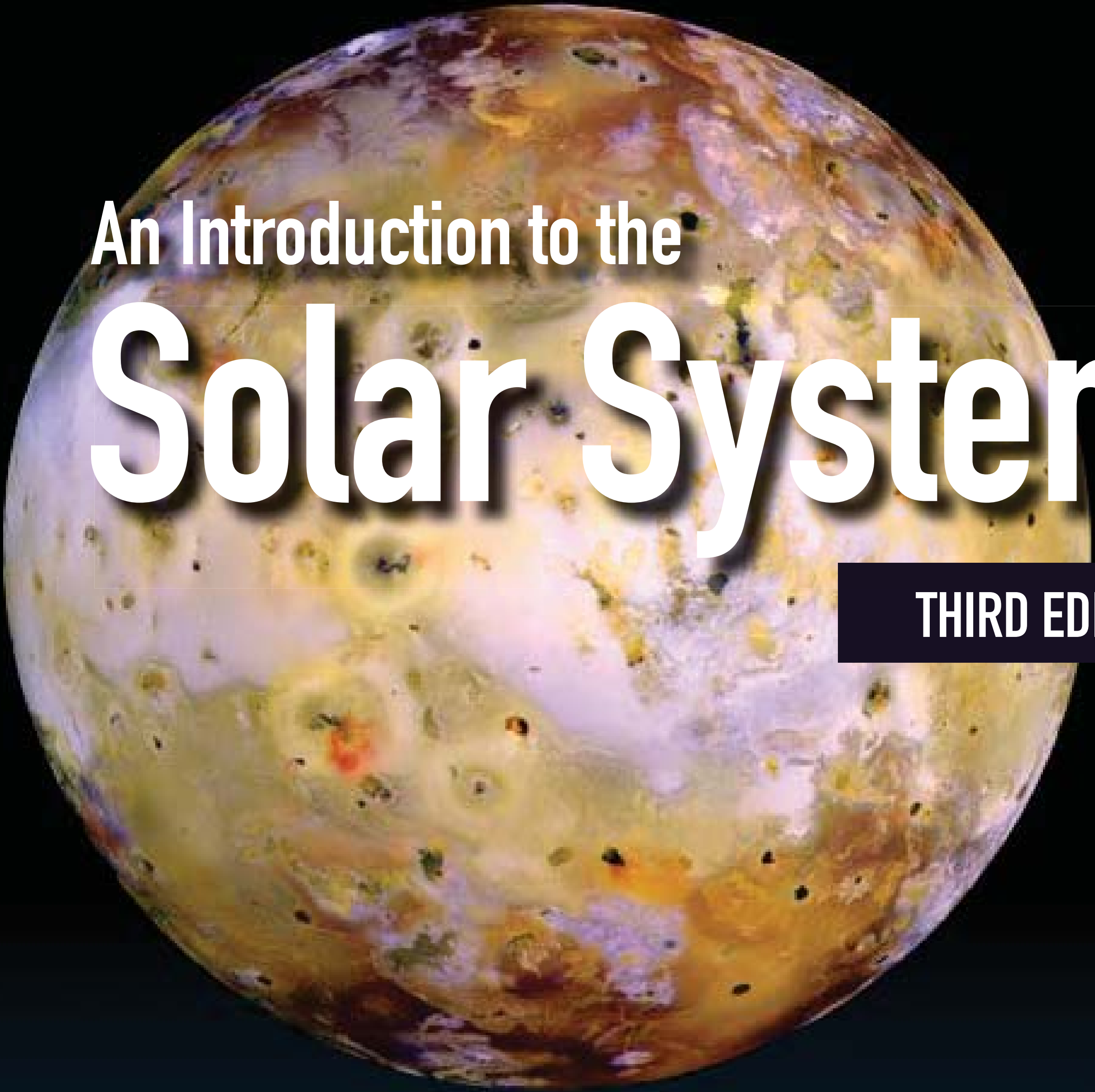
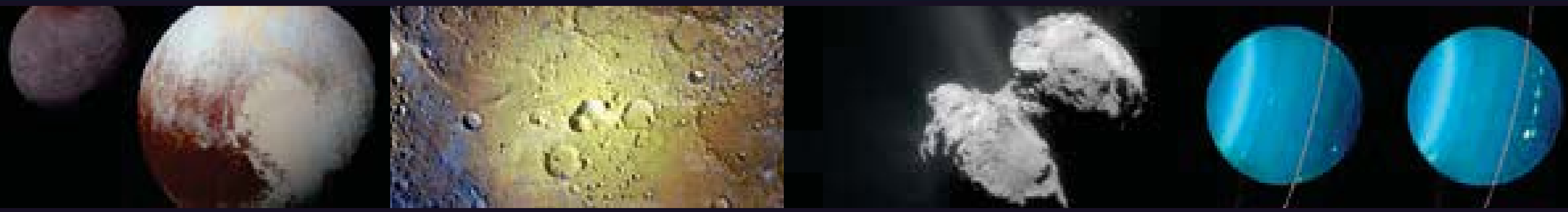


