronomy.

2.1.6 Tycho—The Great Observer

We are now going to briefly discuss a man whose observations laid the groundwork for the first truly mathematical theories of planetary astronomy. That man was Tycho Brahe (1546–1601). Tycho had a very eventful life, full of intrigue and a fair amount of danger.

It was well known that Tycho was a great womanizer, to such an extent that in a duel over a woman part of his nose was cut off, and thereafter he wore a false one of silver and gold. What is less known is that he was also an astrologer, an alchemist and had his own theory of planetary motion that disagreed with the Copernican system. In it he stated that the five known planets revolved around the Sun, which in turn revolved around Earth, with the whole celestial sphere turning around Earth once a day.

What is important, however, is that although not a mathematician, he was ingenious at designing and constructing astronomical instruments at his extensive private observatory, along with his outstanding ability as an observer. Over his lifetime, he made innumerable accurate measurements of the positions, in the sky, of the planets and stars. These measurements, and the following analysis of them, are probably, in this author's opinion, the greatest pieces of pre-telescope astronomical work done.

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[12] At about the same time, Thomas Digges (1546–1595), an English member of Parliament, mathematician and astronomer, expounded the Copernican system in English, but more importantly, discarded the notion of a fixed shell of immoveable stars and instead proposed an infinite number of stars at varying distances. He was also first to postulate the "dark night sky paradox," later referred to as "Olber's paradox." We shall discuss this paradox in the final chapter.

[13] Only one man believed in the Copernican system, and that was Giordano Bruno. He taught it, defended it with courage and died for it. He was called before the Roman Inquisition, tortured, and then burned alive at the stake.

2.1.7 *Kepler—The Great Theoretician*

Kepler[14] (1571–1630) worked as an assistant to Tycho, and over several years used his observations to develop ideas of his own that he was formulating.

However, the end result was worth the effort, as he developed three laws of planetary motion[15] that are still used today, whether they be for planets, asteroids, comets, and even, in a modified way, for the orbits of stars around the Milky Way.[16]

He realized that he could get an accurate model of the motion of the planets around the Sun[17] if one dismissed two previously held concepts.[18] These were:

- circular motion
- uniform or constant motion.

By discarding these concepts Kepler was able to successfully describe the behavior of the planets around the Sun.

When one looks at the laws, a couple of them may seem rather odd, and not at all easily understood. However, after giving the formal statement of the laws, we will present easily understood explanations.

The laws are:

1. All planets move in elliptical paths, with the Sun at one focus (the law of ellipses) (Fig. 2.4).
2. An imaginary line that is drawn from the center of the Sun to the center of the planet will sweep out equal areas in equal intervals of time (the law of equal areas).
3. The squares of the periods of revolution of the planets around the Sun are proportional to the cubes of their mean distances from the Sun (the law of harmonies) (Fig. 2.5).

$$P^2 = a^3$$

Here are explanations of these rather formally written laws.

Kepler's first law—sometimes referred to as the law of ellipses—tells us that planets orbit the Sun in a path described as an ellipse. A more mathematical description of an ellipse would be "an ellipse is a special arc in which the sum of

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[14] Kepler was also an astrologer, and his mother was tried for being a witch. He obviously had a lively childhood.

[15] Remember that this work was done pre-calculus and was developed using trigonometry and algebra. Amazing!

[16] Kepler did a lot more than just developing his three laws, most of which were incorrect. It is his laws of planetary motion for which he is justly famous.

[17] Except for Mercury, which presented problems until Einstein explained what was going on.

[18] He also dismissed the idea of the layers upon layers of spheres model. He believed forces made the planets move.

