CHAPTER 1

Earth and sky

Almost all of this book is devoted to the practical methods we astronomers can use to study the great worlds and other celestial bodies in our Solar System we can see across millions of kilometres of space. To help us appreciate those other worlds it is as well to have to hand some basic facts about our own planet. Also there are some aspects of our Solar System we can observe and study without even using a telescope. So, let us begin our explorations right here, with a brief overview of our Earth and the phenomena that we can see and study without any optical aid . . .

1.1 PLANET EARTH

The Earth is a rocky globe, 12 800 km in diameter, orbiting the Sun at a mean distance of 150 million km and taking one year to complete one orbit. The Earth is not quite a perfect sphere but is rather an oblate spheroid, its polar diameter being 43 km less than its equatorial diameter. The difference is caused by the forces arising from the daily (technically *diurnal*) rotation of the planet on its axis.

The Earth is but one of eight major planets that orbit the Sun and they all rely on the Sun as a provider of light and heat. All the planets go round the Sun in the same direction and all keep close to the same plane as they orbit. The mean orbital radii of the major planets and their orbital periods are shown in Figure 1.1. The orbital period of a planet is referred to as its *sidereal period*. Hence the sidereal period of the Earth is one year.

The mass of the Earth is 6 million million million million kg. In scientific notation this is written as 6×10^{24} kg. Dividing the Earth's mass by its volume gives it a *mean density* of 5515 kg/m^3. The rocks near the surface of the Earth have measured densities of around 2500 kg/m^3

