Nevertheless, when the flotilla of cold-war probes approached the shy planet, visions of alien rainforests were still very vivid.

A total of ten Soviet probes have landed on Venus, and thirteen orbiters have sent back data on its atmosphere. Because of the no-nonsense, hard-line approach to science of the former Soviet Union, the Venera probes brought back few pictures, but they did measure the temperature, winds and air composition on the planet.

Fig. 2.2 One of the splendidly Sovietic Venera probes. Image credit: NASA

The atmosphere of Venus is very thick, ninety times heavier than that of the Earth. This is enough pressure to crush a modern nuclear submarine. The whole planet is shrouded with thick cloud that culminates about 70 kilometres (40 miles) above the surface, and extends down to 48 kilometres (30 miles). There is practically no water in the clouds – the whole atmosphere is extremely dry, with less than 0.002 percent of water overall. The air is almost entirely made of carbon dioxide. The clouds are made of droplets of sulphuric acid. If the temperature is pleasant at the top of the clouds, it rises steadily underneath, until it reaches about 500 degrees Celsius at the surface.

If Earth is heaven (arguable but debatable), Venus is very close to hell.

Fig. 2.3 Returning Chinese astronauts. Each nation brings some of its heritage to the aesthetics of space exploration. What will Chinese probes look like? Image credit: Xinhua

Size	12,104 km (7,521 miles)	12,756 km (7,926 miles)
Gravity	0.92	1
Pressure at surface	92	1
Temperature at surface	480 C	20 C
Total water	10 cm	3 km

Fig. 2.4 (i-iv) Earth and Venus with their clouds off – and on. Image credit: NASA

Turning Earth into Venus

Scientists think that the atmospheres of Earth and Venus were rather similar after the birth of the Solar System, and that their divergent fate over the following 4.6 billion years was due to their different distances from the Sun. To try to understand how they became so different, let us imagine what would happen if our planet was moved closer to the Sun, to orbit one hundred million kilometres from the Sun instead of one hundred and fifty million.

Fig. 2.5 Size of the Sun from Earth and from Venus.

In the far North, the increased sunshine renders the climate of places like Alaska and Siberia much more pleasant. The mean ground temperature climbs up to 30 degrees Celsius off the northern shore of Siberia. More water evaporates from the sea and lakes into the warmer air, and big tropical thunderstorms refresh the taiga.

Near the tropics, meanwhile, the change is not so benign. The main driver for weather on Earth is the evaporation of water and lifting of the air by heat in the equatorial region. The added sunlight boosts this cycle, making the weather more extreme. The number and strength of tropical hurricanes increases steeply for each additional fraction of a degree added to the global temperature. With twice the amount of sunshine, the change is incomparably greater, with catastrophic hurricanes becoming as frequent as summer storms are today.

Rapidly, the level where clouds and storms stop moves higher than its present 10–15 kilometres because more heat is welling up from the ground.

As the temperature near the Equator reaches 60 degrees Celsius, one unfortunate consequence is that forests and animals start dying out. Plants and animals cannot survive prolonged periods of such heat.

The speed at which the climate heats up depends primarily on the proximity to the oceans. In continental deserts such as the Sahara, the change takes only a few hours. But it takes more than a century to heat the oceans entirely, so in coastal regions and islands the change is much more gradual, giving enough time for mobile creatures to fly, run or hop towards the polar regions.

In the polar regions, conditions become pleasant enough for most species, including humans. Deep in the oceans, the changes are not felt for years; luminescent fish and blind crabs quietly go about their business, marvelling at the increased amount of nutrients drifting down from above.

It takes only a few years for all remaining glaciers and polar ice caps to melt away, increasing the levels of the sea by 80 metres (260 feet), engulfing the deserted remains of most of the world's major cities.

About a century later, when the oceans have finally become warm throughout, the air temperature reaches 100 degrees Celsius near the Equator. Then equatorial oceans start boiling away, filling the air with huge clouds, and drowning higher latitudes with diluvian rains.

At that point Earth would be about 100 degrees Celsius warmer on average because of the increased sunshine – still a long way from the ground temperature on Venus. Imagine a world where tropical regions are sizzling deserts with boiling oceans, with a few more temperate patches remaining near the poles or at the top of the highest mountains, and life still teeming at the bottom of the warm polar oceans.