An Introduction to the
Solar System

THIRD EDITION



Edited by David A. Rothery, Neil McBride and Iain Gilmour

An Introduction to the Solar System

Compiled by a team of experts from The Open University and substantially revised for this edition, this textbook has been designed for introductory university courses in planetary science. It starts with a tour of the Solar System and an overview of its formation. The composition, internal structure, surface morphology and atmospheres of the terrestrial planets are then described. This leads naturally to a discussion of the giant planets and why they are compositionally different. Minor bodies are reviewed and the book concludes with a discussion of the origin of the Solar System and the evidence from meteorites. Written in an accessible style that avoids complex mathematics, and illustrated in colour throughout, this book is suitable for self-study and will appeal to amateur enthusiasts as well as undergraduate students. It contains numerous helpful learning features such as boxed summaries, student exercises with full solutions, and a glossary of terms. The book is also supported by a website hosting further teaching materials: **http://www.cambridge.org/solarsystem3**

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DAVID A. ROTHERY is Professor of Planetary Geosciences at The Open University, with a background in geological remote sensing and a special fascination for the moons of the outer planets. He has been involved in several space missions, and leads the Surface and Composition Working Group for the European Space Agency's BepiColombo mission to Mercury.

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Background image: A false-colour image of Io, a satellite of Jupiter, taken by the Galileo spacecraft. This false-colour image uses near-infrared, green and violet filters to enhance the subtle colour variations of Io's surface. (NASA)

Thumbnail images: (from left to right) Pluto and Charon seen by New Horizons (NASA/JHUAPL/SwRI); exaggerated colour view of a probable pyroclastic vent on Mercury seen by MESSENGER (NASA/JHU APL/CIW); Comet 67P/Churyumov-Gerasimenko as imaged by Rosetta in November 2015 (ESA/Rosetta/NAVCAM); Uranus and its rings as seen in the near infrared by the Keck telescope 11 and 12 July 2004 (Lawrence Sromovsky, University of Wisconsin-Madison/W.W. Keck Observatory)

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Contents

INTRODUCTION

In astronomical terms, the Solar System is our backyard. Set against the vast number of stars in our Galaxy, the colossal number of other galaxies in the observable universe and the incredible distances involved, our Solar System is an extremely tiny part of the Universe. However, this is where we live. It is where life on Earth developed, and it gives us our only vantage point from which to view the rest of the Universe.

Unlike other planetary systems, the objects in our Solar System are close enough to visit with space probes and to study long-term and (in some cases) in reasonable detail using telescopes. As well as revealing the splendour and diversity of the worlds that make up the Solar System, these studies allow us to try and understand 'what makes the Solar System tick'. By doing this, we not only attempt to understand the system in which life evolved, but also gain an insight into the likely diversity of individual planetary bodies and their possible histories all over the Universe.

One of the more fundamental questions often asked is, 'why is the Solar System the way it is?' In answering this question, we have to address more detailed questions such as, how were the planets made? What were the planets made from? Were all the planets made from the same material? Why do they look so different? Do all the planets have the same internal structure? Does their surface appearance change with time? The answers to these questions lie in the physical and chemical *processes* that act on the bodies within the Solar System. Understanding these processes allows us to appreciate how the planets and the other Solar System bodies have formed and have been changed over time, and hence why they look the way they do today. In this book, you will be looking at these *processes* in detail.

