Chapter 7

Terrestrial Exoplanets

As impressive as giant planets may be, they are not "our kind of planet". The ones we really want to know about are the smaller, Earth-like worlds. Not exactly like Earth, just close enough so we can relate to them, imagine ourselves there, roaming alien landscapes, the kind of places where we might even encounter life in some recognisable form.

About one hundred years ago, a common assumption was that the Universe and the Solar System itself were teeming with life. One of the reference books of popular astronomy at the time, by the French author Camille Flammarion, introduced its readers to likely Venusian jungles, ancient Martian cultures, and even ethereal inhabitants of Saturn's rings. Space was a natural stage for the extension of the great age of European exploration, and soon the galaxy was dotted with exotic alien tribes, egg-laying princesses and seven-armed beasts. All the medieval monsters and chimeras that had been chased from the terra incognita of Africa and Asia by explorers had retreated into outer space – where, indeed, they still are to this day.

But the planetary probes of the late twentieth century have blown a cold and dry wind on these alien dreams. Mars, then Venus, turned out to be totally hostile to life, and one by one planets and moons have been shown to be admittedly beautiful but totally mineral worlds. In spite of all the efforts of science communicators, planetary landscapes remain lifeless and emotionless, and become fascinating within the narrow confines of mineral elegance and abstract harmony.

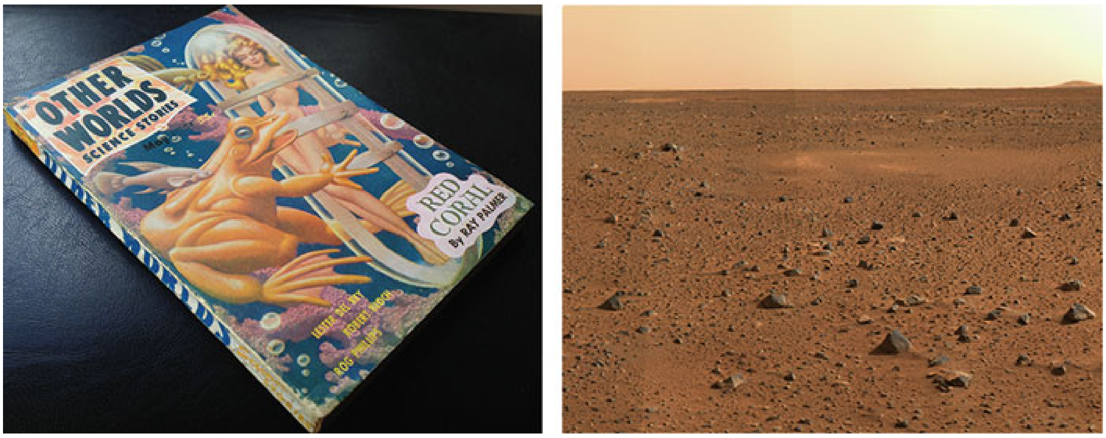


Fig. 7.1 Planetary landscapes do not measure up to fictional expectations. Image (right): NASA

But the alien dream is still there, filling books, movies and computer games by the hundreds, and its faint echo drifts up to the arid research institutes which pursue the study of terrestrial exoplanets. “Ocean planets”, “super-Earths”, “lava worlds”, “sub-icecap oceans”, these words all conjure up powerful emotions.

Let us now turn to these other worlds, as they are imagined by planetary scientists from the present, very patchy observations.

The planet gap

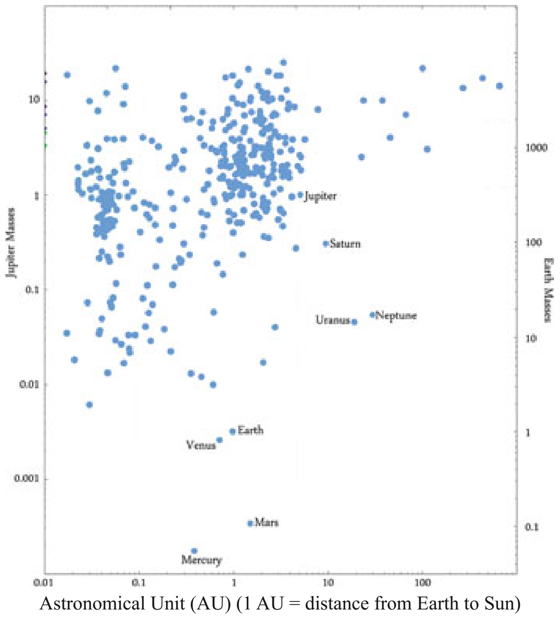
In the Solar System there is a large gap in mass between the smallest giant planet, Uranus, and the largest rocky planet, Earth. Uranus is 14 times heavier than our planet. Neptune has a mass close to that of Uranus, and Venus to Earth. But there is no planet in the mass interval between one and 14 times the mass of the Earth.

As we have seen on page 71, this division is caused by the snow line, the imaginary limit in planetary systems separating the inner regions that are too warm for water to condense into ice and snow, from the outer, colder regions. In the Solar System, the snow line is some three Astronomical Units from the Sun, between the orbits of Mars and Jupiter. The planets fall neatly into two groups, the small “dry” ones, made of rocks and metal, within the snow line, and the large “wet” planets, made mainly of ices and gas, beyond the snow line. There is about 15 times more water than rocks in the interstellar gas from which stars and planets are made. This is a reflection of the much higher abundance of hydrogen and oxygen than silicon and metals in the interstellar gas (see Astronomer’s Periodic Table, page 70).

Because the snow line is present around all stars, we would predict a dearth of planets in the one to 15 Earth-mass range among exoplanets, as well.

However, the on-going census of exoplanets has shown that there are plenty of planets with masses between two and 14 times the mass of the Earth, and the expected gap is completely absent from the overall distribution of masses. Worse still, these planets do not particularly congregate at orbital distances related to the position of the snow line.

Fig. 7.2 Mass versus orbital distance diagram of known exoplanets.



Armaggedons

Indeed, the most striking result from the hunt for exoplanets is that every plausible combination of planet size and distance seems to exist in some system somewhere. The exoplanets found so far show none of the order expected from the Solar System. They often orbit very close to their star – regardless of whether they contain ice or not – and generally follow more eccentric and tilted orbits than any planet in the Solar System.

This suggests that many planetary systems have messy histories, with plenty of near-collisions and orbital changes, which have shuffled the planets around and blurred the limit defined by the snow line. The Solar System seems to have been spared these gigantic rearrangements.

The science of exoplanets is still young and our views may shift as more planetary systems are discovered, but at present the understanding is that, after the dust in the disc had dissipated, most systems found themselves with more planets than they could accommodate. When planetary orbits are packed too close to each other, the planets repeatedly tug at each other gravitationally until their orbits become more and more eccentric. At some point this may bring two planets so close that the heavier one sends the lighter one on a wide loop, wreaking havoc on the whole system. Occasionally, planets can collide with each other and end up very close to the star – like hot Jupiters – or on the contrary very far away. They can even be swallowed by the star or be flung out of the system altogether.

After the birth of their system, planets find themselves locked in a gigantic game of musical chairs. There may be more than a dozen planets by the time the disc of gas around a new-born star dissipates, but room for less than ten. When a planetary system becomes unstable, two of its planets can crash against each other, forming a larger single planet, sometimes with moons formed out of the debris. However, the outcome can be more cataclysmic. If two gas giants interact so strongly that one of them spirals inwards towards the star to form a hot Jupiter, all the smaller planets in the system may well be lost in the process.

In the Solar System, each planet is about 1.5–2 times farther out than the previous one. This is about as tight as orbital dynamics would allow. If a new planet was inserted in the gap between two planets, it would make the whole system unstable. The one exception to the rule, the large distance between Mars and Jupiter, makes the point: it harbours cohorts of asteroids, the remains of a failed planet that was too close to Jupiter to form.

Upheaval in the Solar System

Our Solar System has escaped large-scale disaster. Its planets are on almost circular orbits, and they seem to have remained close to their birth places (in the sense that their present locations correspond to their internal composition, with rocky planets inside the snow line and ice-rich planets beyond).

However there is convincing evidence that we have had a very narrow escape. A team of scientists have reconstructed what may have been the most dramatic moments in the life of our planetary system. Here is the story.