Greenhouse to madhouse

Just as the world tries to adapt to these new, warmer conditions, it gets much worse. The greenhouse effect of water vapour sends the atmosphere into ever-increasing temperatures. Water vapour is a greenhouse gas like carbon dioxide, and as the greenhouse effect of the added vapour kicks in, the temperature rises. In the greenhouse effect (the lower glass pane of Chapter 1), as more carbon dioxide is pumped into the air, more sunlight gets trapped near the surface. The problem with water vapour is that as the temperature rises, more water evaporates from the oceans. This is a positive feedback loop, a vicious circle in plain English: more water evaporates, the greenhouse effect becomes stronger, the temperature rises, more water evaporates.

On Earth, the effect of water vapour also amplifies the greenhouse effect of carbon dioxide, but the feedback loop stays under control. However, in the case of our overheating Earth, the feedback loop goes wild. The heat increases the evaporation of the oceans, exacerbating the greenhouse effect, and there is no limit until all the water in the ocean is vaporised.

At some point there is more water than nitrogen and oxygen in the atmosphere. The atmosphere as a whole becomes thicker. When the first 100 metres of the oceans have boiled away, the atmosphere is 90 percent water, and the pressure at the surface is 10 bars. At this point, the surface of the ocean is simmering at around 150 degrees Celsius – hotter than 100 degrees because the boiling point of water rises with the higher pressure.

Earth has now become a giant steam chamber. The whole planet is shrouded in thick clouds. Above the clouds, the temperature is relatively cool – below 20 degrees. Raindrops sometimes form, but evaporate before reaching the ground. Only in some remote corners of the Arctic and on high mountains does warm rain occasionally reach the ground. Steaming, temporary rivulets snake down the slopes, but evaporate before reaching the boiling sea. The last human survivors gather underground near these streams, in volcanic caves under Mount Erebus in Antarctica.

Since the weight of water in the ocean is 300 times larger than the total weight of the air in the atmosphere, when the last puddle of the former global oceans vanishes, the atmosphere is 300 times heavier than now, and made up of 99.7 percent water vapour. At that point, a few decades after bringing it nearer to the Sun, the planet looks like Venus in many respects, entirely shrouded in thick clouds, with an enormous surface pressure and very high temperature.

Something very strange happens by the time the oceans are entirely vaporised – something that brings out an aspect of the nature of water that our intuition has not prepared us for (as we'll see in Chapter 6, there are more surprises in store from that apparently familiar substance). The pressure and temperature now exceed the so-called "triple point" of water, at 221 bars and 374 degrees Celsius, the point at which liquid water and vapour become indistinguishable. This is known as "super-critical water" and is difficult for us to imagine. The only place where water takes such a form naturally on Earth is at the mouth of undersea volcanoes.

Under normal pressure, when water vapour cools from, say, 500 to 50 degrees Celsius, it abruptly condenses from a gas to a liquid when it crosses the 100 degree mark.

However, under very high pressure, anywhere above the critical point at 221 bars, at 500 degrees Celsius water is a gas-like vapour, and at 50 degrees it is a liquid-like fluid, but there is no specific temperature at which an abrupt transition occurs. There is no longer any surface between atmosphere and ocean, the change is gradual, like honey or butter coalescing as it cools.

Water escape

There is still one key difference between this steam-chamber Earth and Venus: the atmosphere is made almost entirely of water rather than carbon dioxide. We now need to run the clock forwards for millions of years rather than decades to understand what happened to the water on Venus.

Water is one of the most abundant substances on the surface of planets, and Earth, Venus and Mars probably all possessed generous amounts of surface water in the early days of the Solar System. However, water has a fundamental weakness – as H_2O, it contains two atoms of hydrogen, the lightest element in the Universe. The gravity of Earth is not strong enough to keep hold of free hydrogen. As long as the hydrogen atoms are tied up in a water molecule, they are fine, but if they ever become separated, they drift off into space.

That is why there is no free hydrogen in the atmosphere of Venus, Earth or Mars, despite the fact that hydrogen is by far the most abundant element in the universe and makes up most of the Sun, Jupiter and Saturn. Giant planets and stars are heavy enough to keep hold of all atoms, including hydrogen, but not Earth-mass planets. Their gravity can only retain heavier molecules, like water (nine times the weight of hydrogen), nitrogen (14 times) and carbon dioxide (22 times). At the other end of the scale, small celestial bodies like the Moon cannot even retain these relatively heavy gases, and soon become airless.