CHAPTER 1
A TOUR OF THE SOLAR SYSTEM

A great way to start your study of the **Solar System** is to get an overview of what our planetary system looks like by taking a tour of the **planets** and their **moons**. In this introductory chapter, you will see the incredible diversity that the Solar System offers, made accessible by the use of spacecraft sent into space to gather scientific data (an important part of that is in the form of high-resolution images). The tour will set the scene and highlight the planetary features that can be explained by the processes considered in detail later on. So let us begin our tour of the Solar System.

Some major missions are listed in Appendix A, Table A7.

1.1 A grand tour

There are eight planets in our Solar System. Each planet travels on an approximately circular **orbit** around the Sun, which lies at the heart of the Solar System. In order of increasing distance from the Sun, the eight planets are Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus and Neptune. The sizes of the planets vary greatly, but all are dwarfed by the Sun. Figure 1.1 shows the relative sizes of the planets and the Sun. In the figure, the planets are aligned in the correct order with increasing distance from the Sun, although the relative distance from the Sun is *not* shown (you will consider this later). You can see that there appears to be a broad division between the four small inner planets and the much larger outer planets. Beyond that lie many icy bodies, of which the 'dwarf planet' Pluto is one of the largest.

The four inner bodies (Mercury, Venus, Earth and Mars) are called the **terrestrial planets**, whereas Jupiter, Saturn, Uranus and Neptune are usually referred to as the **giant planets**.

Many of the planets have moons (also called **satellites**) that orbit the planet in the same way as the Moon orbits the Earth. Some of the moons that you will meet on our tour are similar to the terrestrial planets in terms of their composition or structure, and are sometimes called **terrestrial-like** bodies.

We start our tour by taking a closer look at each member of the Solar System. As the Sun lies at the centre of the Solar System, it seems a sensible place to start. This book focuses on **planetary bodies** (a term that refers not only to the planets, but also to their moons and other small bodies such as asteroids) and you should appreciate that the Sun is *not* a planet, but a **star**. It is a huge ball of gas, consisting mainly of hydrogen and helium (although other elements are also present in smaller amounts). At the centre, nuclear reactions release energy. This is why the Sun is hot – about 5770 K at its surface and an amazing 15 000 000 K at its centre. (Note the SI unit of absolute temperature is the kelvin, K. 0 K = −273 °C, and 0 °C = 273 K.)

Figure 1.2 shows an impressive image of the Sun. Material, seen above the surface, can be lost to space. Ejection of material from the Sun can have consequences here on Earth (you will meet this in Chapter 5).

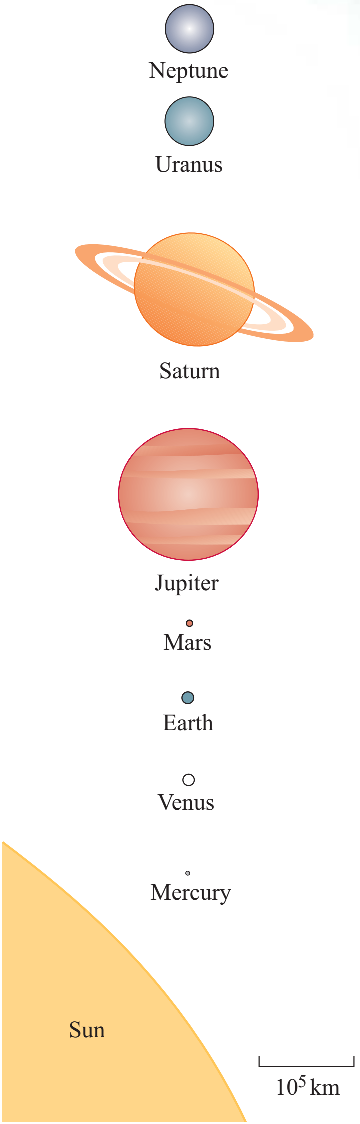


Figure 1.1 The relative sizes of the planets and the Sun. The planets are shown in the correct order (with increasing distance from the Sun), although the relative distance from the Sun is *not* shown to scale.