Around 38 hundred million years ago, when the Solar System was seven hundred million years old, its giant planets were closer to each other than they are today, and Neptune and Uranus were in reverse order, with Neptune on the inner side, i.e. closer to Saturn. Over time, with the millions of small gravitational interactions between the planets, Saturn edged closer and closer to Jupiter, until it became too close for comfort. Jupiter began pulling Saturn into a more eccentric orbit, until its point of nearest approach became dangerously close to it. At some point the whole system snapped, Saturn was sharply pushed away by Jupiter, in turn sending the two smaller outer planets into wildly unstable orbits. Neptune was flung out to almost twice its former distance from the Sun while Uranus was bowled over so that it now spins almost upside-down. The myriad of minor planets crowded at the outer reaches of the Solar System (of which Pluto is the best-known example) were scattered all over the place, so that some were captured as satellites, some crashed into the giant planets, and some were sent inwards to fall onto the Earth or the Moon.

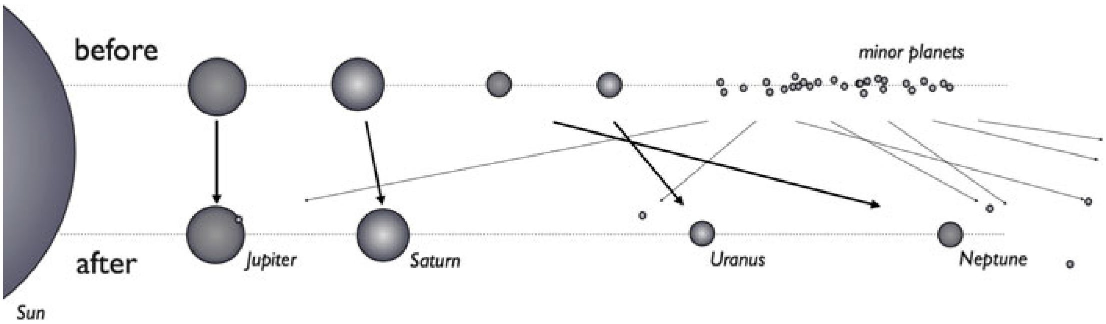


Fig. 7.3 Sketch of the Solar System before and after the upheaval of the "Late Heavy Bombardment" event, according to a plausible reconstruction. A resonance between Jupiter and Saturn spreads chaos throughout the outer regions of the Solar System, sending Uranus and Neptune to their present location, and sending a swarm of comets and asteroids everywhere.

This episode is known as the Late Heavy Bombardment. It is recorded by many huge craters on the Moon. It is "late" because it occurred about 700 million years after the formation of the Solar System, when such cataclysms were supposed to be a thing of the past. If this scenario is correct Jupiter almost killed his father a second time, destroying half of creation in the process.

Planetary dynamics offers the ultimate expression of the butterfly effect that we encountered earlier when talking about turbulent flow: how tiny changes in one place can propagate into the largest of consequences elsewhere. The dynamics of planetary orbits are very sensitive to this effect, indeed the butterfly effect and mathematical chaos were first described in relation to planetary orbits by the French mathematician Henri Poincaré in the nineteenth century. Poincaré was trying to prove that the configuration of planets in the Solar System is stable, that its orbits go on ticking forever like the model orreries built by astronomers. Instead, he got the first insight into the strange world of mathematical "chaos": he found that the tiniest of changes in the orbits could grow over time and evolve into unpredictable results.

Had the masses of Jupiter and Saturn been slightly different, the orbit of Saturn might have been perturbed beyond repair. The two giant planets could have collided, or Saturn could have been sent spiralling inwards to become one more "hot Jupiter", or outwards beyond Pluto. The first scenario would have spelt doom for the young Earth – already seven hundred million years old at that time and teeming with life, because all the inner planets would have been destroyed or scattered by a giant the size of Saturn spiralling towards the Sun.

Giant planets with orbits as circular as that of Jupiter are very rare among exoplanets. Less orderly outcomes of orbital interactions seem far more common. One could be tempted to speculate whether the uncharacteristic neatness of the Solar System is somehow related to our presence in it. It may be rare for Earth-like planets to be granted billions of years of quiet orbital cycles, so that organic life can evolve and prosper in peace. A single asteroid wiped out the dinosaurs, but that is next to nothing compared to rearrangements of whole planetary systems.

In case you are wondering, we seem to be safe this side of the Late Heavy Bombardment. Calculations about the future orbits of planets in the Solar System suggest that no further upheaval lies in store. There is a tiny chance that the orbit of Mercury will become more eccentric and start messing with the other rocky planets, but that is all. In computer simulations of the Solar System dynamics for five billion years in the future (the remaining lifetime of the Sun) 98 percent of cases have orbits remaining much as they are now. In 1–2 percent of cases, the orbit of Mercury becomes perturbed by Jupiter to such an extent that it either collides with Venus or falls into the Sun. In only one out of 2,500 of these simulations is the Earth strongly affected: the demise of Mercury bends the orbit of Mars until the inner point in its orbit crosses that of Earth. In a dramatic illustration of chaos theory, these different outcomes are obtained by changing the starting position of Mercury in the simulation by just one metre!

Composition of the atmosphere of terrestrial planets

Planets in the Solar system show that there are many possibilities for the atmosphere of terrestrial planets, indeed no two cases seem to be the same. Venus, Earth, Mars and Titan all have very different atmospheres, while Ganymede, Callisto and Europa – like our Moon – have no atmosphere at all.

As you may recall from Chapter 5, there are three possible origins for the gases which create atmospheres: they can be directly captured from the protoplanetary disc, expelled from the inside of the planet by volcanoes and lava flows, or added later on by comets and icy bodies crashing onto the planet.

In the first case, the planet must be heavy enough for its gravitational pull to retain the primordial gases even under the bombardment and collisions of the formation of the planet itself. Our Earth was not heavy enough for this, and must have lost all its initial gases early on, for instance during the giant impact that formed the Moon a few million years after the birth of the Solar System. However, planets around ten times heavier than Earth are able to retain their initial atmospheres, composed mainly of hydrogen and helium, like those of the Solar System's giant planets.

Alternatively, after the planet is formed, some lighter compounds trapped in the rocks may be released, in what is known as outgassing. A good example of this is planet Earth, where active volcanoes still spew out vast amounts of gases in the atmosphere and our atmosphere was mainly formed in this way. As convection in the Earth's mantle brings magma upwards, the lowering of the pressure causes chemical changes and rearrangements in the rocks that free volatile substances such as carbon dioxide, water and sulphur.

The importance of volcanism for the atmosphere of terrestrial planets may be surprising for most people, who live on large continental masses where magma and lava are remote presences underground, only providing heat for the occasional spa. But just as the rubbing together of continental plates is more familiar for people living in Japan, with weekly tremors as reminders, if you have visited places like the Yellowstone National Park in the United States, with fumaroles, bubbling lakes and geysers constantly blowing toxic fumes into the air over thousands of square kilometres, then the notion that the whole of Earth's atmosphere was ejected from the ground becomes more plausible.

Another source of volcanism is even less visible to us: the large chains of underwater volcanoes that form the ridges where tectonic plates surface from the interior of the Earth. The mid-ocean ridges are not only where new plates are formed, but also where the gases trapped in these plates are released into the oceans, later to make their way into the atmosphere.

On some small planets we can actually observe this process in a purer form. Io, the closest satellite of Jupiter, has hundreds of active volcanoes. Each time a volcano erupts it sends a plume hundreds of kilometres up into space, which forms a thin, temporary sulphur-rich atmosphere. But soon this tentative atmosphere is lost to space because the satellite's gravity is too low.

Volcanism and outgassing is not limited to lava and heavy gases as on Earth. On planets made mainly of ice, the main volcanic gas is water. This is "cryovolcanism": volcanoes of ice spewing out water vapour, a phenomenon that we have encountered on page 62 in the spectacular geysers of Enceladus.

Finally, comets visiting from outside the snow line can crash into a planet, vaporise on impact and enrich its atmosphere with volatile compounds such as water, ammonia, methane and carbon dioxide. This must also have happened on Earth to some degree, and some of the water in the oceans must come from comets.