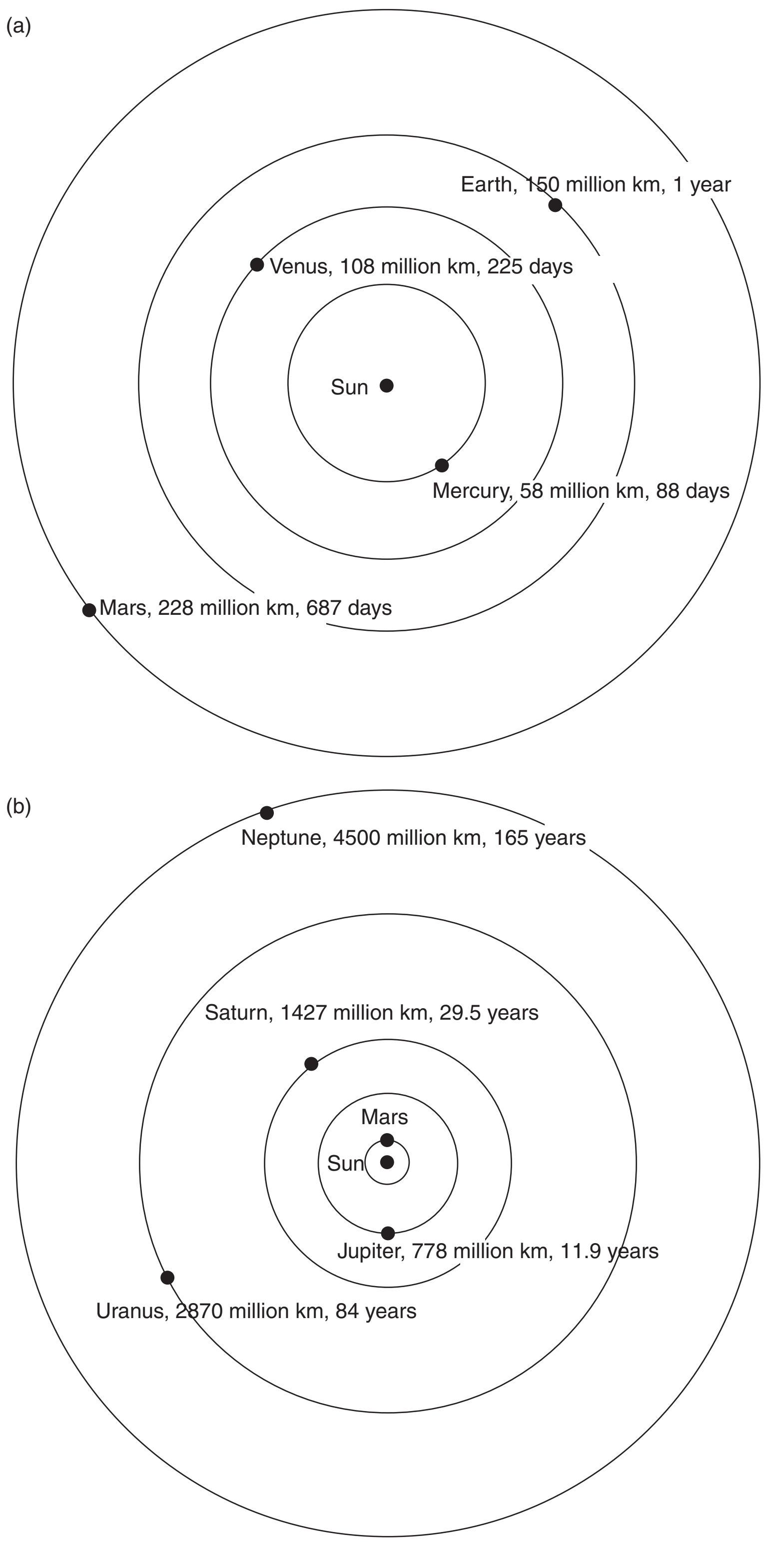

Figure 1.1 (a) The orbits of the inner planets;
(b) The orbits of the outer planets.

and so it is obvious that the Earth's density increases towards its centre. This is because the Earth is *chemically differentiated*, meaning that when the Earth was formed the lighter and more volatile substances rose to the surface while the heavier substances sank towards the its centre.

Seismographic studies have revealed that three distinct zones exist within the Earth. These are the *core*, the *mantle* and the *crust*. The core extends from the Earth's centre out to a radius of 3500 km and consists of two parts: a fluid outer core and a central solid core. The solid component has a radius of about 1250 km. The core is composed of iron and nickel, with some cobalt.

Over the core, extending out to a radius of about 6370 km, lies the mantle. It is mainly composed of silicates and is rather plastic in its mechanical nature. Overlying the mantle, with an average thickness of about 33 km, is the crust upon which we live. Radioactive decay, together with the heat left over from the formation of the Earth, causes the temperature to increase towards its centre. The temperature at the Earth's core is thought to be of the order of 5000°C.

The surface of the Earth is mainly composed of volcanic and *sedimentary* rocks. Sedimentary rocks are those deposited from an aqueous environment by any of various mechanical and biological mechanisms. Weathering, erosion and biological action turn these rocks into soils. Two-thirds of the Earth's surface is covered in water and most of this is saline.

A notable feature of this planet is that it is geologically active. Indeed, the very crust of the Earth resembles a huge broken eggshell with each of the pieces of shell floating on the mantle below it. These segments are called *plates* and the study of their movements is called *plate tectonics*.

Hundreds of millions of years ago there was just one major land mass above the level of the ocean. Since then tectonic activity, more commonly known as *continental drift*, has split this into parts and caused each to separate and spread over the Earth into their present locations.

Enormous forces build up at the boundaries between the crustal plates. Earthquakes are propagated along these *fault lines* when one plate slips against (or under, or over) another. Volcanoes are also active along fault lines.

The range of temperature that is experienced on the surface of the Earth is moderated by the blanketing effect of the atmosphere. Heat is retained during the night and the surface is shielded from the harshest of the Sun's rays during the daytime. The temperatures on the Earth range from a little below −50°C at night at the Earth's frozen poles to a little above +50°C during the hottest days near the Equator.

The sea-level pressure of the Earth's atmosphere is 101 325 N/m^2 (newtons per square metre). Air is a mixture of different gases. Its composition by volume is 78% nitrogen, 21% oxygen, with carbon dioxide and argon making up most of the remaining 1%. The lower portions of the Earth's atmosphere are also quite rich in water vapour.

There are traces of atmosphere hundreds of kilometres up but most of the mass of the air is concentrated in the first 10 km. As Figure 1.2 shows, the atmosphere can be divided up into distinct layers. These are marked by temperature variations. The lowest region is the *troposphere*, which is the region of weather.