Every now and then, a water molecule in the air is broken apart by sunlight (ultraviolet light can do that), and the two hydrogen atoms can escape into space. Slowly but surely, the hydrogen in the water leaks away and, over millions of years, all of the hydrogen in the water of a planet becomes lost to space. The oxygen remains behind. Since oxygen is a very reactive element, it usually combines with carbon to form CO_2 or with rocks to form oxides.

Earth has not lost its oceans because the temperature in the upper atmosphere is low enough that water condenses before it reaches the altitudes at which it could be dissociated by sunlight and escape forever. With the atmosphere heated by more intense sunlight and an enormous greenhouse effect, the water vapour in our hotter Earth leaks out into space inexorably.

Volcanic gases

On Earth, dozens of volcanoes erupt every year, and they range from discreet smoke plumes to colossal disasters that can change the climate of the whole planet. The Tambora in Indonesia caused the "year without a summer" in Europe in 1816, and Santorini wiped out the Minoan civilization of Crete during the Bronze Age. Volcanoes spit out a vast array of gases, but the dominant ones are carbon dioxide and sulphur. In our planet, these gases do not accumulate in the atmosphere because they are recycled into the oceans or the ground; carbon dioxide is fixed into carbonate rocks, while sulphur dissolves in rain drops, producing "acid rain" that ends up in the oceans, ultimately finding its way back into the ground through ocean sediments.

However, both these processes require water. With the water gone on our hot Earth, carbon dioxide and sulphur simply accumulate in the air. Over millions of years, as the plumes of every volcano that has ever erupted merge into a single, planet-circling cloud, the whole atmosphere is choked in carbon dioxide and sulphur. There is about 40 atmospheres worth of carbon in the ground on Earth, most of which has cycled through the atmosphere at some point. If this carbon accumulates in the atmosphere, the pressure at the surface of the planet will exceed 40 bars – the pressure at the bottom of an imaginary pit some 20 miles below ground.

The temperature at the surface rises to several hundred degrees, under the combined effect of increased pressure and the powerful greenhouse potential of CO_2. The air is mostly carbon dioxide, with thick, yellowish clouds of sulphuric acid hovering in the haze. Sulphuric acid rain constantly falls, but evaporates before reaching the ground. The landscape of red-hot rocks shimmers like a mirage in the heat. We have reached our destination, the planet Venus.

The real Venus

A ground of hot volcanic rock; air a poisonous mixture of volcanic gases at high pressure, so thick that it feels as much like a liquid as a gas, gloomy red light filtering through thick clouds. The closest Earth analogue to these nightmarish conditions at the surface of Venus may be sitting on top of a deep-ocean volcano.

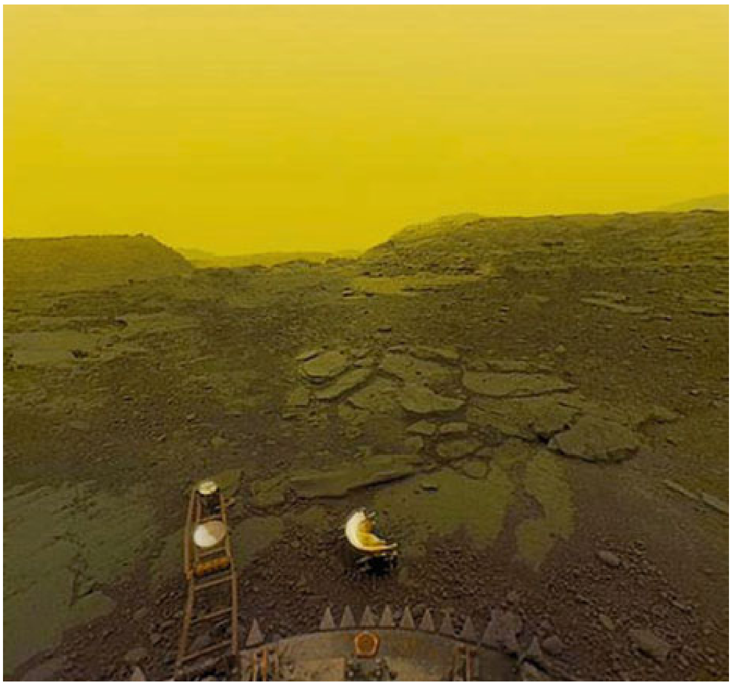


Fig. 2.6 View of the surface of Venus from one of the Venera probes. The geometry of the image has been reconstructed and the colours adapted to make them as close as possible to what a human eye would see. Image credit: Don Mitchell