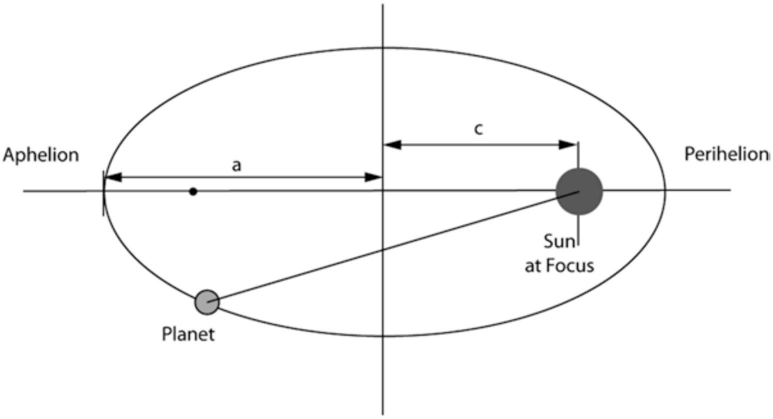

Fig. 2.4 Diagram to illustrate the parameters of Kepler's First Law

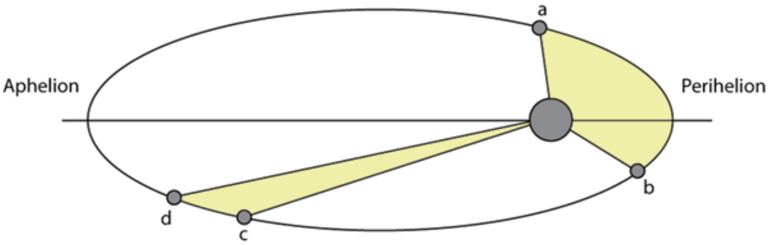

Fig. 2.5 Illustration of Kepler's laws

the distances from every point on the curve to two other points is a constant, the two other points being known as the *foci* of the ellipse."[19] The closer together these foci are, the more closely the ellipse resembles a circle. In fact, a circle is the special case of an ellipse in which the two foci are at the same location. Thus Kepler's first law is very simple: All planets orbit the Sun in an elliptical orbit with the Sun being located at one of the foci of that ellipse.

Notice in the diagram illustrating the first law that there are two additional quantities, a and c. The former is the distance from the center of the ellipse to the end of its longest axis, and is called the semi-major axis, a. The latter quantity, c, is the distance from the center of the ellipse to a focus (either one). Using these quantities one can get a measure of the *ellipticity, e,* of the ellipse, which quantifies how elliptical the ellipse is.[20] In other words, is the orbit almost circular, slightly squashed, or like a thick cigar? An example is given in Math Box 2.1.

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[19] The Sun is at one focus, there is nothing at the other, it is just a mathematical entity.

[20] I apologize for the oddness of this sentence, but there isn't really any other way to write it.

Math Box 2.1 Eccentricity of an Ellipse

The eccentricity of an ellipse is given by

$$e = \frac{c}{a}$$

An asteroid is discovered with the following parameters:

$$a = 3.00 \times 10^8 \text{ km}$$

$$c = 1.05 \times 10^8 \text{ km}$$

Therefore, the eccentricity is given by

$$e = \frac{1.05 \times 10^8}{3.0 \times 10^8}$$

$$e = 0.35$$

The eccentricity of Earth's orbit is currently about 0.0167; Earth's orbit is nearly circular. Over millennia, the eccentricity of Earth's orbit has varied from nearly 0.0034 to almost 0.058 as a result of gravitational attractions typical of the planets. Mercury has the greatest orbital eccentricity of any planet in the Solar System, with an e of 0.2056. Before its demotion, Pluto was considered to be the planet with the most eccentric orbit, $e = 0.248$, and the Moon's value is 0.0549. Many of the asteroids have orbital eccentricities between 0 and 0.35, with an average of 0.17. These comparatively high eccentricities are believed to be due to the influence of Jupiter and to past collisions.

The second law, although appearing a tad strange, is actually quite easy to understand. Kepler’s second law—sometimes referred to as the law of equal areas—describes the speed at which a planet will move while orbiting the Sun. Again, refer to the diagram under the second law. Look at the points a, b, c and d, and imagine that it takes, say, 1 month to go from position a to position b, and it takes the same amount of time to travel in its orbit from position c to position d. It doesn’t matter what time interval one takes as long as they are both the same. The law tells us the colored regions that the line sweeps out will be of equal area. In the example given, the area enclosed, from a to b, is the same size as the area from c to d.