These three kinds of atmospheres, originating in primordial gases, magma fumes or comets, look dramatically different, a difference that can be spotted at a distance of several light-years. The first type of atmosphere is very extended because the hydrogen and helium molecules are the lightest molecules. Instead of dropping by half every six kilometres as on Earth, the density of a hydrogen atmosphere drops by half every 40 kilometres.

Three categories of terrestrial planet atmospheres:

Size	*Composition*	*Origin*
Extended	mainly hydrogen and helium	from interstellar gas
Medium	water, methane	from comets or water volcanoes (cryovolcanoes)
Compact	carbon dioxide, nitrogen, sulphur	from volcanoes

In one case, the planet Anubis[14] situated in the Ophiuchus constellation, transit observations suggest that the atmosphere is compact. The size and mass of this planet suggest that it is mainly made of water, so a water vapour atmosphere would be a natural explanation. At this stage the evidence is mostly indirect, though a compact atmosphere is inferred from the fact that no spectral lines were detected during the transit in spite of many attempts with telescopes on the ground or in space. In a hydrogen-helium atmosphere these lines would be large enough to be seen.

There may be a fourth category of atmospheres. Some planets are so close to their star that all the light elements will have been blown into space by the high temperatures in the atmosphere (a higher temperature means that the molecules move about faster, and faster motion means an easier escape from the planet's gravity). If the planet has a rock mantle, its lava surface would exude silicate and metallic vapours that may form a thin atmosphere of "rock vapour".

---

[14] Another name I've just made up, the planet is officially called GJ1214b.

Exploring the zoo of imaginary terrestrial exoplanets

What do terrestrial exoplanets look like, feel like, smell like? Planetary scientists are not waiting for more observations before they start exploring the zoo of possibilities. But before taking a stroll across the bestiary that they have created, we must pause for a little warning. The history of science in general, and exoplanet science in particular, has not been too kind to unbridled speculations or unconstrained models. Confident predictions later overturned by observations are too many to mention. Indeed, conversely, model predictions later confirmed by observations are so rare as to be counted on the hands of a Saturnian (which, according to Camille Flammarion, must have robust hands to deal with the higher gravity, implying a lower number of fingers than us).

There is good news, however; what the observations reveal is very often wilder, more varied, more colourful and more interesting than what the models predicted. Keeping this in mind, let's take a tour of the exoplanet zoo and stop briefly in front of a few exotic specimens.

Ocean planet

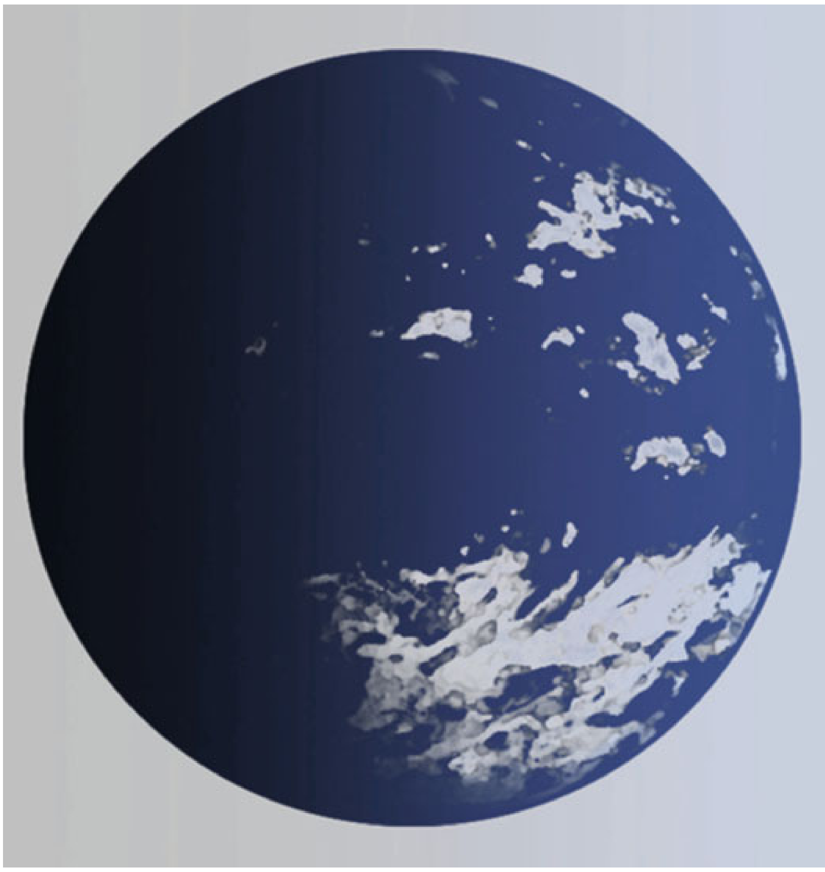


Fig. 7.4 Ocean planets: the dream.

First, we come across one of the water worlds. This one has the correct temperature for water to be liquid, so we will call it Aquaworld, to distinguish it from its cooler (ice) and hotter (supercritical) water-rich cousins. To imagine what such a planet would be like, we start from a climate model of the Earth, and raise the level of the oceans until

Fig. 7.5 Switzerland now, with sea level 1,500 metres (5,000 feet) higher, and four kilometres (13,000 feet) higher.

all the continents are covered.

On Earth, the continents divert the flow of currents in the oceans, forcing them along a complicated loop which snakes around the whole world, transporting heat from the Equator to the poles in the process.

Without continents, oceanic currents would be much simpler. They would behave like the atmospheric currents, with mostly eastwards currents because of the planetary rotation (on a planet the “east” is by definition the direction of rotation).

That would make the poleward transport of heat less efficient, leading to more deeply frozen poles than on the present Earth.

In fact, this phenomenon is visible on Earth: near the North Pole, the climate is relatively benign, with people living as high north as latitude 70 degrees, because the shapes of the continents channel the warm Atlantic currents all the way into the Arctic Ocean. The relatively pleasant town of Tromsø in Norway is at +69 degrees 40 minutes, the somewhat tougher town of Barrow in Alaska is at +71degrees 17 minutes. In the south, by contrast, the sea currents can circle the whole Antarctic continent using the Drake Passage between South America and the Antarctic Peninsula. This is why the south polar region remains frozen from around –60 degrees southwards. The southernmost towns on Earth are Puerto Williams and Ushuaia in Tierra del Fuego at a latitude of –54 degrees south. Incidentally, the opening of the Drake passage by tectonic motions about 41 million years ago was one of the drivers for the ice ages that have seized the Earth at various intervals during the last few million years. An apparently local event such as the opening of Drake’s passage has caused global climate change!

Fig. 7.6 Global ocean currents now, and in the time of Pangea, 200 million years ago.

Figure 7.7 shows, step by step, how simplified models of the position of continents can make us understand the circulation on hypothetical Aquaworld and on Earth.

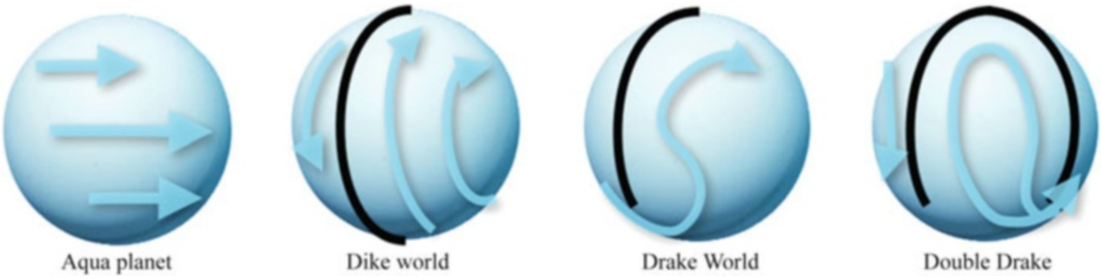


Fig. 7.7 Ocean currents with four highly simplified distributions of continents. Present Earth broadly corresponds to the fourth case.

In Chapter 3 we mentioned the daunting engineering project of rendering Mars inhabitable. The comparison of the currents in our "Drake World" and a hypothetical "Dike World" suggest a way to render Antarctica inhabitable, which, as such grandiose projects go, may be easier than terraforming Mars. We "only" need to build a dike across the Drake passage, and the ocean currents will be diverted. The loop around Antarctica that keeps it locked in a cold polar pocket will be broken. The whole continent will heat up, most of the ice sheet will melt, and 14 million square kilometres of prime real estate will be made available to an eager human population.

The only work required is to connect the Tierra del Fuego at the tip of South America with the Antarctica Peninsula, a stretch of ocean 1,000 kilometres (600 miles) in length, with a dam of earth and gravel. This is some engineering challenge to be sure, but possibly easier than pumping a whole atmosphere into Mars.

Snowball planet

In its long history, planet Earth has explored configurations that are so different from each other that they could actually represent other planets. Several times in the past, all Earth's continents were gathered up in a single landmass. Soon after its birth Earth was probably covered by a single ocean without any emerging land. In a sense Earth has even travelled several distances from its host star, since the Sun has become markedly brighter along the eons, corresponding to moving the Earth 20 percent closer to its host star since its birth.

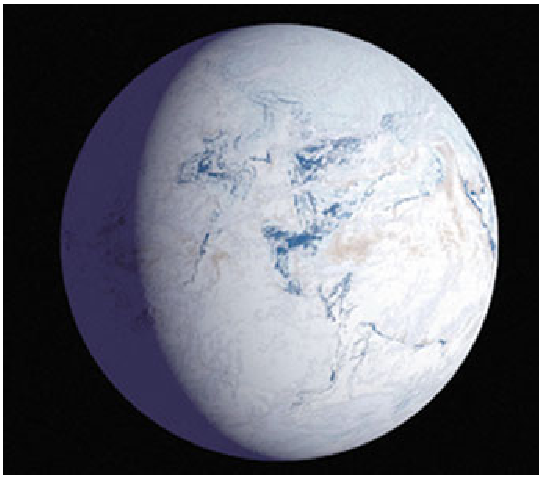


Fig. 7.8 Snowball planet.

Perhaps the most intriguing and unfamiliar state from Earth's past is the one known as *snowball Earth*. At several stages in its life, before the apparition of complex life-forms and the colonisation of land, Earth was seized by extreme versions of the Ice Age, with most of the ocean freezing over, and the global temperature plummeting.

This seems to have occurred at least twice, about 650 million years ago just before the appearance of complex animals in the "Cambrian explosion", and earlier around 2.2 billion years ago. These episodes lasted a few dozen million years before the climate started thawing again.

It turns out that the climate on Earth can find stability in two configurations: the present state, with relatively warm seas and continents which, thanks to the dark colour of water, rocks and vegetation, absorb enough sunlight to maintain the mean global temperature around +15 degrees Celsius; and a snow-and-ice covered state, where most of the sunlight is reflected back into space because snow, being white, absorbs very little light.

Both states are stable, which is a cautionary tale when trying to predict the climate of an exoplanet from models and calculations; even in a single case like the Earth, there are two perfectly valid solutions.

It is not clear what triggered the snowball states on Earth – nor whether they were global. Some part of the oceans near the Equator might have remained ice-free. We are not sure, either, what it was that jolted the planet out of these states. The best candidate so far is the greenhouse effect induced by the carbon dioxide released in volcanic eruptions. Normally, the oceans and rocks on the continents absorb as much carbon dioxide as the volcanoes produce, keeping the amount in the atmosphere constant. This is a delicate balance that can be offset by changes in the position of the continents, the brightness of the Sun or the chemistry of life. If too much carbon dioxide is captured, the greenhouse effect drops, and the temperature crosses the point at which snowfalls start sending the planet into a positive feedback loop: more snowfall means more sunlight sent back into space, cooler temperatures, and more snowfalls.

Fortunately for us, there is a longer-term negative feedback that provides an escape from snowball Earth: once it covers oceans and continents, ice prevents the absorption of carbon dioxide by water and rocks. Volcanoes can pierce through the ice though, and they keep pouring CO_2 into the atmosphere, until the greenhouse effect builds up sufficiently to melt the ice again. The feedback loop is now inverted, with more open seas meaning darker colours, more absorbed sunlight and a higher temperature melting more icecaps.

Terrestrial water planets positioned slightly further away from their host star than the Earth, or orbiting a fainter star, may become permanently blocked in this snowball state, creating beautiful but barren polar worlds.

If the planet is large and young enough, hidden oceans may subsist deep below the ice. In Antarctica, Lake Vostok (which is an enormous lake buried under several miles of ice) is kept liquid by volcanoes buried underneath the ice sheet, in spite of temperatures between –30 and –60 degrees Celsius at the surface.

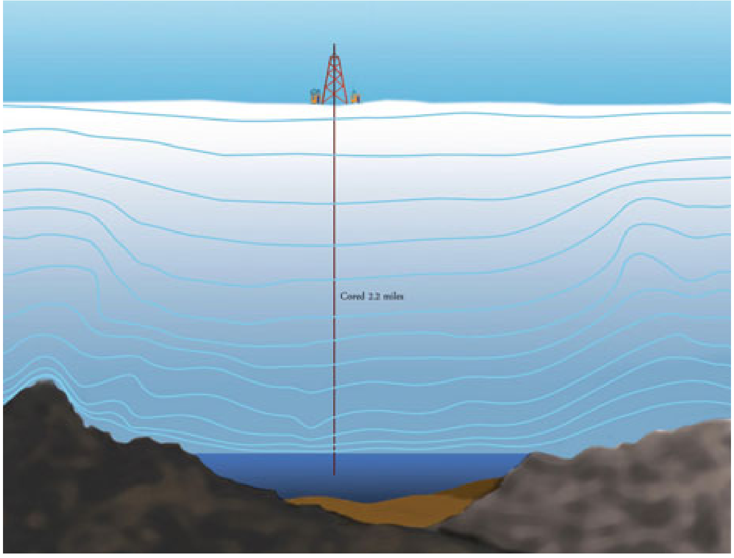


Fig. 7.9 Lake Vostok.

A snowball exo-Earth could keep a large buried ocean in liquid form under a frozen surface.

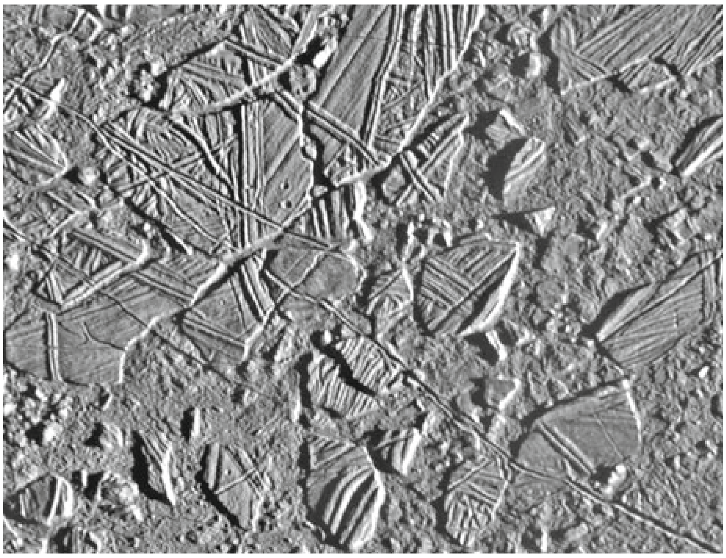


Fig. 7.10 Europa's surface, rafts of ice sheet on a buried ocean. Image credit: NASA

Steppenwolf planet

A planet could even keep an under-ice ocean warm in the absence of light from a star. A planet drifting in empty space, light-years from the nearest star, could still harbour dark but warm seas under the protective cover of a thick ice sheet, heated by underwater lava flows. There is enough residual heat in a planet the size of Earth, and heat generated by the disintegration of radio-active atoms, to keep its volcanoes going for billions of years.

Indeed, astronomers have found that planets drifting in empty space, far from any parent star, are not uncommon. They will have been ejected from their system by a heavier planet or after a close encounter with another star. The idea that such planets might harbour life with their dark interior oceans powered by underwater volcanoes is not that far-fetched. In the depth of the Earth's oceans, thousands of volcanic vents maintain living communities entirely disconnected from the surface world, all along the mid-ocean ridges. The catch is that even if such a planet is teeming with life, it is hard to imagine what kind of detectable signal it would leave on the outside of the planet.

Different Earths

The distance between a terrestrial planet and its host star is the dominant factor for a terrestrial planet, but other parameters of its orbital motion have a strong influence on its atmosphere and climate. An Earth-like exoplanet could have a different rate of spin, changing the length of a day, or a different tilt of its rotation axis, or a more eccentric orbit around its star.

Rotation speed

In Chapter 3 we saw how the speed of rotation affects a planet's climate. At one end of the spectrum slowly rotating planets have a single circulation pattern covering the whole planet. At the other extreme, fast rotating planets form narrow east-west bands. For rotation rates somewhere in-between, the patterns will consist of a few large zones. How would this affect a terrestrial planet? The main effect of rotation would be to prevent the efficient transport of heat from the equatorial regions to the poles. For a planet rotating up to twice faster than Earth, the difference would be slight. The transport of heat from Equator to Pole would be made more difficult by the increase in the Coriolis effect.

But at a faster rotation, with days becoming shorter than about ten hours, the atmosphere would switch to a banded structure like that of Jupiter, and heat transport towards the poles would become inefficient. The poles would remain extremely cold. During the long, dark winters, temperatures would probably reach the point of condensation of carbon dioxide (–78 degree Celsius), so that dry ice would start falling out of the sky in small crystals, a carbon dioxide snow.

Some planets would have become locked to their star so that their rotation period and orbital period would have converged to the same value, in other words the duration of days and years become the same (through the tidal mechanism that we encountered on page 85). Like hot Jupiters such planets have a permanent day side and a permanent night side, and the Sun never moves in the sky. If the planet has little or no atmosphere, the consequences on its climate are drastic, with extreme temperature differences between the two sides of the planet. But with an atmosphere, winds will carry the heat across the planet, and negate some of the day-night contrast. A thick atmosphere like that of Venus will negate the day-night difference almost entirely.

With a "medium weight" atmosphere, for instance an Earth equivalent, the contrast between the day and night side will not be entirely erased. This configuration has been studied by climate specialists, and they predict a mean temperature of +50 degrees Celsius near the Equator on the side of the planet always facing the Sun, and a mean temperature of –10 at the centre of the night side. Powerful westerly winds would bring some of the heat to the night side. The transition from day to night would not be a question of time like on Earth, but a distance covered in space. The Sun would never rise or set in any given place, but a long journey towards the east or west will make the Sun rise or fall in the sky.

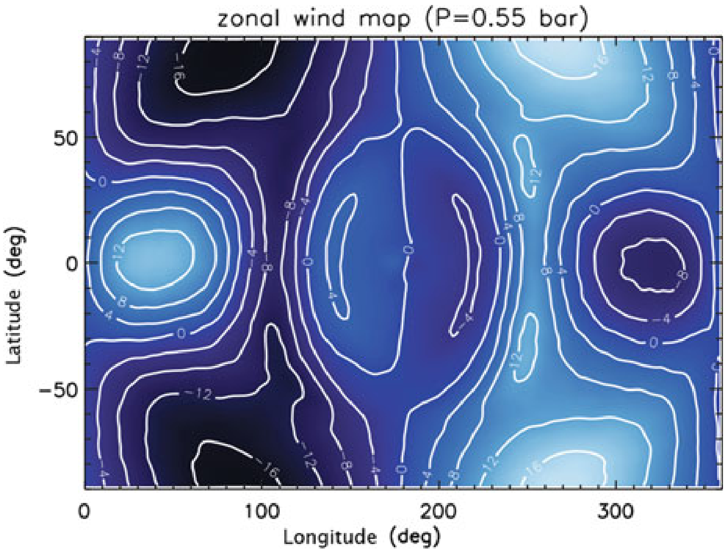


Fig. 7.11 Plot of the wind speed from a climate simulation for a tidally-locked terrestrial planet. Image credit: Heng et al.

Climate on such a rotation-synchronised earth would be peculiar. The difference that we are used to associating with the north-south axis would be reported to east and west. The day side, around longitude zero degrees, would have a permanently hot climate, the centre of the night side, longitude 180 degrees, would be permanently frozen. But the regions near the edge (90 degrees east and 90 degrees west) could have very variable weather, depending on whether the main plume of hot air from the day side crosses the region or swerves past it.

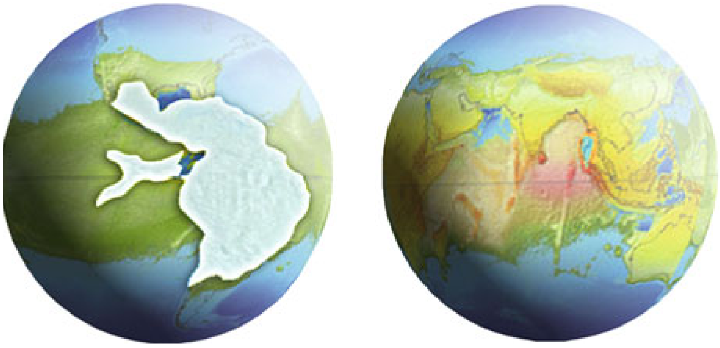


Fig. 7.12 Climate on tidally synchronised Earth. The densest part of Earth, situated in Asia, always faces the Sun. An ice sheet covers most of the Americas. Since the centrifugal force has diminished, the oceans have retreated towards the poles.

Axial tilt

The rotation axis of the Earth is tilted by 23 degrees relative to the Sun. The regions most exposed to sunlight oscillate during each year between latitude 23 degrees north and 23 degrees south, the Tropics of Cancer and Capricorn, and the North and South Pole spend half the year in darkness and half in constant sunlight. In temperate countries, the height of the Sun in the sky changes by 46 degrees between winter and summer. If the rotational axis of the Earth was aligned with the way it rotates around the Sun, each region would receive the same amount of sunlight throughout the year, and there would be no seasons. The poles would still be colder than the tropics because sunlight hits them at a low angle.

There is nothing special about this value of 23 degrees, some planets are tilted completely sideways (Uranus), so that their poles get more sunlight than the Equator, while other are flipped upside down (Venus), so that they orbit the Sun clockwise but rotate counter-clockwise. A planet's tilt is not even constant with time, but can vary under the influence of other objects. Earth's tilt varies by about one degree every few thousand years. It is relatively stable because the gravity of the Moon tends to prevent large swings in its position. Mars, by contrast, is thought to have oscillated between values as different as 11 to 49 degrees.

An Earth-like planet with an axial tilt higher than Earth's present 23 degrees would have more extreme seasons. We get a taste of this in arid, high-latitude regions like the Gobi desert, because dry air amplifies temperature differences. The temperature in Mongolia often rises to +40 degrees Celsius in the summer and plummets to –30 degrees Celsius in the winter.

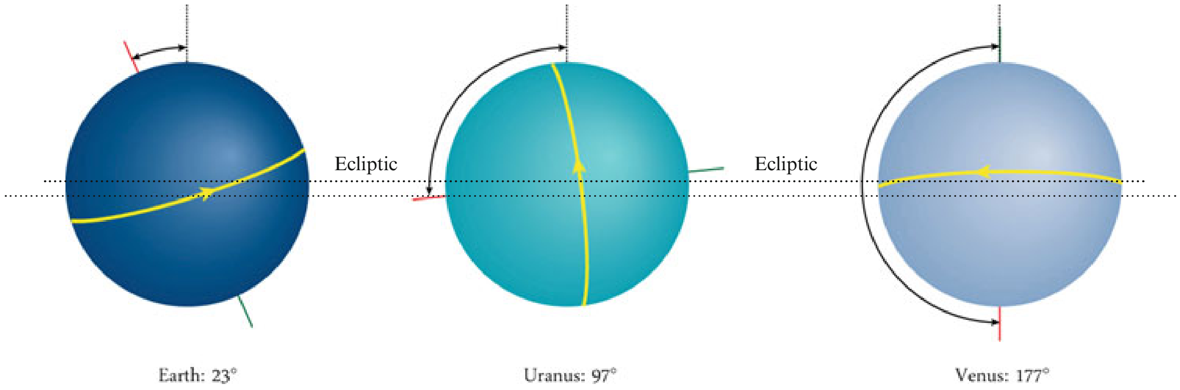


Fig. 7.13 The axial tilt, or obliquity, is the angle between the rotation axis of a planet and the plane of its rotation around the Sun.

Beyond 53 degrees of inclination, the poles receive more heat during a year than the Equator does, reversing the usual hierarchy. On an Earth-like planet tilted at such a high angle, the warmest climate would be found near the poles in summer! The other hemisphere would get extremely cold in the winter.

The appearance of the Sun in the sky viewed from such a planet takes some imagining, and you'll see it better if you just try it out with an orange and an apple than by reading about it. Near the poles, the Sun would stay high in the sky for the whole summer, in a sort of permanent tropical noon, then slowly set in autumn and disappear for the whole winter, causing scarcely imaginable seasonal variations.

Closer to the Equator, the length of the day would more constant, but the seasonal variations extreme, with the Sun barely skimming the horizon in spring and autumn and climbing towards the zenith at noon in summer. Huge storms would form over the summer pole as the winds try to carry the heat away towards the darker hemisphere.

The climate and air circulation on such a planet would be profoundly different. One possibility explored by planetary scientists is that of a "pool planet", covered with ice and snow except in a seasonal opening of the sea at the summer pole. One can only ponder how life would adapt to such a climate. Life could still survive in the ocean under the ice, as in the Arctic on Earth, but all photosynthetic organisms would need to follow the pool of open water with the seasons.

Eccentric orbit

Johannes Kepler proved mathematically in the seventeenth century that planetary orbits follow ellipses, but the elongation of the ellipse can take any value. In the Solar System, the planets follow nearly circular orbits, but elongated orbits are common among exoplanets. In fact, the vast majority of exoplanets follow orbits that are more elongated than those of the Solar System. The nearby hot Jupiter Nephthys[15], some 200 light-years away in Ursa Major, boasts a staggering 93 percent eccentricity. This means that the planet is seven percent of the size of its orbit from the star at the closest point, and 93 percent at the farthest. In other words, its distance from the star varies by a factor of 14, and so does the diameter of the star as seen from the planet! Since apparent size varies with the square of the distance, it implies that its sun appears nearly 200 times brighter at the closest point than at the furthest on that planet.

Mars has the highest orbital eccentricity among Solar System planets – nine percent; this is sufficient to cause a large difference between the climate of its Southern and Northern hemispheres. The South polar cap, which spends its "winters" near the furthest point from the Sun, is much more extended than the North. The Earth's orbital eccentricity is 1.7 percent, which does not appreciably modify the seasons – remembering that the seasons on Earth are not caused by the variation of the distance from the Sun, but by obliquity.

An Earth-like extrasolar planet on a very eccentric orbit has another type of season. These "eccentricity seasons" are not due to change in the height of the Sun in the sky, but to the planet moving toward and away from its sun. On Earth they are imperceptible; on Mars they contribute to triggering global dust storms in the southern hemisphere, when the obliquity and eccentricity seasons coincide.

If the Earth's orbit, for instance, had an eccentricity of 50 percent, it would spend part of the year closer to the Sun than Venus, and another part further away than Mars! Such a planet might spend only a fraction of its time within the "habitability zone", the zone around the Sun where liquid water is stable on a terrestrial planet. Close to the star, surface temperatures would reach water-boiling levels, with lakes and shallow seas evaporated, clouds cleared by the searing heat and the air thickened by a photochemical haze. Then, after crossing the habitable zone, autumn would feature torrential rains pouring all the evaporated water back onto the surface; finally ice fields would rapidly cover all the newly re-formed seas for the winter.

While these conditions seem uncomfortable, would they actually make life impossible? Not necessarily. Even our own planet presents striking climatic variations that are difficult to adapt to. For one thing, it switches from sunlight to total darkness and back every 24 hours. Then the temperature can vary by more than 60 degrees throughout the year in a given location, and some regions see no sunlight for months on end. Life has evolved strategies to deal with these changes, most often by shifting to "intermittent" modes that allow it to wait out the difficulties. Animals sleep at night

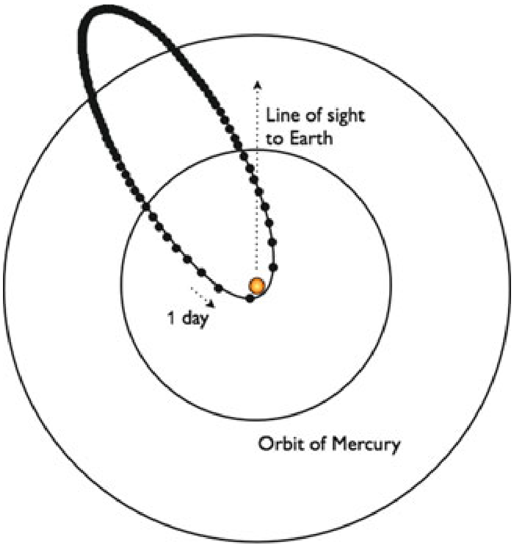
---

[15] Real name HD 80606b.

or hibernate during the cold season, desert plants hide underground during dry spells, bacteria can freeze and thaw again. Maybe adapting to the "eccentric lifestyle" is not that much harder than coping with seasons and diurnal cycles. Moreover, oceans take a long time to heat or cool, so marine creatures remain sheltered from the wild swings of the surface climate.

Another feature of orbital dynamics makes the climate on a very eccentric planet even more interesting. Let us consider, for instance, a terrestrial planet on an orbit like that of Nephthys, with a year of 365 days like Earth but an eccentricity of 93 percent. The pull of the star near the closest point of its orbit is so strong that it will force the planetary rotation into line with the orbital velocity, so that at this time, the planet will always present the same face to the star. During the rest of the year, the planet will keep this rotation speed, but since it proceeds more slowly on its orbit as it moves away from the star, it will rotate faster than it orbits.

Fig. 7.14 The orbit of Nephthys, compared to the scale of our Solar System. The dots are placed one day apart on the highly eccentric orbit. Image credit: Gregory Laughlin



The consequences for the planet are spectacular. The "winter" consists of slow days, lasting about ten Earth days each, with the sun very slowly inching through the sky, then setting for five days, before appearing again. Every night, lakes freeze over, and during the mid-afternoon the sun finally becomes strong enough to melt some pools on the ice sheets until they freeze again ten Earth days later during the following "night". During the course of the year, as spring progresses and the midsummer solstice draws nearer, the climate becomes slowly warmer.

As midsummer approaches, the sun starts slowing down in the sky, the days lengthen so much that summer consists of only one or two month-long days. Come the summer solstice, the view is stunning: the Sun grinds to a halt in the sky, some 14 times larger and 200 times brighter than in the depths of winter, and stays there for hours, before slowly starting to move westward again. All life forms on the day-side of an Earth-like planet with such an orbit would probably dig themselves deep into the ground or sink into the depths of the sea to avoid being roasted by ultraviolet radiation. Gigantic floods would stream down the slopes of the continents, bringing down all the glaciers and icecaps at once. In tropical regions, as the ground temperature hits 100 degrees the rivers and streams would start to boil.

Then a few days later the air cools, and another perfectly normal year on that planet begins again. The dazed inhabitants come out of their summer dug-outs to celebrate the end of the sun festival.

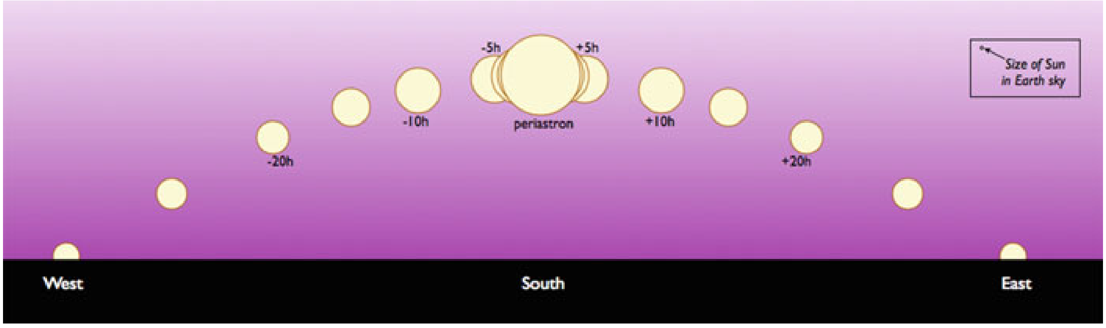


Fig. 7.15 Trajectory of the sun in the sky of an Earth-like planet with a very eccentric orbit, near the summer solstice.

Diamond planets

There is another way in which an Earth-like planet can differ from Earth. We have seen that the abundance of elements in the cosmos constrains the composition of planets. There are no ‘copper planets’ or ‘salt planets’. Planets are basically restricted to three mixtures: rock and metal, ices, and hydrogen/helium.

There is, though, one intriguing possibility, the carbon-rich planets sometimes dubbed “diamond planets”.

In interstellar gas there is more oxygen than carbon. Since oxygen is so reactive, it locks all the carbon into CO and CO_2. Then the oxygen left over is available to combine with metals to form rocks and ore.

But the composition of interstellar gas varies from place to place in our galaxy. Dying stars and supernovae produce different mixes of elements depending on how large they are, and since carbon is a close fourth behind oxygen in abundance, it is possible to imagine that some planet-forming discs could have more carbon than oxygen.

In an oxygen-rich planet like ours, metallic oxides dominate the interior. The vast majority are silicon oxides – silicates – what we commonly call rocks. But in a carbon-rich planet, all the oxygen would be locked up with the carbon, and there will still be carbon left over to bind with the metals and form carbon-only compounds. The planet crust would be rich in silicon carbide, graphite, coal and yes, deeper down at higher pressure, diamond. Silicon carbide is a dark, shiny rock, used in modern car brake discs for instance. It occurs very rarely on Earth, because there is generally enough oxygen around to oxidise it into silicates or carbonates. Diamond is the hardest mineral known to humankind and has surprising properties, not least of which is to separate people from vast amounts of money.

What would the atmosphere of a carbon-rich “diamond planet” be like? The major components would be carbon monoxide (CO) and methane (CH_4), the simplest carbon compounds with hydrogen and oxygen. The surface would consist of very dark rocks,

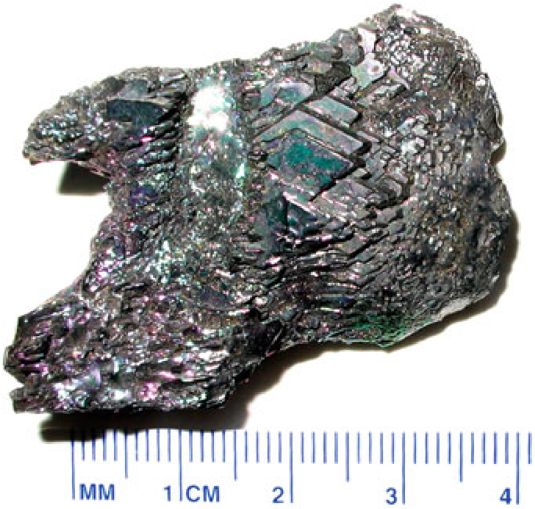


Fig. 7.16 Silicon carbide. Image credit: Steve Karg

Fig. 7.17 A good friend of diamonds. Image credit: Milton H. Greene

graphite, coal and silicon carbide, and a host of other compounds because carbon is chemically versatile, with occasional outcrops of diamonds emerging from the interior. Most striking would be the near complete absence of water.

Plate tectonics would probably be impossible on a diamond planet because of the toughness of carbon compounds, and the absence of the main plate lubricant, liquid water. The internal heat of the planet would have to be evacuated in hot spots, lava flows and large volcanoes, like on Mars. The melting point of silicon carbide is scarily high at 2,720 degrees Celsius, so the magma would be either much hotter than in Earth's volcanoes, or formed from some softer and rarer carbon components. Diamond and graphite are even harder to melt, with fusion temperatures above 3,500 degrees Celsius.

Some planetary scientists have been trying to explore the broad features of such worlds, but we are really out on a limb here. Planetary atmospheres are complex enough for model-makers and require constant supervision in the form of observations and empirical verification. Nevertheless, the image of a silicon carbide mountain range with diamond cliffs is hard to ignore.

Exo plate tectonics

In the Solar System, the intensity and importance of volcanic activity rises sharply with the size of the planet. This is a manifestation of the surface-to-volume, or "elephant and mouse" effect. The mass of a planet rises with the *cube* of its size, and so does the amount of heat it contains. The surface of a planet increases as the *square* of its size, as does the surface available for evacuating the heat. Smaller bodies therefore cool more rapidly, because they have more surface per element of volume. Elephants need huge ears to cool down, while mice have to move fast and eat a lot to keep warm. That is why the Moon can cool without any volcanism at all, losing heat to space by conduction of heat through its crust of rocks, like a radiator. Mars features a few large but very inactive volcanoes and lava flows. The surface of Venus, on the other hand, shows signs of intense volcanic activity, and on Earth chains of volcanoes line the boundaries of the moving plates.

Some terrestrial exoplanets are much larger than Earth. A natural expectation is that the amount of volcanic activity would keep growing with increasing mass. This would imply that “super-size Earths” generally have thicker atmospheres than Earth or even Venus. Another consequence is that, even in the absence of water, the crust could become warm enough and the convection of magma sufficiently intense to force surface plates to slide against each other. Since heat is evacuated by the lava at the plates’ boundary, the best way to evacuate more heat is to create more boundaries. In that case, we would expect the plates to be smaller and more numerous than on Earth.

On such a planet the cycle of gases between the atmosphere and the rocks would occur much faster than on the terrestrial planets in the Solar System. It takes geological eras for the content of the Earth’s atmosphere to cycle through oceans, continents and volcanoes, but with a faster cycle and a thicker atmosphere, there might not be enough time for the atmosphere to evolve on its own, so it would remain close to the composition of volcanic fumes.

At present, there is no measurement of the conditions in the atmosphere of heavy terrestrial planets, and the models have to be pushed so far out of their comfort zone to explore this question that they may be only marginally more reliable than informed guesses.

Now that we have wandered close to the realm of idle speculation, we might as well dip straight into it and talk about life on exoplanets, a topic on which the absence of empirical information is even more complete.

The search for life

Seen from the cosmos, terrestrial planets are tiny by-products of star formations, like crumbs left on the table. The reason we care so much about these planets is that we happen to live on one. Carbon planets, super-Earths, eccentric, tilted or synchronised planets; what we want to know is whether life could appear and thrive on them.

Life has had a profound effect on the atmosphere of our planet, so great, in fact, that the change could easily be spotted from space by alien astronomers. The presence of abundant oxygen in our atmosphere produces features in the spectrum of light emitted by our planet that could be picked up by a telescope dozens of light-years away. Indeed the composition of the atmospheres of Mars and Venus were measured in this way from Earth, one century ago. The ozone layer, formed by the action of sunlight on the abundant oxygen, absorbs ultra-violet light at specific frequencies, leaving its recognisable fingerprint on the spectrum. Alien observers could conclude that something unusual has happened to this particular planet, and, depending on their knowledge and prejudice on the topic, infer the presence of life from the suspicious abundance of substances as corrosive as oxygen and ozone.

To confirm this suspicion, alien astronomers may collect more measurements and spot the weaker signs of methane in the Earth’s atmosphere. Methane and oxygen react strongly with each other (which is why cooking gas burns so well), so their simultaneous presence in an atmosphere implies a constant source producing each of them. Life on Earth does this, with some bacteria exuding methane and photosynthetic plants producing vast amounts of oxygen.

For a few decades now, finding both oxygen and methane simultaneously in the atmosphere of a planet has been “plan A” for scientists in the search for primitive life on Earth-like exoplanets. (In contrast, intelligent life in the Universe is being searched for by the SETI programme, listening in to galactic radio communication.)

Other stars are so distant that measuring the spectrum of a terrestrial exoplanet with sufficient accuracy would be an enormous technical challenge. In the 1980s, space agencies dreamt up a concept involving a flotilla of space telescopes linked to each other to function like a single giant telescope. This is what would be needed to collect sufficiently strong signals to be able to separate the planet from its host star at a distance of several light-years. In 1999, NASA administrator Dan Golding gave a moving speech showing a mock poster of an exo-Earth, with continent and ocean shapes outlined as if imaged painstakingly from an astronomical distance. “Can you imagine….? ” he would say, “in around 30 years, such pictures could be hanging in classrooms.” A powerful dream.

But twenty years on, “around 30 years” is still what it might take to achieve such a project, and the technical and financial hurdles have come more sharply into focus. The space interferometer Terrestrial Planet Finder project has remained on the to-do list for a generation; like those Post-Its that have been stuck on the fridge door for so long that nobody dares to take them away, but when they finally drop off, nobody puts them back.

Or maybe the next generation will. The project has not been shelved entirely, and it is still “plan A”. An important step was taken in 2011, with the Kepler space mission measuring the abundance of terrestrial planets around normal stars. This abundance is high enough for some of them to be within reach of “plan A”, with an Earth twin around every dozen stars or so. The second step is to find a few such twins around nearby stars, and projects are under consideration to launch a space mission to do this by 2020. Then, for the flotilla of probes, we may have to wait “around 30 years”.

It is not only an issue of money and politics. There are also some interesting scientific arguments against focussing too narrowly on oxygen and ozone. Research on the history of the Earth has shown that our own planet has harboured oxygen-producing photosynthetic life for at least 3.4 billion of its 4.6-billion-year life. But for most of that period, no large amount of oxygen has accumulated in the atmosphere. Only in the past 500 million years or so has the oxygen concentration passed the one-percent mark before shooting up to the present 20 percent. And only at these high concentrations has an ozone layer appeared. Bacteria and algae produced oxygen for three billion years in a world that was able to absorb it immediately, without any accumulation in the atmosphere that could be detected from space. Given this, “plan A” seems risky. Even if there are several Earth-like planets in our neighbourhood inhabited by carbon-based life, 90 percent of these planets may still not display the giveaway signs of methane, oxygen and ozone.

“Plan A” has not gone away, in spite of the difficulties, partly because there is no obvious alternative. Our galaxy could be teeming with life forms that do not affect the atmosphere of their planet in a detectable way. But our kind of methane and oxygen-producing life is the only one we can think of detecting with realistic technology.

Living planets

Could that simply be due to a failure on the part of our imagination? Some scientists think so.

Let us return to what is special about the coexistence of methane and oxygen. The key point here is that such coexistence is a sign of *out of equilibrium* chemistry. Maybe, instead of looking for this specific sign of disequilibrium, we could look for disequilibrium in general.

The concept of equilibrium is central to chemistry. In a laboratory, molecules react with each other until they reach an equilibrium, specified by the laws of physics and chemistry. Create an out-of-equilibrium state by mixing two compounds, and they will react with each other to reach an equilibrium.

Outside interference can keep a chemical mix out of equilibrium, for instance the sunlight illuminating an atmosphere, or volcanic fumes being added to it. But these kinds of disequilibrium are nothing compared to what life is able to achieve. Methane in the Earth's atmosphere is about 10^{30} times more abundant than it would be at equilibrium; that is a lot of zeroes.

Maybe we should go back to the reason why oxygen is produced in the first place. Stealing energy from sunlight requires a sophisticated piece of biochemical engineering called photosynthesis. This involves swapping electrons between one molecule and another, using one photon of sunlight. The process requires an "electron donor", and the most common element, hydrogen, also happens to be one of the easiest to part with its electron. So photosynthesis uses hydrogen as an electron donor.

But hydrogen doesn't float around freely in the sea or in the atmosphere, so that photosynthesis has had to find a way of extracting it from another molecule – water. The water molecule, H_2O, is cleaved so that the two hydrogen atoms can be used as electron donors. The remaining free oxygen is released as a highly reactive free radical.

However, water is a notoriously stable molecule, so breaking it requires a lot of energy. Other hydrogen compounds are much easier to break, for instance hydrogen sulphide, H_2S. Some scientists think that photosynthesis may actually have started using these easier sources of hydrogen – H_2S is common in volcanic products for instance – then moved on to more difficult molecules over time. It could have taken hundreds of millions of years to evolve the trick of breaking the most abundant molecule in the ocean, and dealing with its toxic by-product.

One smart hypothesis is that using H_2S may not have evolved directly as a trick to capture the energy of sunlight, but as a way for bacteria living near underwater volcanoes to locate themselves relative to the source of heat. Living near an oceanic "hydrothermal vent" is tricky, because the temperature changes quickly from over one hundred degrees near the vent to four degrees Celsius in areas unaffected by its heat. An organism that could determine its position relative to the vent by detecting H_2S would be at a great advantage for survival. Since we now think that life may have started near these volcanoes in the abyss, far away from sunlight, this hypothesis provides a neat way of explaining the origin of photosynthesis by gradual steps, rather than one big jump.

The implication is that photosynthesis on other planets need not produce oxygen. It may be based on other processes such as sulphur chemistry.

Therefore what we could be looking for is not necessarily a methane-oxygen pair, but any sign of a global chemical imbalance in the atmosphere of a planet.

As of 2014, the next planned landmarks in the search for habitable planets and life include the James Webb Space Telescope, the successor to the Hubble Space Telescope, scheduled for the end of the decade, which could measure the atmosphere of a few Earth-like planets, as well as a smaller space telescope focussed specifically on measuring the signature of molecules in planetary atmospheres in the infrared. The largest telescopes on the ground have already begun the search for planets that can be seen directly – rather than only through the transit method. But reaching planets as small as Earth with this method may require the next generation of telescopes, behemoths with mirrors 30 to 40 metres (100–130 feet) across, instead of the current six–ten metres, that are planned for the 2020s.

Apart from detecting substances in the atmosphere, there are other things that can be learnt about an Earth-like planet, even by an observer too remote to make out any surface features. By monitoring the brightness and colour of an exo-Earth over several days, it is possible to reconstruct a broad-brush map of its surface, and measure how it varies because of changing clouds. Some researchers have used the *Epoxi* space probe, en route to a comet, to measure our own planet for a few days. Putting themselves in the position of alien astronomers, they have inferred the broad position of the oceans and continents from the evolution of the brightness and colour of the planet as its different parts rotated in and out of view during its day.

In terms of surface features and cloud coverage, Earth is strikingly different from other planets in the Solar System. Its surface is divided between oceans (which look dark blue from space) and continents (bright and brown), and about half its surface is covered by white clouds at any given time, in ever-changing patterns. By contrast, the global aspect of Venus is very uniform. Mars has dark and bright patches, occasionally covered by dust storms, but the daily changes in brightness and colours are much less sharp than on Earth.

A similar map of an exo-Earth would not tell us whether it harbours life or not, but it would go a long way to telling us what kind of world it is. Some specialists think that the existence of active plate tectonics on Earth – which is reflected in the separation between oceans and continents – is essential to the development of life. And the presence of clouds thick enough to indicate a healthy water cycle but not so thick as to shroud the whole planet constantly, would also be an encouraging indication.

We might be better off choosing a gradual, flexible approach to the detection of life on other planets, with each step depending on what we have learnt from the previous one, rather than the all-or-nothing gamble of "plan A". The Kepler mission has taught us that Earth-like planets are common. Now we can find some of them around nearby stars, and study them in an open-minded way, trying to characterise the diversity of

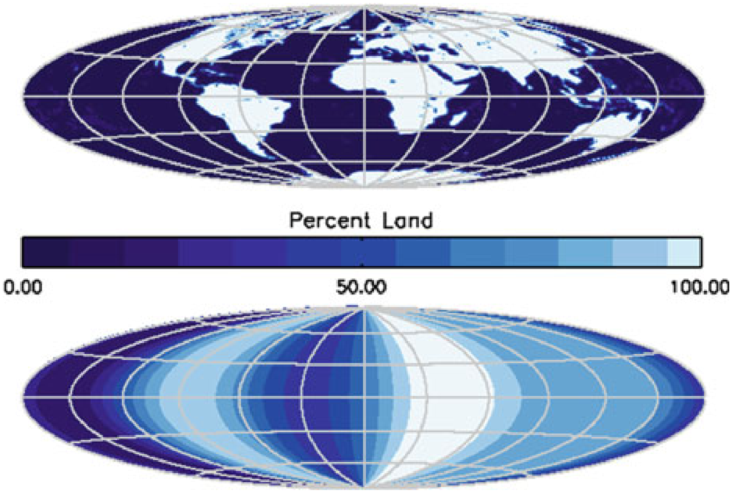


Fig. 7.18 The broad distribution of land and water on Earth reconstructed from distant observations by the Epoxi space probe. Image credit: Cowan et al.

their atmospheres. Then, if and when we have more definite suspicions about one or some of them, we could plan more targeted observations. Of course, each step in this quest is long, complex and expensive, but it is a quest that is as old as civilisation, so we might have to be patient.