The temperature of the atmosphere drops (as does the pressure) with increasing height until a region 12 km up, the *tropopause*, where the temperature levels off at about −60°C (with equator to pole variations – this figure also is subject to fluctuations over time). Cirrus clouds can extend up to a height of about 10 km.

Beyond the troposphere is the *stratosphere*, where the temperature begins to rise slowly until a region known as the *stratopause*, where the temperature levels off at about −40°C. It is in the stratosphere that most (about 90 per cent) of the atmospheric ozone is concentrated. Ozone is formed by chemical reactions between ionised atoms and molecules of oxygen. It is the short-wave radiations that the Sun sends us, along with the beneficial warmth and sunlight, which cause the ionisation of the normal molecules.

The stratopause lies at a height of 40 km and beyond this lies the *mesosphere*. In this region the temperature falls rapidly to a value of about −100°C or so at an altitude of 80 km: the *mesopause*. However, all of the foregoing temperatures are very much average values and are subject to seasonal and diurnal variations, as well as variations with latitude.

While all normal clouds reside below the tropopause, at the level of the mesopause a peculiar type of cloud exists composed of tiny ice crystals. These clouds are very tenuous in nature but can be seen from the ground at dusk from temperate latitudes during the summer months. This is because their height causes them still to be sunlit even when the Earth's surface and the tropospheric clouds have become submerged in the Earth's shadow. We call these gently shining night-time forms *noctilucent clouds*.

Above the mesopause lies the *thermosphere* where the temperature rapidly increases to somewhere around 1000°C at 600 km and then levels off in a region known as the *thermopause*. Finally, above the thermopause lies the *exosphere*, which consists mainly of hydrogen and extends to a height of about 5000 km where it merges with interplanetary space.