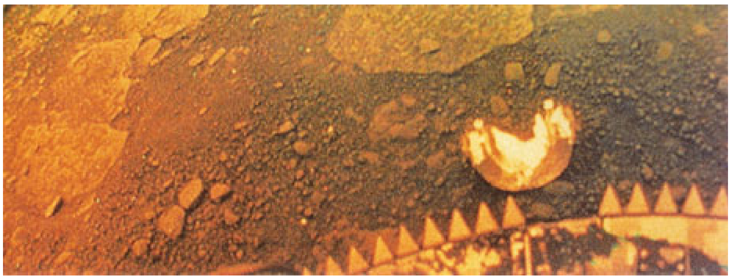


Fig. 2.7 One of the original images from Venera-13. Image credit: NASA

Fifty kilometres above the inferno float the gloomy sulphuric-acid clouds, making the air as acidic as pure lemon juice. About seventy kilometres (40 miles) above the surface, the sulphur clouds start to break and the Sun becomes visible at last, albeit through a yellow haze that extends a further twenty kilometres upwards.

Venus is a highly volcanic world, its surface is littered with recently solidified lava flows and volcanic domes. Volcanoes exist because planets the size of Venus and Earth have a lot of internal heat to evacuate. Planets are born from millions of collisions that leave their cores at thousands of degrees, and when their exterior is made of solid rocks, the only way to evacuate enough heat is through episodic eruptions of lava and gas.

The volcanic nature of Earth is partly concealed by the effects of the oceans and the water cycle. Most volcanic activity occurs underwater, at the mid-ocean ridges where crustal plates are constantly re-generated, and at the boundaries between tectonic plates.

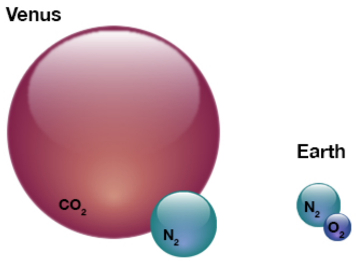


Fig. 2.8 The composition of the atmosphere of Venus (compared to Earth on a scale proportional to the total quantities) mostly carbon dioxide, with a few percent of nitrogen (still amounting to three times the total amount in our atmosphere) and a drizzle of sulphuric acid.

Oceanic lava flows are quickly covered by sediment, and on land volcanic features are erased by erosion and covered by vegetation. Although traces of volcanism are hard to find on Earth, over geological timescales volcanism is one of the main actors in the drama of the Earth's surface and atmosphere. A large fraction of the present land masses consist of volcanic outpourings of magma, such as the Siberian Traps in Russia, the Deccan Traps in India, or the Columbian River Basin in the United States.

Volcanoes on Venus are different in aspect from Earth's volcanoes. Because of the higher surface temperature and absence of water, Venusian eruptions rarely exhibit the cone shape common on Earth, they form mushrooming blobs or meandering lava flows.

The clouds of Venus

Comparing conditions at the surface of two planets can be misleading. When describing a position within an atmosphere, a more natural coordinate than altitude is pressure, which really tells what the place feels like. The drawing overleaf shows the atmospheres of Earth and Venus compared on the same pressure scale. From that viewpoint, the surface of Venus corresponds to the sea floor on Earth, and our sea level equates to about 50 kilometres (30 miles) above ground on Venus, where both the pressure and temperature are similar to those we are used to.

Abandoning our parochial attachment to solid ground, we could arguably call the cloud-tops the "surface" of Venus, in the same way that we consider the top of the ocean to belong to the surface of the Earth, rather than the dark sea floor miles underneath. The thick clouds shroud the entire planet continuously, and that is what we see from Earth. In the Earth-like conditions of pressure and temperature at this level, many chemical reactions can take place in the droplets of sulphuric acid. Some Venus specialists even suggest that we should be checking these clouds for signs of life, since the sulphur chemistry may be complex enough to give rise to biological processes.

Superficially, the clouds on Venus are reminiscent of clouds on Earth but in reality they are extremely different. There is the lemon-juice acidity, but also the fact that whereas clouds on Earth form and dissolve in matters of hours or days, those of Venus ebb and swell but never break. They are also much thinner than Earth's clouds, more like a morning fog or, indeed, industrial smog over a city. The visibility within Venusian clouds is several kilometres, as opposed to a few metres in our water clouds. The Venusian cloud cover is opaque not because the clouds are dense, but because they extend over such a deep layer. Venusian clouds are more transparent than ours because the grains and droplets in them are much smaller, a few micrometres across, whereas

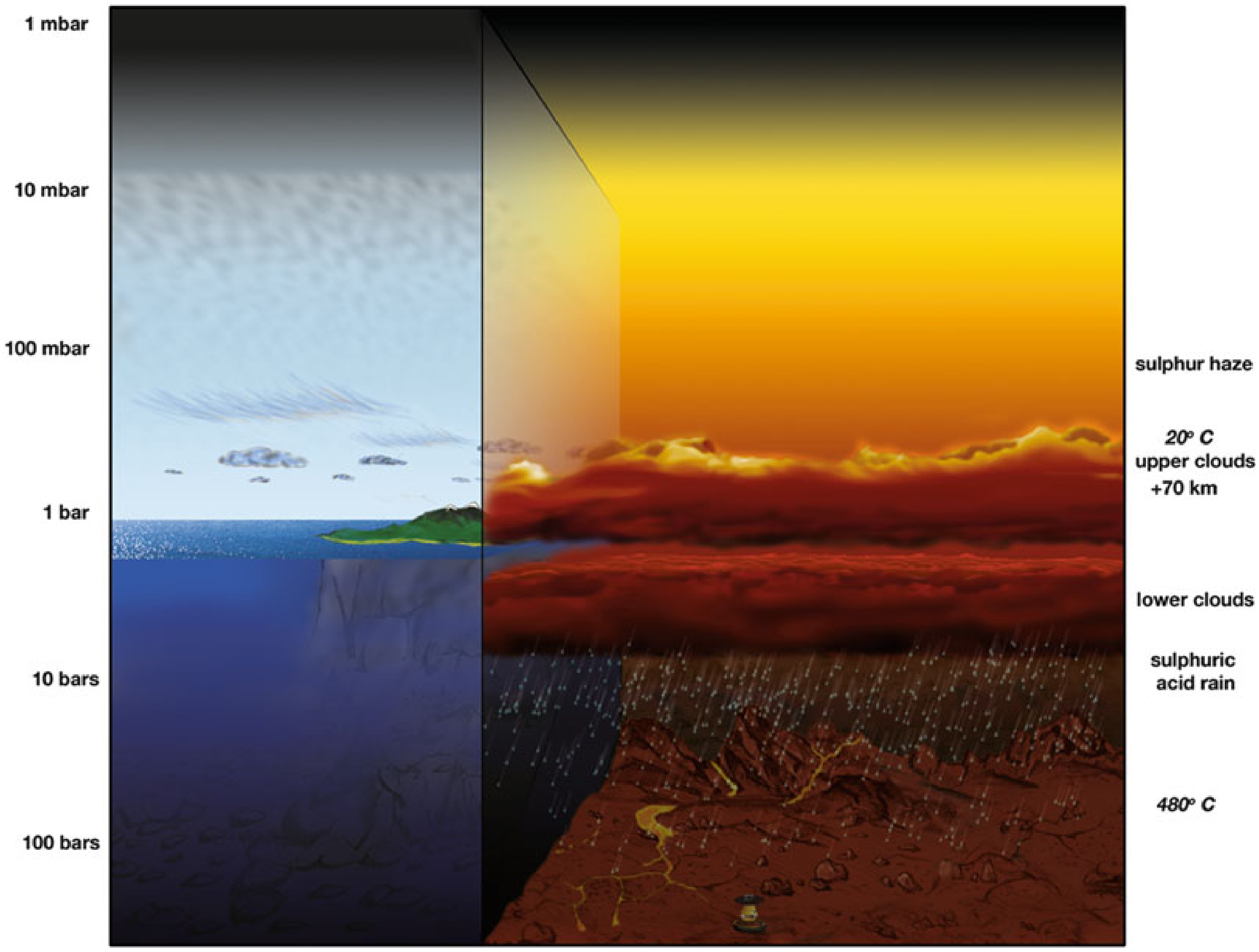
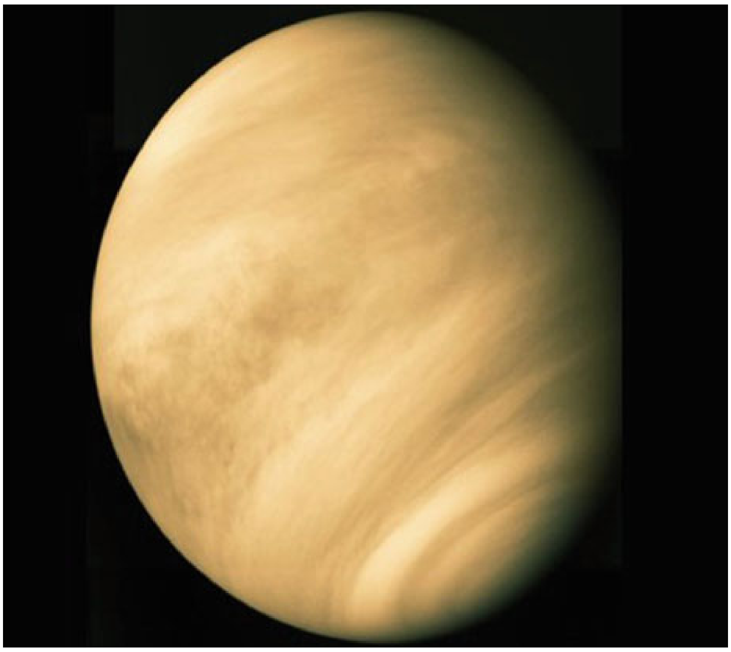


Fig. 2.9 Profile of the atmosphere of Venus and Earth, on the same pressure scale.

Fig. 2.10 Venus in real colours.
Image credit: NASA



typical ice crystals in our clouds measure hundreds of microns, and snowflakes or hail stones can be much bigger. Venus's clouds are also more fluffy, so it is difficult to tell where they begin or end. More than anything, they are far larger than any clouds we know.

The clouds of Venus extend over nearly 30 kilometres (20 miles) in height, in three different layers separated by intervals of clear air. The upper layer is a gradually thickening haze, exposed to full sunlight during the day. In the middle is the main cloud deck of solid and liquid grains, drifting down and raining until they vaporise. The lower deck is formed by upwelling currents which cool sulphuric acid to temperatures low enough for it to condense, in the same way as cumulus clouds form on Earth.

The role of sulphur

Sulphur dominates the chemistry of the atmosphere of Venus. Chemically, sulphur is a very versatile atom that shares some properties both with oxygen and carbon. Like oxygen, it has a propensity to bond strongly with most other elements. Like carbon, it can also bond to itself in chains (although to a lesser degree than carbon). In an oxygen-poor environment, sulphur combines with hydrogen to form hydrogen sulphide (H_2S), the nasty, explosive gas that gives a rotten-egg smell to hot-spring water. If carbon and oxygen are present, sulphur can replace the carbon atom in CO_2 to form SO_2, sulphur dioxide, then H_2SO_4, sulphuric acid.

Sulphur has a very bad reputation on our planet. It is "brimstone" in the Apocalypse of Saint John, and has been called the element of the Devil, one reason being the association of sulphur with volcanoes. Apart from the rotten egg smell, sulphur compounds are also behind the strong flavour of garlic and onion. Elemental sulphur is a yellow powder, rarely found in that form except when it falls from the sky with ashes and cinders after a volcanic eruption.

The clouds of Venus are part of the sulphur cycle, analogous to the formation of acid rain from pollution on Earth. The sulphur dioxide in the lower atmosphere is dragged up by convection, and when it surfaces above the clouds it can react in the sunlight to form sulphuric acid. As the temperature in the upper atmosphere is low enough for sulphuric

Fig. 2.11 Sulphur haze.

acid to condense it will form tiny droplets, making the atmosphere hazy just like smog over a city. Over time the largest drops will start falling, growing in size to form the clouds below. At some point however, the temperature will reach the boiling point of sulphur dioxide (337 degrees Celsius), and the rain will evaporate, never reaching the ground.

Finally, in the high temperatures below the clouds, the sulphuric acid is broken back into its constituent elements, including smelly sulphur dioxide, ready to be carried upwards by the convection of the atmosphere for another cycle.