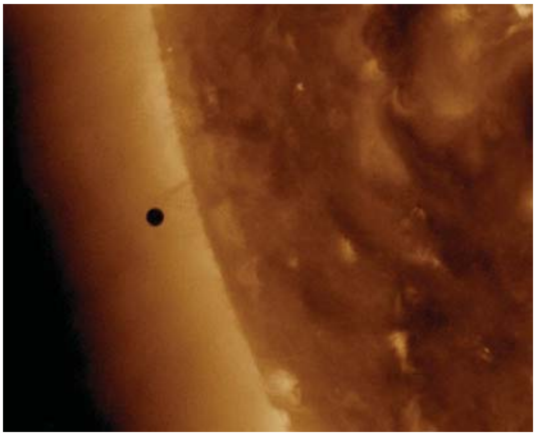


Figure 1.2 Part of the Sun (radius 695 500 km), with the planet Mercury (in silhouette) starting to pass in front of it. The image, taken in ultraviolet light using the SOHO spacecraft, shows that the Sun is rather complex and 'active', and also how much bigger the Sun is than this planet. (NASA/SDO and AIA science team)

1.1.1 Mercury

The first planetary body on our tour is Mercury (Figure 1.3). Mercury, being the closest planet to the Sun, can get very hot. In sunlight, parts of the surface can reach about 740 K (approximately 470 °C), whereas in darkness the temperature can drop to about 80 K (−190 °C). Clearly, the surface of Mercury is not a very hospitable place. Looking at Figure 1.3, perhaps the most striking features are the round 'scars' on the surface. These are **impact craters**. A more detailed view of some impact craters on Mercury is shown in Figure 1.4 and you will consider impacts in detail in Chapter 4. These impact craters have been made by the 'leftovers' of the planetary formation process, namely **asteroids** and **comets** (both of which you will be looking at in detail in Chapter 7). Asteroids are predominantly rocky and metallic bodies, whereas comets have a large fraction of icy material in them. However, both have broadly similar effects when they slam into the surface of a planet at great speed – they leave impact craters. Any undisturbed surface of a planetary body will accumulate impact craters over time. Thus a very cratered surface implies that the surface is relatively old, whereas a lack of craters might indicate that the surface has been renewed in some way, wiping out the craters from the surface. The most prevalent mechanism for **resurfacing** is **volcanism**, whereby **lava** (the melted rock we are familiar with on Earth) flows and covers pre-existing terrain. These concepts will be dealt with in more detail in Chapters 2 and 3.

Returning to Mercury, the cratering over the surface is dense (so we know it must be old) but it is not uniform. Some areas within Figure 1.3 are smoother, which in this case means that they were volcanically resurfaced more recently than the more densely-cratered areas. There are also some scarps crossing the surface indicative of tectonic faults. You can see from the clarity of the images in Figures 1.3 and 1.4 that Mercury does not have an obscuring atmosphere. In fact, Mercury does have some *extremely* tenuous atmosphere, but it is 10^{15} (a thousand million million) times less dense than the atmosphere on Earth, which is actually a better vacuum than any vacuum we can create in a laboratory.

Before you leave Mercury, there is another property of interest to be considered, which is mean **density** (see Box 1.1). Mercury's mean density is about 5.4×10^3 kg m^{-3}, which is almost as high as that of Earth. You will consider densities of the planetary bodies at the end of this chapter, and you will see that this is quite a surprising result considering that Mercury is the smallest of the terrestrial planets. It indicates that Mercury must include a relatively large proportion of dense material.