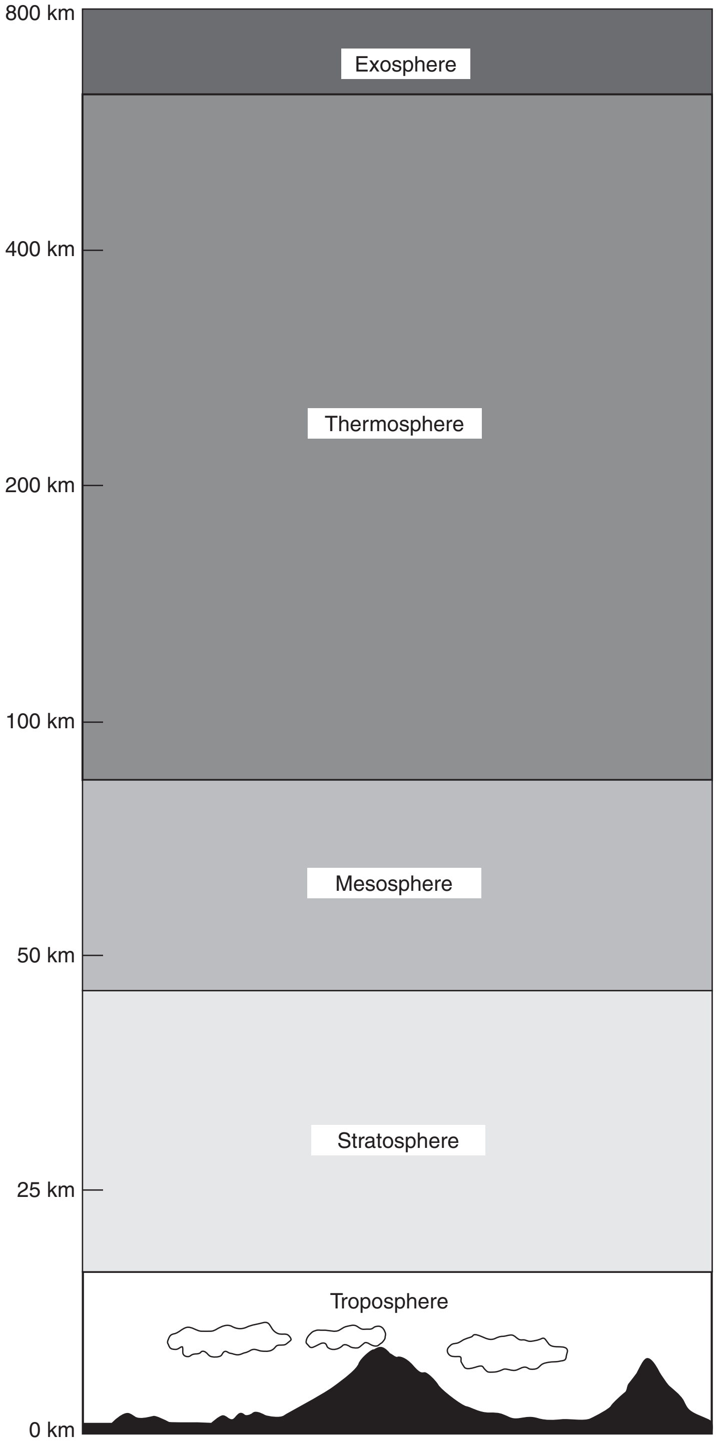

Figure 1.2 The Earth's atmosphere.

The short-wave radiations emitted by the Sun have the effect of ionising the rarefied gases in the upper atmosphere. The *ionosphere* is usually taken to exist between 80 km and 300 km above the Earth's surface, as a series of ionised regions and layers. These can reflect radio waves, so allowing radio reception far round the Earth's curved surface and much further from the transmitting station than would otherwise be the case. The gases above 300 km are also highly ionised but they are also extremely rarefied and so have less effect on radio waves.

1.2 THE EARTH'S MAGNETOSPHERE

The Earth has a magnetic field which is *dipolar* in form, like that of a simple bar magnet. As shown in Figure 1.3, the Earth's rotational and magnetic axes do not coincide. At present they are inclined at 11½° to each other.

The positions of the magnetic poles are not fixed but appear to be very slowly moving in a very roughly circular path. At present the north magnetic pole is moving westwards by about 0°.05 per year. In addition, the magnetic field is not constant in strength. It is currently decreasing

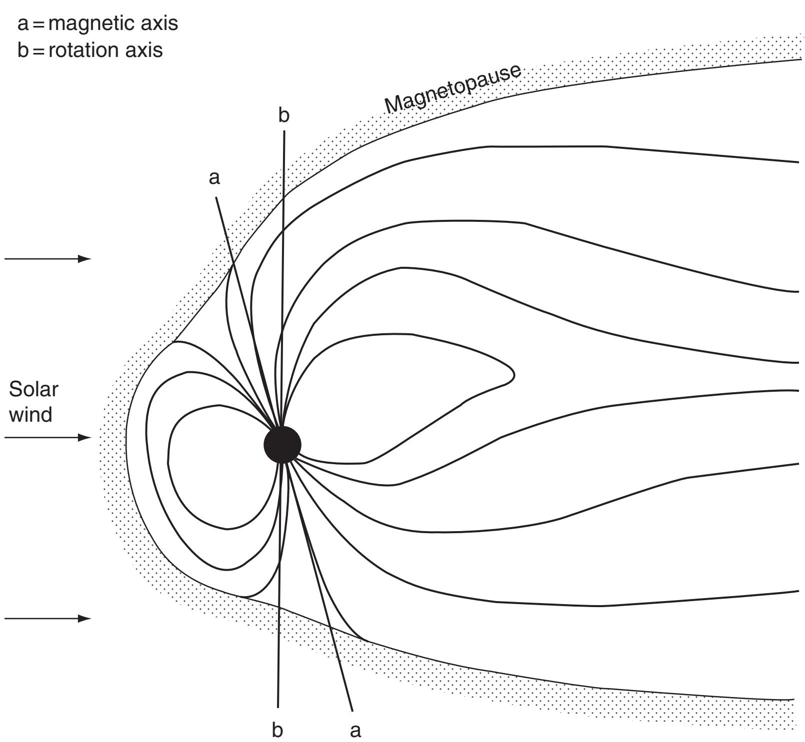

Figure 1.3 The Earth's magnetosphere.

at the rate of 1 per cent every 10 000 years. The Earth's magnetic field has even been known to reverse its polarity. This has happened several times in the past few million years, as revealed by studies of ferromagnetic rocks near the surface.