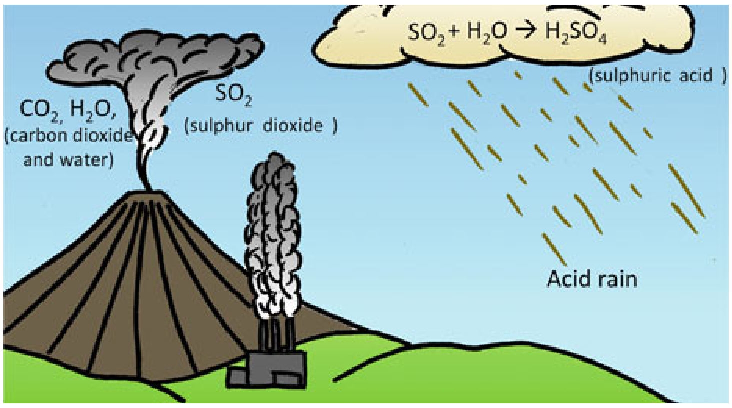


Fig. 2.12 Acid rain on Earth. Sulphur produced by industries – or by volcanoes – is converted to sulphuric acid by contact with water. The acid is carried with the rain, and returned to the ground.
Image credit: Joanna Barstow

There is more to the sulphur cycle than the "acid rain loop". Chemical reactions triggered by sunlight in the upper clouds can also produce chains of sulphur atoms that may change the colours of the clouds and give them a yellow tinge. Sulphur also reacts with the rocks on the ground. Like water on Earth, sulphur cycles between solid, liquid and gas, but in addition, it undergoes chemical changes along the cycle; in that sense the Venusian sulphur cycle is more like the carbon cycle on Earth. In fact, sulphur does both cycles at once. The "fast" cycle between the lower atmosphere, the upper haze and the clouds, is analogous to the production of acid rain on Earth, and takes place in hours or days. The "slow" cycle between the atmosphere, the rocks and the volcanoes, resembles the rock-carbon cycle, and takes years.

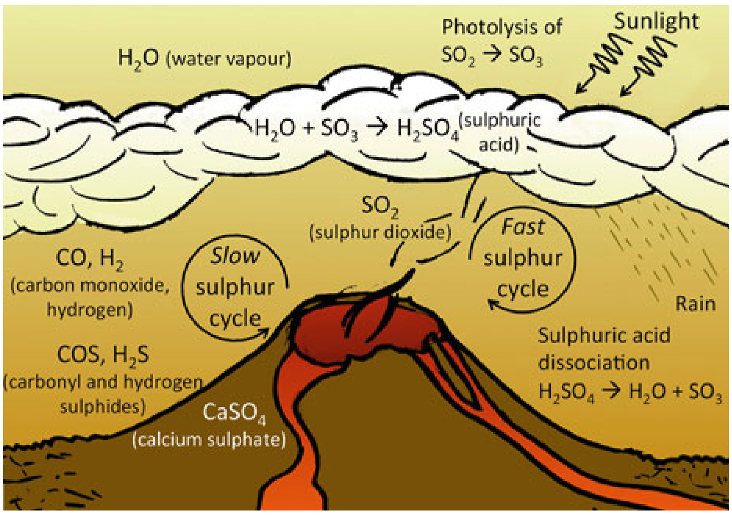


Fig. 2.13 The sulphur cycle(s) on Venus. Image credit: Joanna Barstow

Super-rotation

The clouds of Venus spin around the whole planet every few days. Before they were able to observe the surface, astronomers assumed that this was the speed at which the planet turned on itself. This did not seem unreasonable compared to the 24-hour rotation period of Earth or the 25 hours on Mars.

But in fact, the planet Venus takes 243 days to spin on itself, or eight Earth months! Thus the surface hardly moves at all below the furiously blowing winds that carry the clouds around. The clouds always move from west to east, so it looks as if the planet is spinning on itself much faster than it actually is. The atmosphere is said to be in *super-rotation*. The speed of the winds that push the clouds around reach 300 kilometres per hour (200 miles per hour) in the upper cloud deck. They decrease to 200 kilometres per hour at the bottom of the clouds, and fall to a few kilometres per hour near the ground. However, since the atmosphere near the ground is so much denser, this "breeze" is still able to push dust and even pebbles around like a strong gale can on Earth. This is difficult for us to imagine – a gas so thick that the wind is almost like a current in water.

Why does the whole cloud system rotate around the planet from west to east, as if the planet was spinning on itself? The culprit is the Coriolis effect.

The dominant movement in the atmosphere of Venus is, like on Earth, the circulation between the equatorial regions and the middle latitudes. But since the planet is rotating much more slowly than Earth, the Equator-to-pole rolls get much closer to the poles before being deflected by the Coriolis effect. This time instead of imagining walking on a spinning platform like in Chapter 1, we can think of the "ice skater" illustration of the effect. Consider a ring of clouds that slowly moves round Venus near the equatorial regions, and is brought polewards by the heat circulation. As the whole ring moves polewards it becomes more compact, like a skater bringing their arms closer to the body, which will cause it to spin faster.

In this way the polewards motion of air creates a global eastward rotation, and integrated over the whole planet it gradually makes the whole atmosphere spin in the

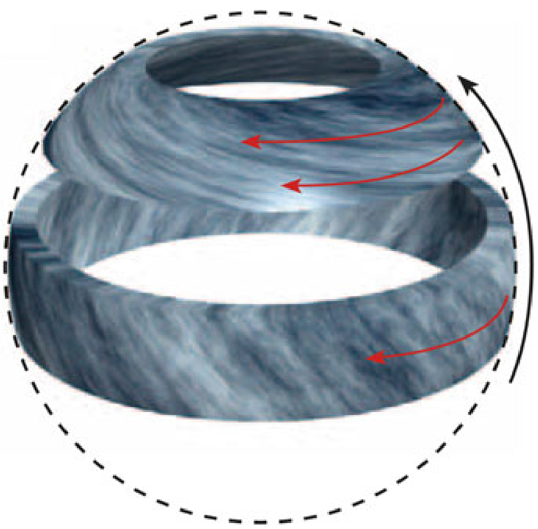
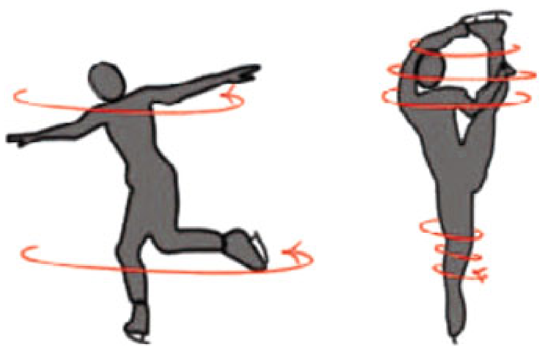


Fig. 2.14 (a/b) Ice skaters spin up by gathering their limbs closer to their axis of rotation. A circular atmospheric current moving towards the pole of a planet spins up for the same reason.



direction of the rotation. Even the slow rotation of Venus (243 days versus one day for Earth) is sufficient to get the eastward flow going, and, once it is set, it keeps being accelerated until the clouds rotate much faster than the planet. Indeed, although we have not yet observed other Earth-like exoplanet atmospheres, the same phenomenon can be seen for hot Jupiters; their atmospheres circle in a few days at most, regardless of the spin of the planet itself. At the kind of temperatures found at the top of the clouds of Venus or on Earth, it takes a few days for 'air' to lose its heat by radiation into space. So, in order for the atmosphere to carry the heat around the planet, it needs to travel from the day side to the night side in less than a few days, otherwise it will have lost its heat. On Earth, the air can hitch a ride on the 24-hour rotation of the planet, so winds are not needed to transport heat from the day side to the night side[6]. But if the planet spins more slowly, the atmosphere as a whole will rotate in a few days to be able to transport the heat from west to east. To an outside observer who cannot see through the clouds, the planet will appear to be rotating in a few days.

This has an implication for the study of Earth-like planets around other stars: from the outside they can appear to be rotating with periods of less than a few days, even if the bulk of the planet is rotating more slowly, or not at all.

Being there

What would it feel like to stand on Venus? At first, it would be like standing inside a deep-sea submersible such as the Russian-designed MIR that filmed the remains of the Titanic. You need this kind of vehicle to resist the 90-bar pressure. Instead of a wrecked ship, one would be peering at a desert landscape in a reddish glow; until the heat kicked in. Then it would feel like being stuck in an oven, with uncomfortable consequences.

The surface of Venus has limited touristic potential. The conditions are much more amenable at the cloud-top level, where, equipped with a proper hot air balloon, it would be possible to enjoy normal atmospheric pressure and pleasant temperatures around 20 degrees Celsius. The problem there would be the vitriolic fog, with the acidity of the clouds high enough to dissolve skin. Nothing, however, that a rubber suit couldn't stand.

Overall, a perfectly decent way to spend an afternoon.

[6] The winds nevertheless take charge of the Equator-to-pole heat transport.

Fig. 2.15 Ballooning in the upper cloud deck of Venus.