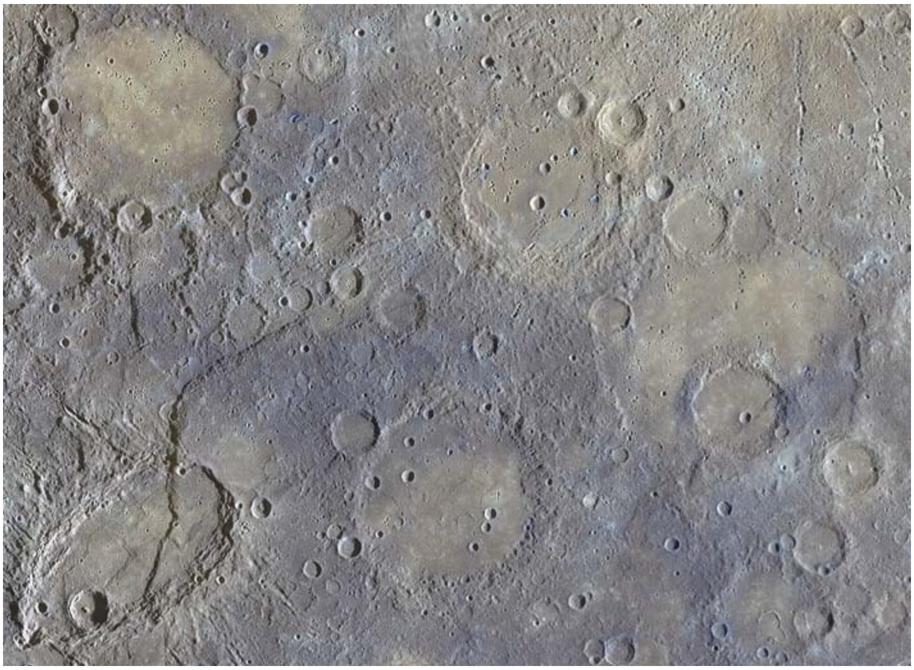


Figure 1.3 A 830 km-wide view of Mercury based on images from MESSENGER, which orbited Mercury 2011–2015. Sunlight is from the right. The surface is a mixture of impact craters and smooth plains. The curved, shadowed feature near the lower left is a step or scarp in the surface interpreted as a thrust fault. (NASA/JHU APL/CIW)

Figure 1.4 A close-up of a 160 km-wide region of Mercury. Impact craters are clearly visible. Sunlight is from the right. (NASA/JHU APL/CIW)

BOX 1.1 DENSITY

Density (sometimes called bulk density) is a measure of the mass per unit volume of a substance:

$$\text{density} = \frac{\text{mass/kg}}{\text{volume/m}^3} \tag{1.1}$$

The SI units of density are thus kilograms per cubic metre (kg m^{-3}). Density values of common materials can cover quite a wide range. Water has a density of 1.0×10^3 kg m^{-3}, whereas a rock such as granite is around 2.7×10^3 kg m^{-3}, and iron is 7.9×10^3 kg m^{-3}. In other words, a cubic metre of granite would weigh 2700 kg, or 2.7 tonnes! Since one cubic metre is somewhat larger than, for instance, the average pebble or rock you might pick up on a beach, these large numerical values for density are often difficult to grasp. Instead, it is often convenient to think of densities in smaller units, so you may come across, or prefer to think of, density values expressed as grams per cubic centimetre (i.e. g cm^{-3}). Thus a density of 2.7×10^3 kg m^{-3} could be expressed as 2.7 g cm^{-3}. However, when making calculations involving density, always ensure you use the SI units for density.

It is important to appreciate that a planetary body might be made of layers of material that have quite different densities, for example it may have high-density material (such as iron) at its core and somewhat lower-density material (such as rock) nearer the surface. The calculation of mass/volume gives rise to a value of *mean density* for the body.

1.1.2 Venus

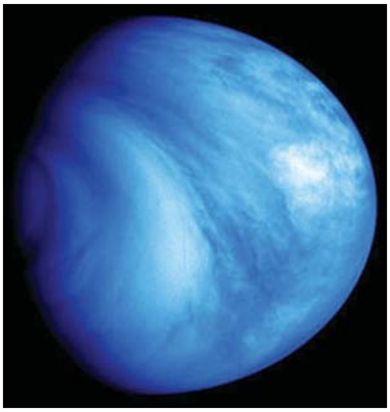


Figure 1.5 The planet Venus (radius 6052 km), seen from a vantage point 35 000 km above its south pole. This image, taken by the Venus Express spacecraft, is falsely coloured and recorded in ultraviolet light to highlight the subtle structure of the clouds which are not usually seen (in visible light, Venus looks more of a uniform white in appearance). (ESA © 2007 MPS/DLR-PF/IDA)