The terrestrial magnetic field is generated by a natural dynamo effect. The material of the Earth's core conducts electricity. Its churning motions, due to convection of the hot fluid and the spinning motion of the Earth, cause electric currents. These electric currents then generate the magnetic field.

As also shown in Figure 1.3, the Earth's magnetic field, or *magnetosphere*, is somewhat distorted on the large scale. The reasons for this are twofold. One is that the Sun has a very powerful and extensive magnetic field that extends outwards into the Solar System, interacting with the Earth's field. The other reason is that the Sun emits a stream of electrified particles that blow through the Solar System like a breeze: the *solar wind*. It is the fact that these particles are electrically charged that gives them the property of being able to distort the Earth's magnetosphere when they encounter it.

The Earth's magnetic field lines are flattened in the direction of the Sun and are extended in the antisolar direction. Near the Earth's globe its own magnetic field is strong and so it is only slightly distorted by solar interactions. However, the field strength decreases in accordance with an inverse-cube law and so the field strength at large distances from the Earth is low and the shape of the field is distorted much more.

At about 60 000 km from the Earth the magnetic-field lines no longer rejoin at the Earth's magnetic poles, this region being termed the *magnetopause*. Beyond the magnetopause lies a boundary layer where a large fraction of the particles from the Sun are deviated in their courses and pass round the Earth and out into the Solar System under the repulsive effect of the Earth's magnetic field. This layer is known as the *magnetosheath*.

However, some rather more energetic solar particles are trapped lower in the Earth's magnetosphere in two torroidal regions, the *Van Allen radiation belts*, named after James Van Allen who discovered them in 1958 as a result of experiments with rockets. They are depicted in Figure 1.4. The inner torus is filled with protons of energies ranging about 50 MeV (mega electronvolts) and lies at an average height of about 4000 km above the Earth's surface. The outer torus, which lies at an average height of about 17 000 km, is filled with electrons with energies ranging around 30 MeV. These energetic particles loop from end to end within the zones.

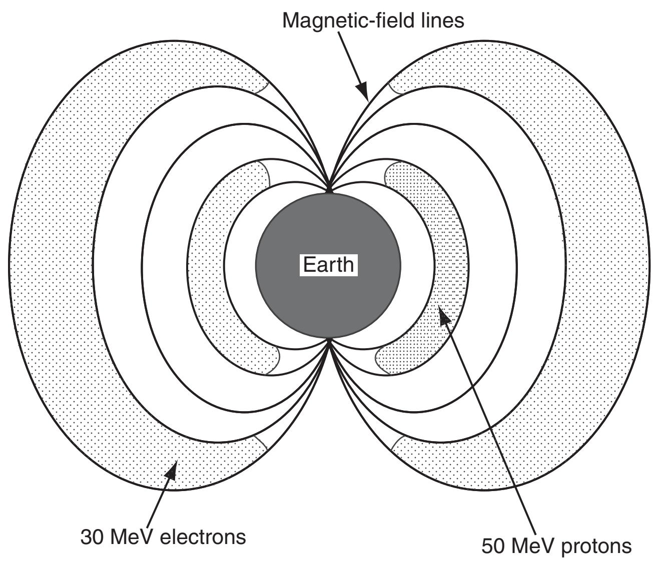

Figure 1.4 The Van Allen radiation belts.

1.3 AURORAE

Known since ancient times, *aurorae* take the form of beautifully coloured glows in the night sky. They are most often seen from far-northerly and far-southerly latitudes. In fact, they are visible on most nights from countries like Greenland and Alaska. They are least often seen from the equatorial regions of this planet.

The colours of the displays are chiefly shades of green and red, though yellow, blue and purple are sometimes seen. Most of the displays seen from temperate latitudes appear to the unaided eye as greyish-white because the auroral light is too dim to stimulate the eye's colour receptors.

A display may take the form of pulsating coloured glows in large, diffuse, patches of the sky, or perhaps just a steady glow. A major display may consist of ribbons and streamers of colour that pulsate and change their shapes in a matter of seconds. From mid-northern latitudes aurorae can sometimes be seen by looking towards the northern horizon, though town lights will completely swamp the effect. People living in mid-southern latitudes should look towards their southern horizon. The aurora concentrated toward the north pole is referred to as the *aurora borealis* – meaning 'northern dawn' – while that concentrated towards the south pole is called the *aurora australis* – 'southern dawn'.