So what, I hear you say? Well, this time look at the length of arc from a to b, and then c to d. Notice that the length of the arc from a to b is much larger than the arc from c to d. But, and this is an important but, the time taken for the planet to go from a to b is the same as for the planet to move from c to d. In order for it to do that, it must be moving *faster* at positions a to b, and *slower* at positions c to d. Thus the speed at which any planet moves through space is constantly changing. A planet moves fastest when it is closest to the Sun—*perihelion*—and slowest when it is furthest from the Sun—*aphelion*.

Finally, Kepler's third law—sometimes referred to as the law of harmonies—compares the orbital period and radius of the orbit of a planet to those of other planets. Unlike the first two laws that describe the orbital motion of a single planet, the third law makes a comparison between the motion characteristics of different planets. The comparison being made is that the ratio of the squares of the periods to the cubes of their average distances from the Sun is the same for every one of the planets.

As an example, consider Mars and Earth:

Planet	Period (s)	Average distance (m)	T^2/P^3 (s^2/m^3)
Earth	3.156×10^7	1.4957×10^{11}	2.977×10^{-19}
Mars	5.93×10^7	2.278×10^{11}	2.975×10^{-19}

You can see immediately that the T^2/P^3 ratio is the same for Earth as it is for Mars. In fact, every planet has nearly the same T^2/P^3 ratio.

Planet	Period (year)	Average distance (au)	T^2/P^3 ($\mathrm{year}^2/\mathrm{Au}^3$)
Mercury	0.241	0.39	0.98
Venus	.615	0.72	1.01
Earth	1.00	1.00	1.00
Mars	1.88	1.52	1.01
Jupiter	11.8	5.20	0.99
Saturn	29.5	9.54	1.00
Uranus	84.0	19.18	1.00
Neptune	165	30.06	1.00

It is very important to note however that in this analysis we always use units that relate to Earth, i.e., the average distance value is given in astronomical units where 1 AU is equal to the distance from Earth to the Sun—1.4957×10^{11} m—and the orbital period is given in units of Earth-years where 1 Earth year is the time required for Earth to orbit the Sun—3.156×10^7 s. See Math Box 2.2 for more examples.

Math Box 2.2 Kepler's Third Law

Kepler's third law states the period squared is related to the average distance cubed. Providing one uses units of years and astronomical units, the law can be stated thus:

$$P^2 = a^3$$

where P is the period and a is the average distance.

An asteroid has a period of 8 years. Calculate its average distance from the Sun.

$$P^2 = 8^2 = 64$$

So:

$$\begin{aligned} a^3 &= 64 \\ a &= \sqrt[3]{64} \\ a &= 4 \end{aligned}$$

Thus the average distance of the asteroid from the Sun is 4 AU.

Math Box 2.2 (Continued)

A comet has a mean distance of 200 AU from the Sun; using Kepler's third law, determine its period.

$$P^2 = a^3$$

$$\begin{aligned} a^3 &= (200)^3 = 4000 \\ P^2 &= 4000 \\ P &= \sqrt{4000} \\ P &= 63.25 \end{aligned}$$

Thus, the period of the comet is 63.25 years.

2.1.8 *Galileo—The Great Experimenter*

Our penultimate character, in this story of discovery, is someone known to us all. Most everyone has heard of Galileo Galilei (1564–1642) and the stories of him dropping things from the Leaning Tower of Pisa,[21] making pendulums and rolling balls down inclined surfaces. However, what interests us is his work in astronomy and the literally devastating effect it had on the geocentric model.

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[21] Probably not leaning at the time, and probably just a fable.

Galileo observed the sky with several homemade telescopes, achieving a magnification of 33×. Surprisingly, it is now believed he wasn't the first person to do so. But, and this is what matters, he was the first person to do so and *publish* his work. It doesn't matter if one makes an Earth-shattering discovery or develops a mind-blowing theory if no one gets to hear about it!

He published his observations in his famous book *Siderius Nancius*, known to us as *The Starry Messenger*. In this he presented ideas stemming from his observations, and it was these that not only eventually put the nail in the coffin for the geocentric model but, alas, got him into trouble with the Inquisition.[22] Nevertheless, by the time the Inquisition had finished burning his books in Italy, and stopped just short of burning him, many copies had traveled throughout Europe, allowing others to see his work and expand on the ideas.

Here are the most important observations he made over several years, which changed everything.

He looked at the Moon and demonstrated the existence of lunar mountains, much to the chagrin of the Aristotelians, who had assumed the Moon to be a perfectly crystalline sphere. In addition he attributed the visibility of the "old Moon," what we now call the new Moon, to Earthshine, sunlight reflected from Earth.

He observed that the Milky Way, previously thought to be an agglomeration of stellar matter in the atmosphere, was now seen to be an endless collection of stars.[23] He saw stars that could not be seen with the naked eye, as they were too faint. This observation was the first step in a long process that culminated in the correct description of the Milky Way as a galaxy.

Considered to be one of his most spectacular discoveries, occurring on January 7, 1610, he observed the moons of Jupiter. Observing over several nights he saw the moons change position, and correctly deduced they were orbiting Jupiter themselves.

These discoveries raised a storm. Kepler wrote to Galileo longing for a telescope to see the moons for himself, and some colleagues refused to believe it (Florentine astronomer Francesco Sizzi), while others refused to even look through the telescope for themselves (philosopher Giulio Libri). The significance of this discovery was much more important than the existence of "additional planets." It gave credence to the Copernican model that Earth was not the center of the universe but is only a planet with a Moon. The inference was obvious. If Jupiter, a planet, had moons, then Earth, with its known Moon, was just another planet, and not unique.[24] The four moons he discovered, now known as Io, Europa, Ganymede and Calisto, are referred to as the Galilean moons, in Galileo's honor.

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[22] Even though he was a deeply religious man, it was another book by Galileo—*Dialogue Concerning the Two Chief World Systems—Ptolemaic and Copernican*, that got him into trouble with the Inquisition.

[23] He also looked at the Pleiades star cluster and saw 36 stars, whereas only 7(?) can be seen with the naked eye.

[24] The Moons also provided more data for Kepler's Third Law.

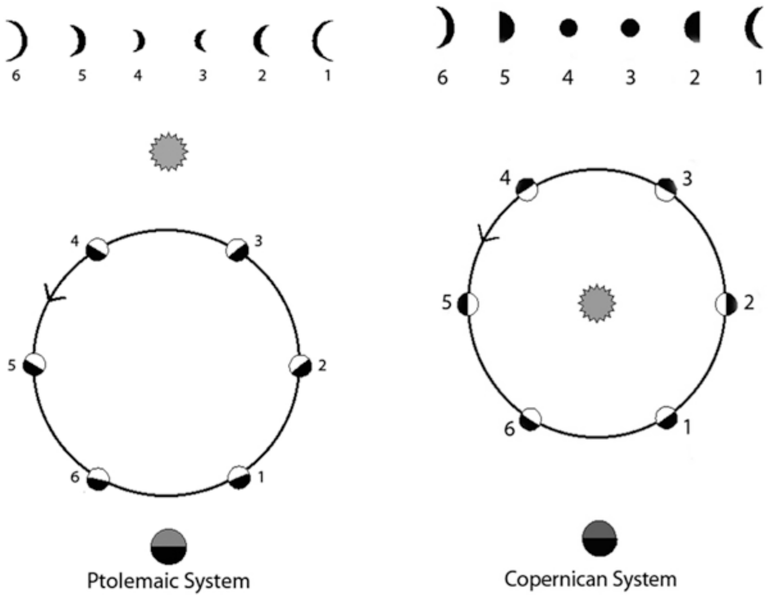

Fig. 2.6 Galileo's description of the phases of Venus

Galileo also looked at Saturn, and although his telescope couldn't resolve the rings, he understandably believed he saw two moons, one on each side of the planet.

A series of observations that once again caused much consternation to the Aristotelians was his discovery of sunspots. Their perfect Sun was covered with spots that, over a short time, formed and changed, and by timing their movement it was implied that the Sun was rotating.

Finally, one set of observations conclusively showed that one planet was not orbiting Earth but was orbiting the Sun, and by inference so was Earth. These were his observations of Venus. One of the main objections to the Copernican model was the apparent absence of particular phases for Venus and Mercury. However, when Galileo saw all the phases this vindicated the Copernican system and ruled out utterly the Ptolemaic model. The following series of diagrams will show what phases were expected, and what Galileo did see (Fig. 2.6).

Even though his work was slowly gaining acceptance, it nevertheless caused great consternation to the established Church, and inevitably, he was called to Rome to attend the Inquisition, even though he was 70 years of age. The sordid details need not concern us here,[25] but the end result will. He was forced to recant

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[25] Everyone should read the details of this trial, as it shows the sordid depths the Church was willing to sink to in its attempts to prevent the truth from being told.

his views, and sentenced to house arrest for the rest of his life. His book was recalled and destroyed, but luckily several copies were smuggled out and reprinted in Leyden, Holland.

Galileo was at heart an experimental physicist, and his contributions to science opened the heavens to further investigations, a process that continues to this day.

2.1.9 Newton—The Genius

We now turn our attention the last player in this saga, who, building on the foundations of the previous participants, put the science of astronomy on a firm footing. We are, of course, talking about Isaac Newton (1642–1727).

Not only did the great man work on and publish on such diverse topics as light, optics, calculus and telescopes,[26] he also put forward the first serious proposal as to why planets move around the Sun and why apples fall to the ground. What concerns us here, however, is his work on the forces that move the planets and how they move. This work was published in his magnificent three-volume opus entitled *Principia*.

Before we discuss these laws of motion, we should define a few concepts. You will probably already know these, but one or two may surprise you, and we will discuss them after listing them.

- *Speed*—the rate at which an object moves, i.e., the distance traveled per unit time [m/s; mi/hr].
- *Velocity*—an object's speed in a certain direction, e.g., "10 m/s moving east".
- *Acceleration*—a change in an object's velocity, i.e., a change in either speed or direction is an acceleration [m/s^2].

The first concept speaks for itself. The second may appear a bit odd. After all, who says "I am traveling down the road at 40 km a minute in a northeasterly direction?[27]" But this relates to the last concept that shows that acceleration need not be an increase or decrease in speed; it can also mean a change in direction, and this is where orbits come into play. For instance, imagine a moon in a circular orbit around a planet, with a uniform, or constant, speed. Because it is moving in a circular orbit, it is changing its direction at every instant of time, and a change in direction is acceleration. So the moon is undergoing acceleration,[28] not by changing its speed but by changing its direction!

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[26] And along the way, developed the reflecting telescope, the main instrument of choice for most amateur astronomers for the past 150 years.

[27] The type of person who has a compass in their car perhaps?

[28] The direction of acceleration is towards the planet, a consequence that need not concern us here, as we would have to delve into vector analysis.

Newton labored for several years, which resulted in his three laws of motion. Once again we will present them as a formal statement, and then explain them in a less formal manner.[29]

1. A body at rest or in motion at a constant speed along a straight line remains in that state of rest or motion unless acted upon by an outside force.
2. The change in a body's velocity due to an applied force is in the same direction as the force and proportional to it, but is inversely proportional to the body's mass.
3. For every applied force, a force of equal size but opposite direction arises.

The first law can be explained like this. Imagine a spaceship in space, with no other objects, be they planets, stars or whatever, anywhere nearby; in fact, assume the spaceship is the only thing around for millions of light years. Now, according to the law, the spaceship will, if already motionless, remain motionless forever, unless something acts upon it, for instance, the gravity of a planet that appeared nearby, or an impact from a micrometeorite. In addition, consider the same spacecraft in the same unlikely scenario, but this time moving with a constant speed, neither increasing nor decreasing its speed. If there is nothing else around, it will continue to move at that constant speed, in a straight line, forever!

In reality, of course, the planets, asteroids, the Sun, and the moons do affect a spacecraft in the Solar System; everything in fact, will alter its motion. Ever wondered about those tiny little rockets on space missions to the planets? Well, they are there to make course corrections to the vehicle as it progresses to its target, as its motion is constantly being affected by the gravitational force of everything in the Solar System.

The second law can be thought of like this. Imagine you have a cricket ball and a cannonball, both the same size, but naturally the latter will have more mass. They are then thrown with exactly the same force. The cricket ball will travel further than the cannonball. Similarly, if you have two cricket balls of precisely the same mass, but one is thrown with greater force, it will travel a larger distance.

The final law explains something that many people will have experienced for themselves. Both yourself and a friend are standing on ice. You push your friend away, and not only do they move away from you, shouting expletives with arms waving, but you move in the opposite direction to them. Another example is a rocket launch. The rocket is propelled upward by a force equal and opposite to the force with which the gas exhaust is expelled out of its back.

Newton then went on to perhaps his greatest triumph, showing that gravity was the force that made the planets move in a stately motion around the Sun. He was able to show that the gravitational attraction between any two objects is dependent firstly on the masses of the two objects and secondly on their distance apart.

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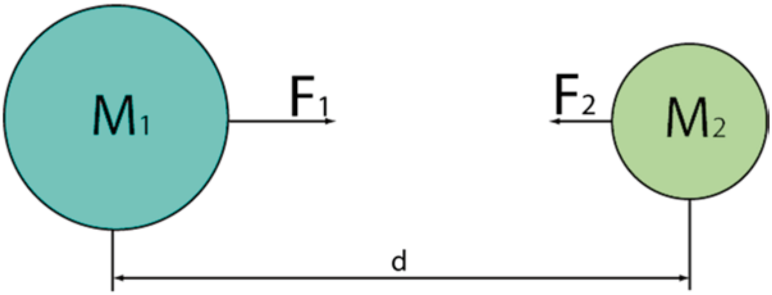
[29] Newton credited the first two laws to Galileo and the last to Christopher Wren and Christian Huygens.

A more mathematical definition would be that the force is proportional to the product of the masses, and inversely proportional to the square of their distance apart. Mathematically:

$$F_1 = F_2 = G\frac{(M_1 M_2)}{d^2}$$



M_1—Mass of first object (kg)
M_2—Mass of second object (kg)
d—distance apart (m)
G—Gravitational constant $= 6.67 \times 10^{-11}$ N·(m/kg)^2

What this means in plain English is that the larger the masses, the larger the force of attraction, but with the caveat that as the distance between the two objects increases, the force of attraction decreases. Note that the distance, *d*, is from the center of the mass of the objects, which can be considered to be approximately true for spherical objects such as planets and large moons, but not for potato-shaped asteroids. The gravitational constant, denoted by the letter *G*, is an empirical physical constant involved in the calculation of gravitational force between two bodies. The resulting force will be in the units called Newtons[30]—*N*. An example of the formula in action can be seen in Math Box 2.3.

At this point it is well worthwhile looking at the formula in some detail. Notice how one can work out the gravitational force perfectly for two objects and get a precise solution. However, it is not so simple for three or more objects,[31] and in fact there is no one single formula for any system that has more than two objects. Don't think for one second that the forces and motions cannot be worked out in this scenario, they can, but it involves much more rigorous mathematics. Just imagine, if you will, the complexity of, say, accurately calculating the gravitational effect of all the planets in the Solar System, along with their attendant moons, the Sun and the asteroids, on the behavior of a spacecraft, all moving so that their distances apart constantly change. It is complicated.

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[30] 1 Newton, N, is the force of Earth's gravity on a mass of about 0.102 kg, 102 g.

[31] A partial solution has been worked out for three objects, but nothing as exact as Newton's formula.

Math Box 2.3 Newton's Universal Law of Gravitation

Assume you are on Earth, with a mass of 70 kg, the Earth's Moon, mass 7.35×10^{22} kg, and the Andromeda Galaxy, mass 1.41×10^{42} kg. The Earth-Moon average distance is 3.8×10^{8} m. The Earth-Andromeda Galaxy distance is 2.4×10^{22} m.

Calculate the gravitational force of attraction between the following:

i. You and the Moon.
ii. You and the Andromeda Galaxy.
iii. Determine how many times greater the stronger force is to the weaker.

i.

$$F_1 = F_2 = G\frac{(M_1M_2)}{d^2}$$

$$F_1 = F_2 = 6.67\times10^{-11}\ N\cdot(m/kg)^2\,\frac{(70\ kg\times7.35\times10^{22}\ kg)}{(3.8\times10^{8}\ m)^2}$$

$$F_1 = F_2 = 6.67\times10^{-11}\ N\cdot(m/kg)^2\,\frac{(5.15\times10^{24}\ kg)}{(1.45\times10^{17}\ m)}$$

$$F_1 = F_2 = 2.37\times10^{-3}\ N$$

ii.

$$F_1 = F_2 = 6.67\times10^{-11}\ N\cdot(m/kg)^2\,\frac{(70\ kg\times1.41\times10^{42}\ kg)}{(2.4\times10^{22}\ m)^2}$$

$$F_1 = F_2 = 6.67\times10^{-11}\ N\cdot(m/kg)^2\,\frac{(9.88\times10^{43}\ kg)}{(5.76\times10^{44}\ m)}$$

$$F_1 = F_2 = 1.14\times10^{-11}\ N$$

iii. Ratio of stronger force to weaker force:

$$\frac{2.37\times10^{-3}}{1.14\times10^{-11}} = 2.08\times10^{8}$$

Put another way, the force of gravitational attraction between you and the Moon is nearly 200 million times stronger than the force between you and the Andromeda Galaxy.

Also, consider this scenario. Imagine that, for some reason, the Sun were to completely and utterly disappear.[32] Then, with Newton's concept, Earth would "react" to this instantaneously! This means that using Newton's description, gravity propagates faster than light. Thus you can immediately see that although we can

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[32] I don't mean be eaten by a black hole. I mean vanish!

use Newton's formula to get very accurate results, it cannot be the correct description of gravity. In fact, this became apparent early on when astronomers tried to explain the strange motion of Mercury around the Sun and measure the deflection of light rays by gravity. We had to wait for another genius to give us the true description of gravity, and that genius was Einstein.

However, the formula works very well when one is considering velocities much smaller than the speed of light, and with situations where the gravitational force is small, or the masses involved are small.

There is no doubt that Isaac Newton was a genius, and even though he understood *how* the planets moved due to gravity, he did admit he didn't know what gravity was. Nevertheless his insight started a stream of discovery that still flows today, and although his life was, at times, beset with controversy and intrigue—he was after all an alchemist—he was a towering intellect.

Here we leave our theoretical exploration[33] of the Solar System and now concentrate, albeit briefly, on the observational aspects of the Solar System.

2.2 Observing the Solar System

Observing the planets, their moons, the asteroids and the Sun is a wonderful pastime for amateur astronomers, and many have devoted most of their observing time to just such a passion, but there is no way we can give it the full coverage it deserves in this book. Each planet really needs its own book, and to that end we have listed such books in the appendices. However, there are a few things one can look out for, without any optical equipment at all, except the naked eye, and so that is what will be presented here.[34] In fact, regard them as observing challenges, now known as the "Inglis Naked-Eye Planetary Phenomena Observing Challenge," INEPOC for short.[35]

The positions for the planets can easily be found online, or by using planetarium software.[36]

2.2.1 *The Moon*

Observing our Moon can be a lifelong study, and will of course need a telescope, but there is one specific observation that can be done without resorting to optical aid—to glimpse the very young or very old Moon. In fact, many observers spend

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[33] We shall not bother with the Titus-Bode law, as it is not believed to be a law at all but rather a rule, and possibly a coincidence.

[34] Solar observing has its very own techniques and equipment. Suffice to say NEVER look at the Sun through a telescope, or even just with the naked eye. You'd be a fool to do so.

[35] Perfect!

[36] Naturally, not all the planets will be mentioned here, as this is a naked-eye exercise.

an inordinate amount of time doing just this. Try to locate the Moon either as soon as possible after it is new, or as late as possible before it becomes new. It helps if you have a good horizon view to either the east or west.

2.2.2 Mercury

The planet closest to the Sun has its own attendant problems, because of its location in space. At greatest elongation, which varies between 18° and 28° due to its elliptical orbit, it can only be glimpsed for about 1 h (considerably less when its elongation is the minimum value), either before sunrise or after sunset. Therefore, the sky will still be bright, and so the challenge here is, basically, to just find it. Needless to say you will need a more or less completely unobstructed view of the horizon. That's to say, no trees, houses, breweries, etc., that could obscure the view. It's tricky, but once glimpsed, you'll wonder why you've never seen it before, and the first time you actually locate it will be an event you won't easily forget.

2.2.3 Venus

Believe it or not, it is possible to observe the phases of Venus with the naked eye. When a phase is at its most extreme, those lucky individuals blessed with exceptionally acute eyesight can see it. It will be, however, at the limit of human perception. This is because the angular resolution of the naked eye is about 1 minute of arc, whereas the apparent disk of Venus' extreme crescent measures between 60.2 and 66 seconds of arc, depending on the distance from Earth. Of course, perfect atmospheric conditions will be necessary. This is not something that is hearsay, but comes from many substantiated reports from observers worldwide.[37]

2.2.4 Jupiter

OK, this section isn't actually about Jupiter itself but rather its Galilean moons, and even then we are talking about only Ganymede and Calisto. Unknown to many amateur astronomers is the fact that all four moons are bright enough, apparent magnitudes between 4.6 and 5.6, when Jupiter is at opposition, to be visible from Earth without a telescope—if only they were further away from Jupiter. However, the problem that arises is twofold. Firstly, Io and Europa are too close to Jupiter to be resolved with the naked eye. However, the maximum angular separations of

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[37] The author, although plagued with poor eyesight now, did manage to observe an elongated Venus with the naked eye when I was much younger and had all bodily parts in working order.

Ganymede and Calisto are 351 arc seconds and 618 arc seconds, respectively, and thus are the likeliest targets for potential naked-eye observation. The second problem is the glare from Jupiter itself, which floods the eye with light, thus preventing observation of the satellites. In order to remedy this try obscuring Jupiter with an object, e.g., a tree branch, telephone pole or anything similar that is perpendicular to the plane of the moons' orbits.[38]

2.2.5 *Uranus*

The last challenge is, like with Mercury, to just locate Uranus. At opposition, Uranus has a magnitude of around 5.7, and thus, from a very dark sight will be within reach of those with excellent eyesight. The problem here is that due to its faintness, it will appear to be just like a faint star, set among many other faint stars, and so a prerequisite for a successful identification is to have a good knowledge of the sky in which it will be (hopefully) observed. This is where experienced amateurs excel, as they know the night sky intimately.

For all the above observations, good eyesight is essential, along with transparent skies and little or no light pollution.

Now let us leave the Solar System with its planetary motions and explore the stars and galaxies.

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[38] I have tried this and truly believe that although I didn't see actual separate moons, I did see an elongation of Jupiter, the Moons being located on either side of Jupiter.

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