The next planet on our tour is Venus. The chances are that you have seen Venus with the naked eye, even if you didn't realize it at the time. Venus is often seen as an extremely bright 'star' an hour or two before sunrise or after sunset, depending on the relative positions of Venus and the Earth in their orbits. A small telescope can resolve Venus as a disc. The planet may also look like a crescent or a gibbous object, depending on the Earth–Venus–Sun geometry at the time. Even powerful telescopes tend to show Venus as a featureless planet due to the presence of a thick atmosphere. In terms of its size and mean density, and the fact that it has a significant atmosphere, Venus could be considered as the 'twin' of Earth. In fact, there are very important differences, particularly regarding the composition of the atmosphere and the resulting surface environment. Figure 1.5 shows an image of Venus, which picks out some cloud structure that is not normally apparent. The clouds are made from tiny droplets of sulfuric acid, hinting that Venus might not be the most welcoming environment for us to visit!

A view of the surface terrain can be obtained using cloud-penetrating radar. One such image is shown in Figure 1.6. The surface of Venus is very complex, with far fewer impact craters than on Mercury, but with many volcanoes and lava plains suggesting significant resurfacing. The only images obtained from the surface of Venus were taken from a series of Soviet Union spacecraft, called Venera. Taking

Figure 1.6 Details of the surface of the planet Venus, which is usually totally obscured by clouds, taken by the Magellan spacecraft using cloud-penetrating radar. (NASA)

images on Venus was an impressive technical feat considering the hostility of the surface environment. The surface atmospheric pressure was almost a hundred times that on Earth, and the temperature was around 670 K (400 °C). A high-pressure oven is not a good place for sensitive scientific instruments! However before the equipment expired, the Venera spacecraft returned their precious images.

Figure 1.7 shows one of the few colour images obtained by the Venera 13 spacecraft. The surface shows evidence of old lava flows, with a cracked and rugged appearance. The action of the atmosphere has also given rise to surface erosion. The atmosphere of Venus is mostly (97% by volume) carbon dioxide (unlike Earth which is mostly nitrogen and oxygen). The carbon dioxide gives rise to a strong 'greenhouse effect' that traps heat below the lower layers of the atmosphere – hence the very high surface temperature. Venus, while an Earth-twin in some respects, would definitely not be a hospitable place to visit.

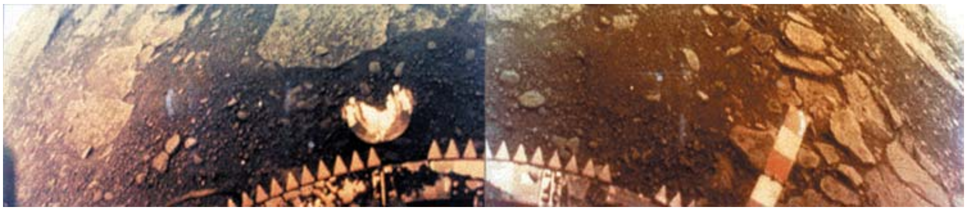


Figure 1.7 The surface of Venus obtained by the Venera 13 spacecraft in 1982. Part of the spacecraft is seen at the bottom of the image. (Courtesy of the Russian Academy of Sciences/RNII KP/IPPI/TsDKS)

1.1.3 Earth and the Moon

The next planet on our itinerary is Earth. The familiar blue planet is shown splendidly in Figure 1.8. Although Earth may seem rather familiar, and even rather boring in the context of exploring exciting new worlds in the Solar System, sixty years ago this was an iconic image for showing us our home planet and its place in the Solar System. Before the space age, we could only imagine seeing our planet from afar. But now we have an appreciation of the Earth as a finite, isolated and even rather fragile planet in space. Today we have spacecraft stationed 1.5 million km sunward from the Earth that routinely capture the Moon crossing the face of our plane (Figure 1.9).

The Earth also allows us to study at close quarters many of the mechanisms that influence and characterize the other bodies in the Solar System. Our understanding of the internal structure of large terrestrial-like bodies, volcanism and atmospheres, is greatly enhanced by looking at what happens on (or *in*) the Earth, and using this knowledge to consider what must happen elsewhere. For this reason much of the material considered in the following chapters looks closely at the Earth to enhance our understanding of the other planets.

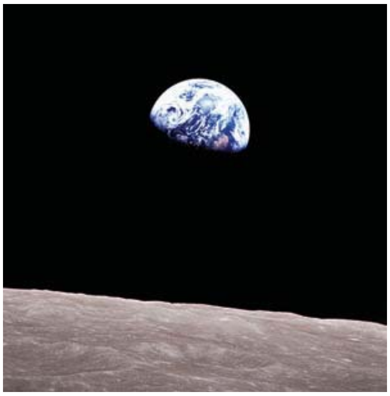


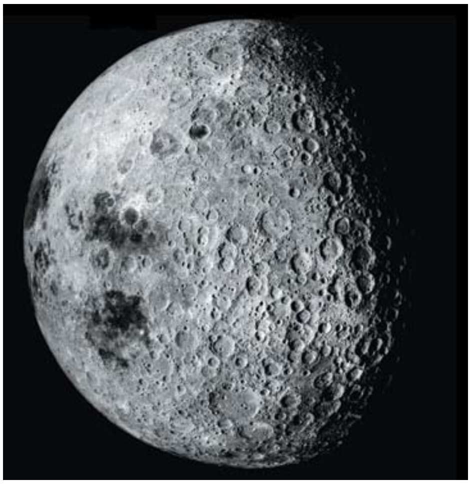
Figure 1.8 The Earth seen from lunar orbit by Apollo 8 in 1968. (NASA)

The atmosphere of the Earth (which you will look at in more detail in Chapter 5) is crucial for the survival of life on the planet. Our atmosphere causes a significant rise in surface temperature because of a 'greenhouse effect', which is mainly due to carbon dioxide and water vapour (modest compared to Venus, but still accounting for a 33 K higher temperature than an atmosphereless Earth would have). This means that the *mean* temperature at the surface is 288 K (15 °C), allowing liquid water to exist over much of the planet. The atmosphere also carries heat away from the Equator, so that the Equator is not as hot as it might be and the polar regions are not as cold as they might be. This allows life to thrive at a greater range of latitudes than would be the case if we didn't have atmospheric circulation. The Earth's atmosphere comprises (by volume) 78% nitrogen and 21% oxygen, with other gases (including carbon dioxide) being just a small part. It is perhaps a sobering thought to bear in mind that Venus is an example of what could happen if greenhouse gases such as carbon dioxide became a really significant proportion of the Earth's atmosphere.

The other familiar planetary body on our tour is the Earth's only natural satellite, the Moon. Often ignored due to over familiarity, the Moon actually has some pretty spectacular terrain. Viewed with the naked eye or, better still, through binoculars or a small telescope (best viewed when *not* at full Moon to obtain the best visual contrast), the relatively bright 'highland' regions peppered with impact craters, and the darker and less cratered *mare* (pronounced mar-ray) regions, are clearly seen.

Figure 1.9 The Moon (radius 1738 km) passing in front of the Earth (radius 6371 km) as seen 5 July 2016 by the DSCOVR spacecraft, 1.5 million km from Earth. The image shows the oceans (blue), land (brown) and cloud (white). Note that the Moon is darker than (reflects less light than) the Earth's land areas. (NASA/NOAA)

Figure 1.10 The Moon (radius 1738 km). A false colour view of the Moon's near side recorded by the Galileo spacecraft. The various colours of the image highlight the dissimilar mineralogy of the regions. (NASA)



The Moon orbits the Earth about thirteen times each year, and presents the same face to us all the time. This is because its **rotation period** (the time it takes to turn once on its axis) exactly matches its **orbital period** (the time it takes to travel once around the Earth). This is called **synchronous rotation**, and is common among moons throughout the Solar System. Figure 1.10 shows an image of the Moon. False colours have been used in this figure to differentiate predominant surface minerals. Figure 1.11 shows a photograph that reveals some of the far side of the Moon. Fewer mare regions are seen and more impact craters are obvious in this image. The mare regions are younger formations formed by the flooding of lava that buried many ancient impact craters. You will consider the formation and composition of the Moon in Chapter 2, and the historical impact record of the Moon in Chapter 4.

Figure 1.11 An image of the Moon, taken from Apollo 16, showing some of its heavily cratered far side (right-hand part of the image). (NASA)

1.1.4 Mars

Continuing our tour outwards from the Sun, we next encounter Mars (Figure 1.12). It is not hard to understand why it is often referred to as 'the red planet' (although in fact, most people would probably describe it as orange). Mars can often be seen with the naked eye as a 'star' that has a very obvious orange hue to it. Figure 1.12 shows some striking features. The image shows a huge canyon system (called *Valles Marineris*), which represents a fracture in the planet's surface that extends about 4000 km across the planet. This canyon dwarfs the Earth's Grand Canyon, having regions that are 11 km deep and 200 km wide. Also very obvious are the dark, circular features near the left-hand side of the image. These are enormous, old volcanoes. The largest volcano on Mars, *Olympus Mons* (not visible in Figure 1.12), which is also the largest volcano in the Solar System, is 24 km high and has a volume a hundred times greater than Mauna Loa in Hawaii – the largest equivalent feature on Earth.

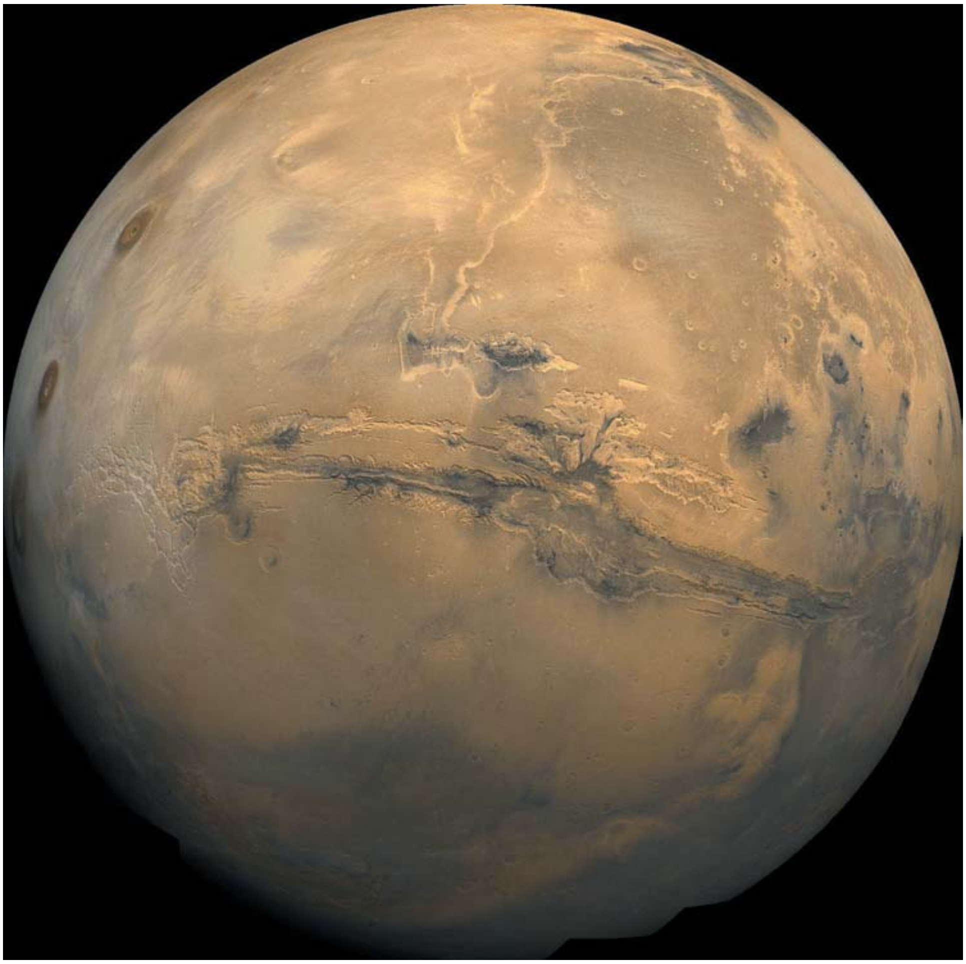


Figure 1.12 The planet Mars (radius 3390 km). This is a composite image produced from images obtained by the Viking Orbiter spacecraft. (US Geological Survey)