The aurorae are caused by energetic solar wind particles finding their way into the Earth's inner magnetosphere. The precise details of the mechanisms that happen to allow this effect are still being investigated but certainly the most intense clouds of solar wind particles (erupted from the Sun by solar flares and coronal mass ejections – these terms are explained in Chapter 12) cause distortions in the magnetic field with field lines breaking and reconnecting. The normal protective sheath of the terrestrial magnetosphere is breached allowing the solar wind particles to enter. If you want an analogy, then it is a bit like powerful gusts of wind blowing open a door and allowing further blasts of wind to enter a dwelling. The solar wind particles spiral down the Earth's magnetic-field lines preferentially toward the poles.

The particles ploughing through the ionosphere constitute electrical currents that give rise to the coloured glows in the same manner as in the gases of the low-pressure fluorescent-tube discharge lamps so commonly used today. This is by particle collisions exciting electrons bound within gas atoms. On de-excitation the electrons re-emit the energy as photons of electromagnetic radiation – in other words light.

The gases causing the coloured glows are molecular nitrogen, atomic nitrogen, and atomic oxygen. The chief emissions originating in the atmosphere at heights below 100 km are from molecular nitrogen and these mostly produce red colourations. The strongest emissions in a display are normally produced by excited atoms of oxygen. These create green and red glows, originating mostly at heights above 150 km. In most displays it is the green light of oxygen that dominates. Sometimes purples glows are visible. Nitrogen is responsible for these, this time originating mostly at an altitude of the order of a thousand kilometres.

The probability of an auroral display happening, and the intensities of any displays that do occur, vary from year to year. This is because the Sun produces solar flares and coronal mass ejections with a frequency that also varies from year to year. There is much more about the Sun and how to observe it in Chapter 12, but suffice it to say here that the Sun's activity waxes and wanes with a period of about eleven years. It is at times of highest solar activity (actually often a year or so after the peak of the visible sunspot cycle) that auroral displays are at their most frequent and most spectacular.

The most spectacular auroral display I have ever seen was that of the night of 13/14 March 1989. At dusk on 13 March I was busy with one of the telescopes of the former Royal Greenwich Observatory at their Herstmonceux site. At one point early on I left the dome and noticed a peculiar glow along the northern horizon, like a row of searchlight beams fanning upwards. As I watched I could see the glow wavering slightly and changing in brightness.

I had observed the Sun earlier that day and had noted its high activity (it was then close to the time of maximum activity in its cycle). I realised what was happening and alerted the only other observer on site at that time, Peter Strugnell, who was preparing to operate the satellite-tracking camera in another dome. We climbed onto the roof of an adjoining building between two domes and watched and photographed as an

Figure 1.5 The brilliant auroral storm of 1989 March 13^d photographed by Peter Strugnell and the author. Peter's camera happened to be loaded with 100 ISO colour-print film (Kodak Gold 100) and 30 second exposures were made during the course of the display. The camera was fitted with a 35 mm focal length lens, set to f/2.4. This is looking east and the brightest star visible just above the dome is Arcturus. Notice the tropospheric clouds silhouetted against the bright auroral light visible in the lower left of this picture. [This image is also reproduced in colour as PLATE I (upper), between pages 304 and 305].

amazing auroral display unfolded (see Figure 1.5). At times, vast arches of blue-green light pulsed low down in the north, with upward shafts and wavering curtains of light becoming yellow higher up and finally a rich vibrant red extending to the zenith.

The display continued, showing amazing variations. For instance, at one point the whole sky became a vivid red colour and the scene around us became quite unearthly. At another point later in the display a white patch formed at the zenith, which then broke into moving ripples at the same time as tickertape-like darts of light formed in the south. The telephone lines to the observatory became jammed with callers and that aurora became an international news story. It was an awesome experience and yet it is rare to see the aurora at all from southern England.

1.4 VISUALLY OBSERVING AURORAE

The best way of ensuring that you know that an aurora might happen or is happening is by belonging to the aurora observing section of a national astronomical society. More about that in Section 1.12. The following websites may also be of use: