Chapter 5

Giant planets

Four giant planets dominate the Solar System family. Their colossal scale is difficult to grasp. More than one thousand Earths would fit inside Jupiter. The giant planets represent 99.5 percent of the mass of planets in the Solar System, with Jupiter totalling 318 times the mass of the Earth, Saturn 95, Uranus 14 and Neptune 17. Their truly majestic nature is one of the most distinguished discoveries of space exploration in the second part of the twentieth century.

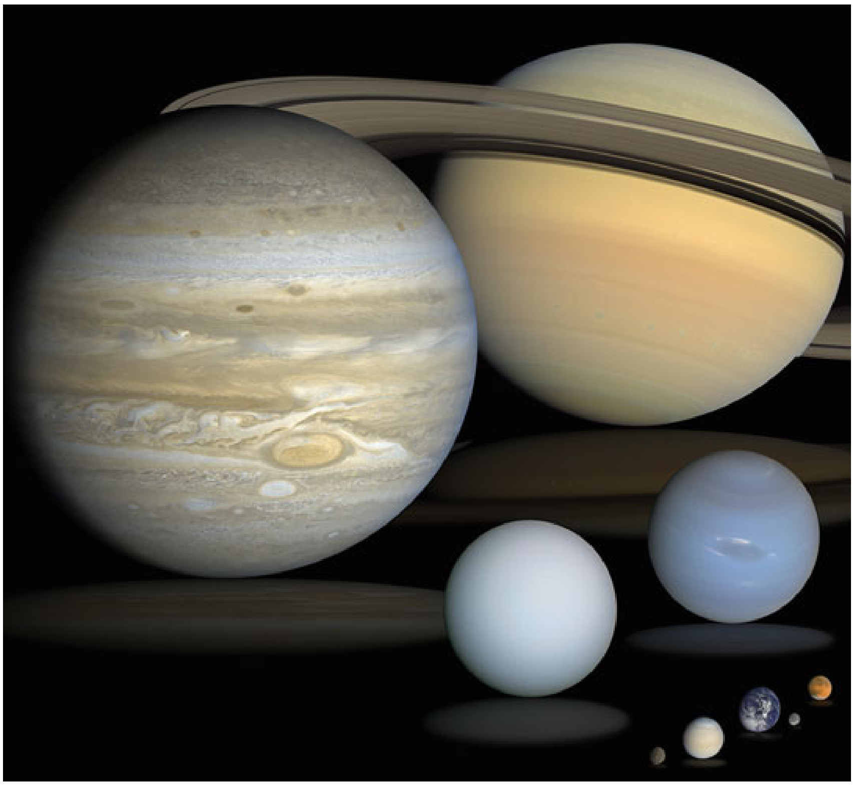

Fig. 5.1 Jupiter, Saturn, Uranus, Neptune, Earth, Venus, Mars, Mercury and the Moon. Image credit: NASA

This majesty is reflected in their names, and the echoes of Greek myths. Jupiter, the Roman name for Zeus, is the King of the Gods and god of thunder and lightning (he is often depicted wielding thunderbolts). In the Iliad, when faced with a mutiny by the other Olympian gods, Zeus challenges them all to hang on one end of a rope, while he alone pulls on the other end. He boasts that he could lift them all up, as well as all the land and sea, then “leave them dangling in space”.

This is a fitting metaphor; the planet Jupiter is heavier than all the other planets combined, and could scatter all of them out of orbit if they came too close (some scientists think this actually happened, see page 105). A wiggle in Jupiter’s orbit could scatter the lesser planets and send Mercury, Venus, Earth and Mars hurtling through the Solar System like mere comets.

Saturn was Jupiter’s father and was known as Kronos in Greek. Warned by a prophesy that his sons would overrule him, Kronos devoured his children as soon as they were born. But when his wife Rhea gave birth to Zeus, she managed to trick

Kronos into swallowing a stone instead. In due course, Zeus grew up to lead a revolt of the gods against his father.

As for Uranus, he was Kronos's father and the god of the sky itself. So the story goes that Uranus and Gaia were the parents of Kronos (and many others), who in turn fathered Zeus (among several others), each son replacing his own father after an episode of violence.

The actual planets stand up to these magnificent tales.

Gas and ice giants

Jupiter and Saturn are known as *gas giants*. They are made mostly of a mixture of hydrogen and helium, the material that stars are made of too, and have no real surface. The name *gas giant* can be misleading though, because these planets are not fluffy balls of gas. In their interior, the pressure is so extreme that the hydrogen/helium mix is compressed to very high density, and starts behaving more like a metal than a gas.

Neptune and Uranus, by contrast, are known as *ice giants*. From the outside they look similar to Jupiter and Saturn, with an atmosphere of hydrogen and helium, but their interiors consist mostly of dense water, methane and ammonia, or "ices" in the jargon of planetary science.

The formation of planets

Planets form by aggregation of dust and gas in a swirling disc around a nascent star. Stars like the Sun are always surrounded by a disc of gas and dust as they form. Close to the star, only rocks and metals condense. They gather into particles, then grains, pebbles, asteroids, and finally, through random collisions, an Earth-like planet can form. Further away from the star, the temperature is low enough for lighter substances like water, methane and ammonia to condense. These compounds are much more abundant than metals and rocks in the interplanetary gas, therefore far larger planets can form, such as Uranus and Neptune, which are mostly made of water. When a solid planet becomes heavier – a few times heavier than the mass of the Earth – the nascent planet is heavy enough to capture the remaining gas in the surrounding disc and swallow everything in its reach. This is what Jupiter and Saturn have done.

At some point the nascent star becomes bright enough to blow the disc of gas away and halt the growth of its planets. The whole process takes a few million years.

Because of these diverse formation processes, atmospheres can have different origins. The gas envelope of giant planets is made up of material captured directly from the disc of gas around the new-born star. Terrestrial planets, by contrast, formed by accumulation of asteroid-like elements, remain too small to retain the gases they had at birth. Any atmosphere they might have had would be blown away into space by the impact of their formation. Any subsequent atmosphere comes from the hot interior, through successive volcanic eruptions. Some of it may also come from later, gentler impacts of other asteroids and comets wandering through the early planetary system. For instance, it is thought that some of the water in the Earth's oceans may have come from comets, which are known to be mainly made of water in ice form.

Let us take a look again at the "Astronomer's Periodic Table", with the elements arranged according to their abundance in interstellar gas. This is the basic material which is available to form planets around most stars. According to the table, the most abundant atoms here are hydrogen, helium, oxygen, carbon and nitrogen. These atoms will tend to combine as water (H_2O), methane (CH_4), and ammonia (NH_3), with the noble gas helium staying aloof.

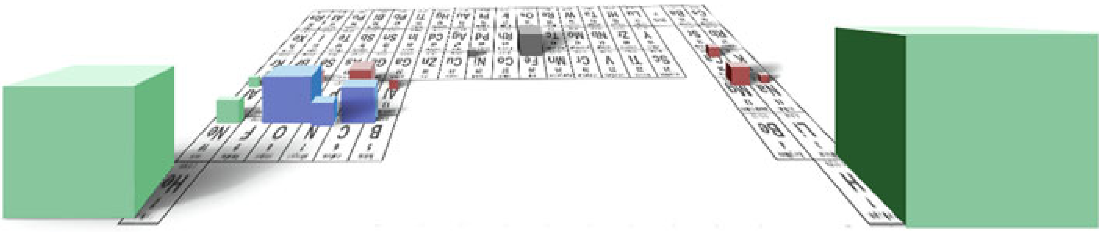

Fig. 5.2 (1.12 repeated): Astronomer's periodic table.

The temperature in a disc of gas at 150 million kilometres from the Sun (the same distance as between Earth and the Sun, i.e. one Astronomical Unit) is around 0 degrees Celsius, and hydrogen, helium, water[8], methane and ammonia are in vapour form. The main solids available are compounds containing silicon, magnesium, aluminium, iron, calcium or sodium. Most of these metals condense as oxides, forming what we would generally recognise as "rocks". Some heavier metals like iron and nickel can also condense in metallic form.

The asteroids roaming between the orbit of Earth and Mars since the birth of the Solar System are made of a mixture of rocks and pure metal. This is also, in fact, what the Earth itself is made of – a core of liquid iron and a mantle of rocks, mostly silicates. Although it is dear to us, the thin layer of water and gas on the outside represents less than a tenth of a percent of the total mass of the planet.

Further away from the Sun (3-5 Astronomical Units and beyond), the temperature becomes low enough for water, methane and ammonia to condense. These familiar molecules condense into solid ices, and therefore become available for the formation of grains, then bigger lumps and clumps, and finally planets. In interstellar gas, oxygen, carbon and nitrogen are far more abundant than silicon or metals, so they will dominate the composition of grains in the cold regions of the immense disc, which stretches out from the surface of the star to hundreds of Astronomical Units. The comets scattered in the far reaches of the Solar System are mainly made of water ice, with some frozen methane and ammonia, mixed with a few pieces of rocks or iron in the centre. Except for the fact that they are a lot smaller, they are similar to the frozen moons of Jupiter and Saturn.

Gas capture and ice line

A planet can only attract and keep hold of an atmosphere if it is heavy enough for its gravity to keep the gas from floating back into space.

Planets the size of Earth can keep hold of nitrogen, oxygen and carbon dioxide, but not of lighter elements like hydrogen and helium. Since most of the gas in the disc

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[8] Water freezes at zero degrees on Earth, but in the vacuum of space it freezes only below –60 degrees Celsius.

around a nascent star is hydrogen and helium, the Earth did not capture very much of these gases.

It requires around ten times the mass of the Earth to be able to retain the lightest gases. When a young planet reaches this mass, it no longer needs to grow by accumulation of solids and collision of asteroids, but starts to swallow gas directly from the disc around it. This is a runaway process: the larger it becomes, the more its gravity is reinforced, and the more gas it can capture from the disc. The process only ends when a gas-free gap opens in the disc: the planet has captured all the gas it could acquire.

Saturn and Jupiter reached their enormous sizes in this way. At their core sits a mass of ice and rock around ten times larger than the whole Earth, surrounded by an envelope of 90 Earth masses (for Saturn) and 300 Earth masses (for Jupiter) of hydrogen and helium gas captured from the disc[9].

There were not enough rocks and iron in the disc around the Sun to form solid cores heavy enough to keep hold of hydrogen and helium. This is why giant planets did not form in the inner parts of the Solar System, where the temperature is too high for ice to condense. The outer parts, however, are cold enough for water, ammonia and methane to freeze and form solid bodies, and since these compounds are much more abundant than rock or iron in the cosmos, they could form cores large enough to reach the critical size which triggers the formation of a gas giant planet.

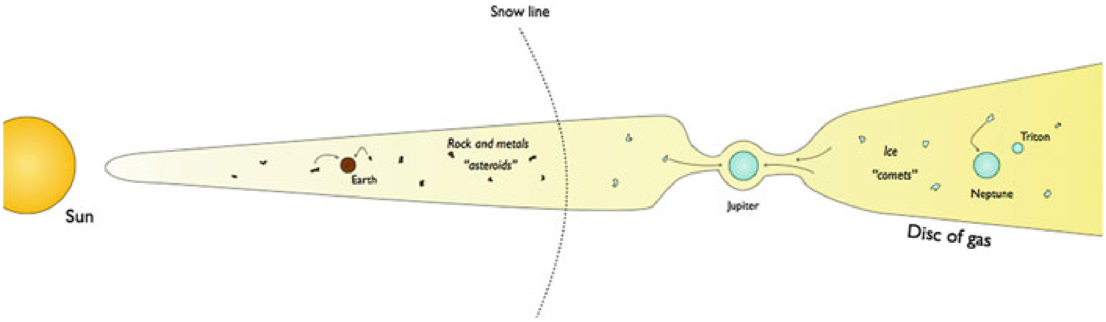

Fig. 5.3 Formation of planets and the snow line. Planets form by the accumulation of solidified material in the disc of gas that surrounds nascent stars. Close to the star, only rocks and metals can condensate. Further out, beyond the *snow line*, water condenses as ice. Larger planets can form. The largest bodies become heavy enough to accrete the gas from the disc directly.

The imaginary line separating the inner part of the Solar System – too hot for the condensation of water in space – and the outer reaches, is called the *snow line* (or *ice line*). Within the snow line, only rock-and-iron planets are expected to form, like the terrestrial planets Mercury, Venus, Earth and Mars in the Solar System. Beyond the snow line, gas giant and ice giant planets can form, as well as icy satellites such as Ganymede, Europa and Titan.

When small bodies visit the Earth hailing from other parts of the Solar System, we call them asteroids if they are mainly rocks and metals – these were presumably formed within the snow line. If they are mainly made of ice we call them comets – they presumably formed in the outer parts of the Solar System. The tails of comets are produced by the evaporation of ices under the heat of the Sun, as they travel towards

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[9] For the record, it is not known whether Jupiter has a central core of rocks and ices, or whether these heavy elements are mixed up with the concentrated gases which form the bulk of the planet. We should know this in a couple of years, thanks to the JUNO mission which is on its way to the Jupiter system as this book goes to press.

warmer climes. But nothing evaporates from asteroids, since they were formed at relatively warm temperatures and do not contain ice or other material that could be easily vaporised.

Three types of planets

In broad terms, planets can form from the accumulation of asteroids, the accumulation of comets, or by the capture of hydrogen and helium gas by an already large core.

This is therefore what we would expect to find around a star with a disc rich enough in metal and ice grains to form planets:

> i. Small rock-and-iron planets in the vicinity of the star, closer than the vaporising point of water, ammonia and methane in space. In our Solar System these are Mercury, Venus, Earth and Mars; all these planets are closer than three Astronomical Units from the Sun.
>
> ii. Larger planets made mainly of water, methane and ammonia, with some rocks and iron, further out from the star. Examples: Uranus and Neptune, as well as the satellites of the giant planets such as Ganymede, Europa and Titan.
>
> iii. Giant planets made mainly of hydrogen and helium gas, with a rock/iron/water core of around ten Earth masses. Examples: Jupiter and Saturn.

Once planets are large enough to melt their interior, the heavier components tend to flow towards the centre and the lightest to float up to the surface. That is why planets adopt a “Russian-doll” structure, with an iron/metal core in the centre, a rock layer, then a layer of ices, and a hydrogen and helium envelope. Not all planets have all of these layers, but they always come in the same order. A planet with, for instance, a core of ice and a mantle of iron would not be stable, and the iron would sink to the centre over time.

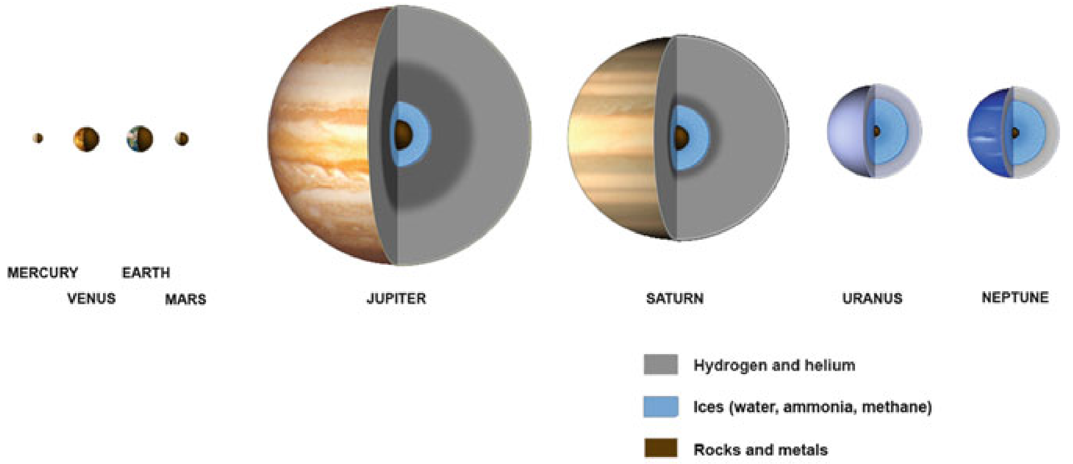

Fig. 5.4 Internal structure of planets in the Solar System.

Uranium-core planets?

If heavier elements sink more than lighter ones, what about the tiny fraction of very heavy elements, all the way down the periodic table, from gold and platinum to uranium? Shouldn't they sink to the centre as well? The central core of planets would then be composed of an onion-skin structure of pure heavy metals in ascending order of atomic weight. Are all planets powered by a natural nuclear reactor at their centre, a blob of pure uranium? In fact not.

Gravity is able to sort gases or liquids according to their relative weights, as can be seen in a vinegar-and-oil sauce. But atoms combine into molecules, and molecules stick to each other in solids and liquids, so that individual atoms are not free to move around as they wish. The links between atoms inside a molecule are stronger than gravitational stratification, so it is not elements that are sorted out by gravity, but molecules in gas, and associations of molecules in liquids and solids.

Heavy metals like uranium get trapped in molecules or alloys that tend to be less dense than iron. On Earth, they remain stuck as a very rare fraction of the lighter rocks in the mantle, and don't even make it into the iron-nickel metallic core. Uranium, like most metals, forms oxides, which aggregate as rocks, and these rocks are less dense than elemental iron. The Uranium of the Earth (0.000002 percent of the mass of the Earth, still about one hundred thousand billion tonnes) remains safely locked in rocks dispersed through the whole envelope of the planet.

Why is the inner core of Earth-like planets made of iron? This is due to a quirk of nuclear physics. Iron happens to be the most stable nucleus among all the elements. In the furnace of a supernova explosion – where most heavy elements in the cosmos are produced – the cataclysmic rearrangement of protons and neutrons favours the formation of iron over all other metals.

Deep inside

Hot concentrated ice, boiling iron, metallic hydrogen… the interiors of planets are made of familiar materials in unfamiliar states.

In our daily lives we are familiar with the way matter changes state under the influence of temperature. Ice melts, water boils, grease and honey turn solid in the fridge, and volcanic lava solidifies when cooling. We are less familiar with the way pressure affects matter, because pressure does not vary as much as temperature around us. We may have felt a little short of breath on the top of a mountain, or we may have experienced the pain of water pushing on our eardrums when diving, but these pressure changes are not large enough to affect the behaviour of common materials.

In the interior of planets, the pressure is enormous, millions of times that on the surface of the Earth, and materials become compressed into increasingly compact structures. Hydrogen is a gas near the surface, but in the depths of a gas giant the pressure is so great that it snatches electrons from individual atoms and forms a solid mass called *metallic hydrogen*. Scientists use this term because metals are characterised by the presence of free-ranging electrons in a lattice of atoms.

If you want to know what is inside a planet like Jupiter, you have to calculate how dense hydrogen would become under extreme pressure. Hydrogen is the simplest atom, consisting merely of one proton orbited by a single electron. Nevertheless, it turns out that the density of hydrogen at extreme pressures (millions of bars) is difficult to calculate, and has to be measured with experiments.

One of the ways to do this is to let a thermonuclear bomb explode, and measure the results. Indeed, some of the measurements on high-density hydrogen come from Russian thermonuclear bomb tests. Other, more gentle ways exist, such as using lasers to produce strong local shocks.

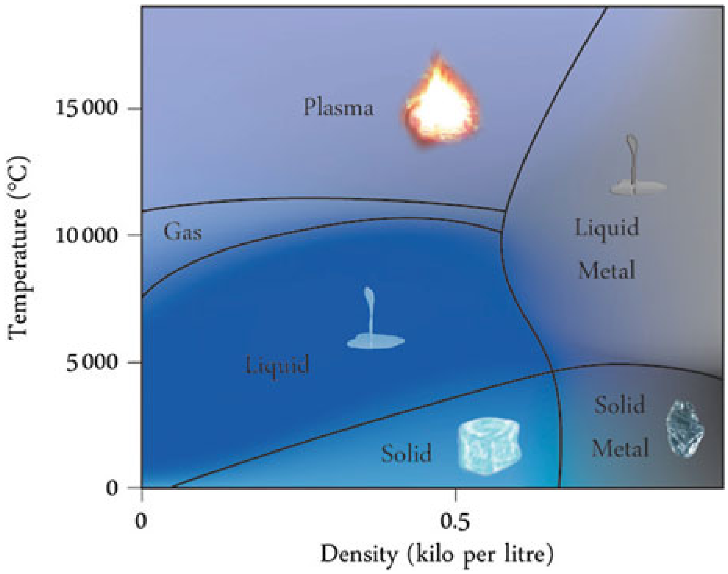

Fig. 5.5 States of hydrogen under different temperatures and pressures.

On ice giant planets such as Neptune and Uranus, the main constituent is water. The behaviour of water at high pressures is unexpectedly complex, with no less than twelve possible crystalline structures. We know one of them quite well, ice, which scientists call *ice Ih*, but this form of ice is just one among many. In giant planets, as the pressure increases, water is compressed into various semi-fluid, compact forms

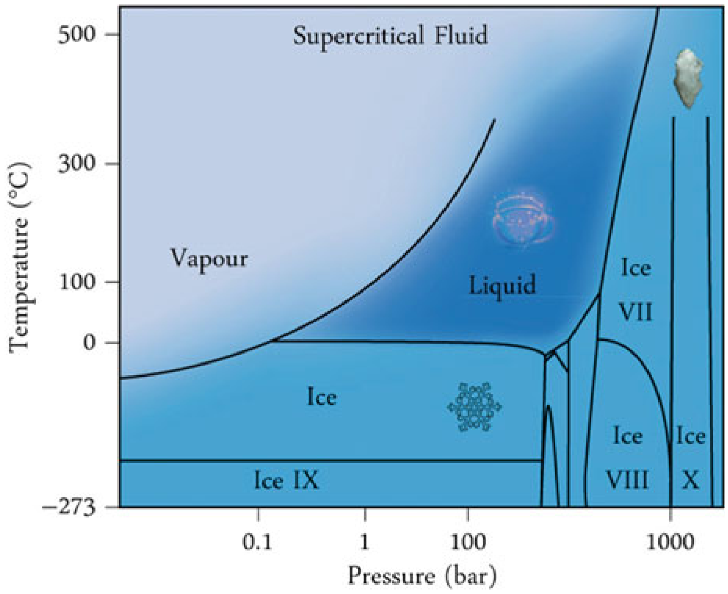

Fig. 5.6 States of water under different temperatures and pressures.

very different from ordinary ice. The interior of Neptune for example is thought to consist of a hot slush of water, ammonia and methane crystals, something heavy and sluggish like the magma found in Earth's mantle.

The interior of ice giant planets reaches several thousand degrees, as hot as the surface of the Sun; and lumps of hot ice from there, if ever brought to the surface, would emit a bright, blinding white light. A block of water straight from the mantle of Neptune would fry us in an instant.

There is another difference between ice giant planets and terrestrial planets: the lack of an identifiable surface. The material in giant planets transforms from a dense liquid to a thin gas without a well-defined phase transition. There is no boundary, the pressure and temperature gradually drop from the white-hot magma interior all the way to the thin gas of the atmosphere.

Atmosphere of Jupiter

We know the atmosphere of Jupiter quite well, thanks to the heroic sacrifice of the Galileo probe that plunged into the planet on 7 December 1995. Let us follow it in its descent.

When the probe first starts feeling the atmosphere, its thermal shield heating up due to the friction of the thin hydrogen gas, the air is clear and the temperature a chilly –120 degrees Celsius. Gradually, the probe sinks into thicker air and slows down. About 300 kilometres further down into the planet, the temperature starts rising, and we approach the highest tops of the first layer of giant clouds. These clouds are made of droplets of ammonia. A few dozen kilometres deeper, the probe crosses a second layer of clouds, made of a compound of ammonia and sulphur. Sunlight cannot penetrate the thick clouds and it is now pitch dark.

Finally, about 80 miles below the first cloud cover, the probe glides between giant clouds of water ("our" kind of clouds). The temperature has now reached a pleasant 20 degrees Celsius, but the pressure is crushing. The air is so dense that the probe no longer dives but sinks slowly like a pebble in a jar of honey, until it melts and dissolves in a thick, black, unsavoury brew.

Clouds

Clouds are the dominant feature in the atmosphere of giant planets.

We have seen that clouds form when the temperature drops below the condensation point of one of the components of the atmosphere, making it gather into droplets or grains. In a completely still atmosphere, these droplets and crystals simply drift down in a single episode of rain or snowfall, until the air is dry and clear again. That is why clouds do not only require the right temperature to form, but also atmospheric motions to bring the molecules that form the droplets back into the cooler regions.

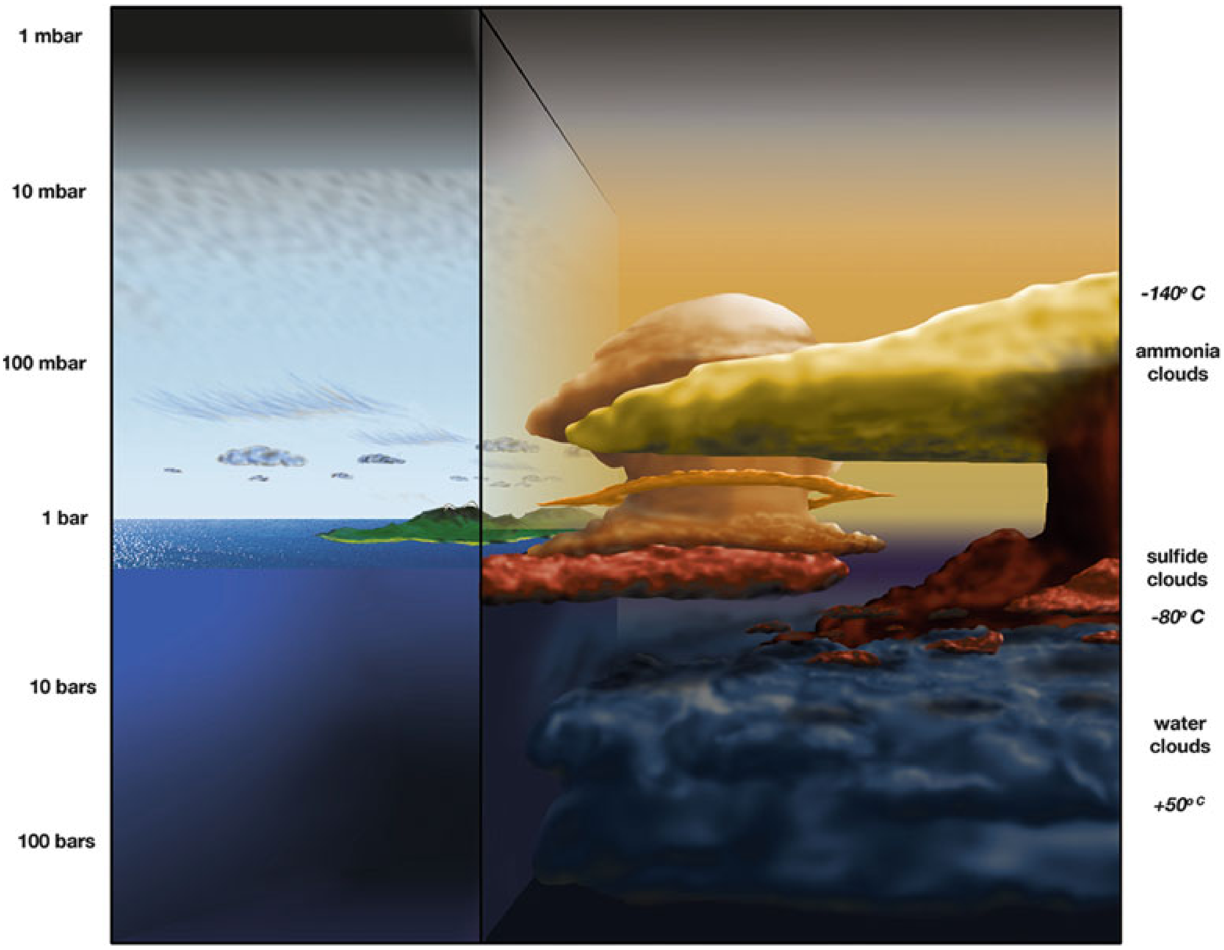

Fig 5.7 Atmosphere profile for Jupiter, on the same pressure scale as the Earth.

We saw in Chapter 1 how this explained the rarity of clouds on Earth above the tropopause, the level at which commercial airplanes fly. The churning of the lower atmosphere by vertical convection and horizontal weather systems constantly moves new water from warmer to cooler regions, while this does not happen in the stable stratosphere.

On Earth, clouds almost never form in the stratosphere, although there are rare and spectacular exceptions. Sometimes over polar regions the air becomes so cold that even the low amount of vapour present in the stratosphere can condense. These clouds are called *iridescent clouds* because they are so thin that they only become visible in the grazing light of the setting or rising sun, producing colourful displays.

Even thinner and even rarer, *noctilucent clouds* sometimes form at amazingly high altitudes, high above the ozone layer at around 60 kilometres (35 miles) above sea level. They can become visible at dusk once the Sun has set over most of the atmosphere but still illuminates the upper levels. We are still on Earth but these clouds have a slightly alien feel to them.

Fig.5.8 The variety of clouds, on Earth and Mars. Image credit: NASA

Fig. 5.9 Noctilucent clouds from International Space Station. Image credit: NASA

The type of compound likely to condense into clouds depends on the temperature, and varies from planet to planet. Earth has water clouds[10]. Carbon dioxide clouds sometimes grace the Martian sky, and Venus is shrouded in sulphuric acid clouds. On the giant planets, successive cloud decks are made of different compounds as the temperature increases in the deeper layers.

The sequence of condensation temperatures for common molecules indicate which clouds can form on which planet. These molecules are, from colder temperature to hotter:

Methane	–161 °C
Ammonia	–78 °C
Carbon dioxide	–33 °C
Water	0 °C
Sulphuric acid	340 °C

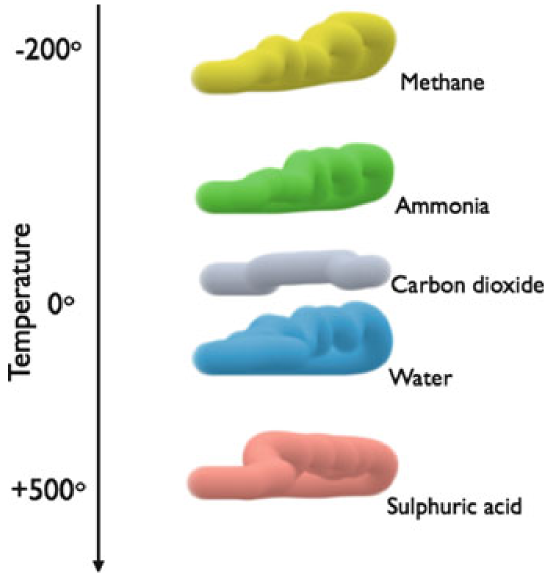

Fig. 5.10 Cloud-forming substances in planetary atmospheres for different temperatures

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[10] Sometimes we also refer to “dust clouds” or “smoke clouds”, which are not formed by condensation but by the presence of solid grains that make the air opaque. In this book we call this “haze” or “dust storms”. They are also an important component of atmospheres, we have met them on Mars in Chapter 2 and will encounter them again on hot Jupiters in Chapter 6.

Why are these substances forming clouds and not others? Once more this is a consequence of the abundances of elements in the astronomer's periodic table. The atmosphere of giant planets is full of hydrogen, so the dominant form for the three abundant elements C, N and O is their hydrogen-rich versions H_2O (water), CH_4 (methane) and NH_3 (ammonia). It follows that these are the dominant sources of clouds on those planets[11]. Sulphur can also participate through NH_4SH, ammonium hydrosulphide, which forms clouds just below the level of ammonium clouds on Jupiter.

Jupiter is too close to the Sun for the temperature to drop below the condensation point of methane, but it does exhibit substantial ammonia and water clouds, whereas methane clouds readily form on Uranus and Neptune.

Circulation and weather

Clouds are a big part of what we call the "weather". On Earth as in other planets, clouds make the atmosphere visible, and allow us to follow its currents and circulation. The most spectacular clouds in the Solar System are undoubtedly on Jupiter, and there is apparently no limit to the variety of patterns that can play out on the King of planets. Indeed, Jupiter features so many clouds that they tend to blur into a psychedelic tapestry and make it difficult to visualise its atmosphere in three dimensions.

Cloud patterns are easier to interpret using infrared radiation which traces heat, and since clouds seen from space block out our view of the warmer regions below, the higher they are in the atmosphere, the darker they appear (weather satellites use this trick to monitor clouds on Earth during the night).

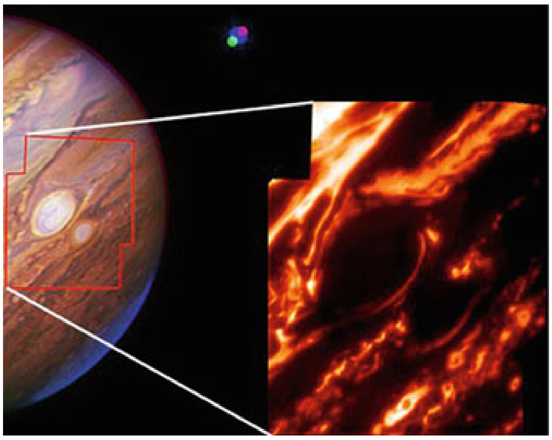

Fig 5.11 Jupiter clouds in visible and infrared light. In infrared, the bright patches show deeper, hotter regions between the high clouds. Image credit: NASA

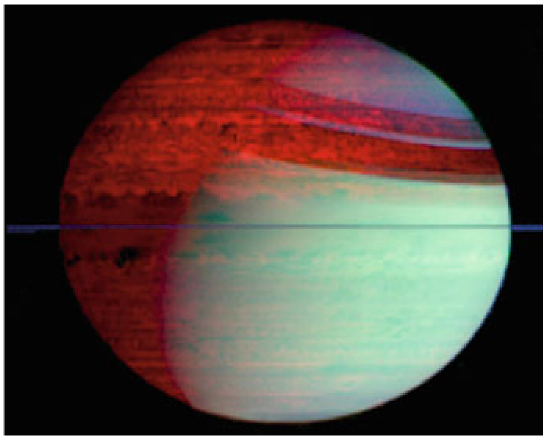

Fig 5.12 combines two views of Saturn, one in visible light, the other in the infrared. Visible light shows a smooth greenish diffusion from haze high up in the atmosphere, whereas in the infrared images, the patchy clouds below are visible, arranged in bands as on Jupiter, with the higher decks of clouds appearing as dark patches and the lower ones in bright red.

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[11] Do clouds in gas giant planets smell bad? Ammonia and methane have something of a bad name. Ammonia is the smellier part of urine, and is the body's way to get rid of excess nitrogen. It smells foul, but is not very toxic. Methane is odourless but highly explosive. It is the main component of commercial natural gas. Cooking gas has a smelly compound added to it to help people detect leaks, so methane is often considered smelly by association.

Patterns of circulation

Why are the clouds on Jupiter and Saturn arranged in narrow bands? The difference between the global aspect of clouds on Jupiter and on Earth illustrates a profound relationship between rotation and atmospheric circulation.

Some science museums feature a large globe filled with coloured fluids, which the visitors can spin. If you rotate it very gently, nothing happens at first, then the fluids inside the transparent sphere start spinning with it. Push the sphere a bit faster, and some large motions begin to form, and in due course they majestically swirl across the sphere.

Push it faster still, and individual vortices appear, then the whole sphere starts looking like a satellite weather map of our planet.

Then, if you send it spinning even faster, something spectacular happens. At some point all poleward motion stops, and the currents arrange themselves in horizontal bands. The transition is sudden and startling. Push it a bit faster, and a new band appears out of nowhere.

Finally, if you give some irregular nudges to the globe, eddies form between the bands and evolve in fascinating patterns of waves, spirals and tentacles. The resemblance between this simple sphere and what is actually going on in Jupiter is striking.

This experiment illustrates some profound features about the circulation of planetary atmospheres, and why the main factor in determining the large-scale structure of the circulation is how fast the planet rotates on its own axis.

There are broadly three possible regimes for the motion of a fluid on a sphere as the rotation increases:

i. If the rotation is slow compared to the size of the planet, the fluid can move across the whole face of the globe, in large swirls and gentle waves. This can be seen on Mars, where dust storms propagate from the hemisphere closest to the sun to eventually cover the planet from pole to pole. Hot Jupiters are also in this regime.

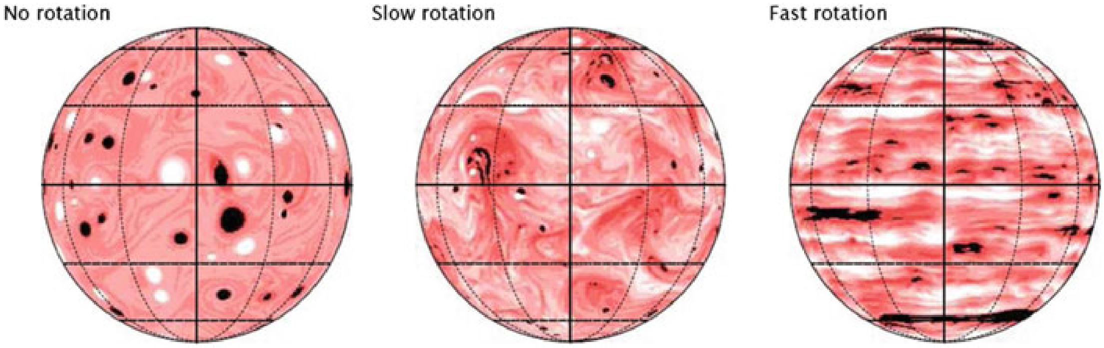

Fig. 5.13 Three regimes of atmospheric circulation. (Peter Read, after Yoden et al. 1999; Hayashi et al. 2000; Ishioka et al. 1999; Hayashi et al. 2007)

ii. As the rotation becomes rapid enough for the Coriolis effect (ice-skater/

rotating platform –see Chapter 1) to twist the currents before they can cross the whole planet, the circulation regime moves to a state dominated by a limited number of large vortices, arranged in a few bands lying parallel to the Equator.

Earth is an example of this regime. We do not see it so well because clouds cover only a fraction of the Earth and tend to avoid the tropics, but Earth's circulation follows six clear bands. The "bending distance" for weather patterns is approximately equal to the width of the bands, so that cyclonic patterns span a few thousand kilometres each. At any given time, about half a dozen high-pressure/low-pressure systems can be seen around each hemisphere.

Fig. 5.14 Earth's clouds. At any given time, the Earth's atmosphere shows about half a dozen weather systems in the mid-latitudes. Image credit: NASA

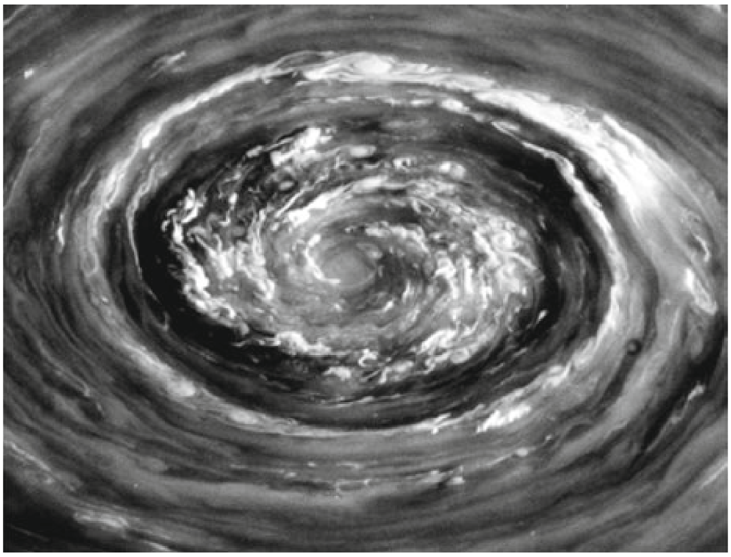

Fig. 5.15 Atmospheric circulation near the pole of Saturn. Image credit: NASA

iii) Finally, when the rotation is too fast for the fluid to travel polewards, the Coriolis effect becomes dominant and the currents fall into narrow horizontal bands. This is the state of Jupiter and Saturn.

Jupiter weather bulletin

The bands in the third type of circulation are far from static. Astronomers have been charting Jupiter since the time of Galileo (the man, not the probe), and it is clear that coming to understand the weather on this gas giant takes some patience, because the timescales are longer than on Earth.

The famous Great Red Spot is thought to be a slowly-evolving giant storm, which might last a few hundred years. In 2009, an even faster sign of evolution was observed: one of the bands, the large dark band just north of the Red Spot, simply vanished. Some whiter clouds seem to have formed at a higher altitude and quickly spread around the band.

Could space meteorologists have seen it coming? Can they explain it? The answer is the same as for weather on Earth, and brings us to one of the most challenging topics of modern physics.

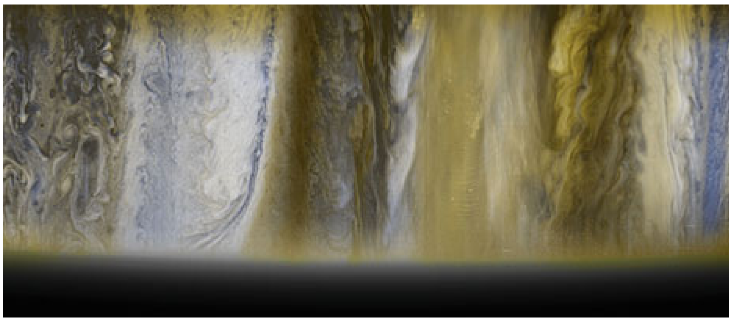

Fig. 5.16 Jupiter's clouds. The different colours correspond mainly to different heights in the atmosphere. Notice the bluish regions, where gaps in the clouds allow us to see deeper into the planet. Image credit: NASA

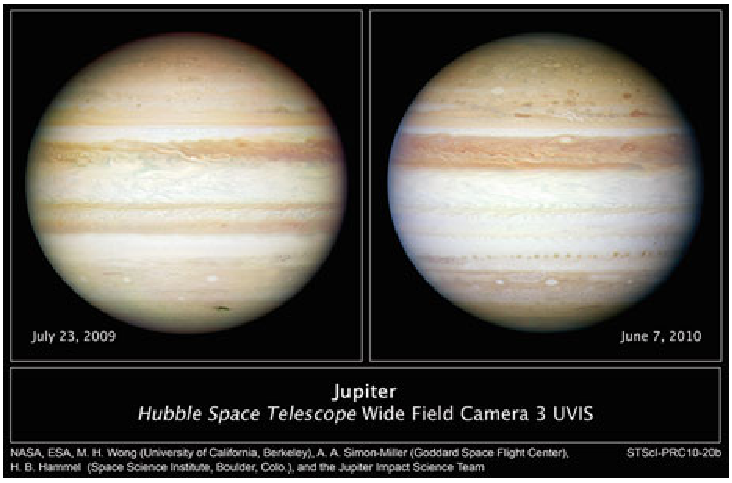

Fig. 5.17 Jupiter at two different times. Note the disappearance of the main Southern band. Image credit: NASA

The role of turbulence

Eddies, twirls and swirls; the flow in planetary atmospheres is generally *turbulent*. Turbulent flow is a technical term used in physics to describe one of only two fundamental types of fluid flow, the other being laminar flow. The classic example of the difference between the two is that of cigarette smoke, which first rises straight up in a laminar manner, then abruptly breaks into turbulent swirls and curves. But most of us are now acquainted with another, more impressive transition from laminar to turbulent flow: when we are comfortably installed in an airplane, that seems to glide through air so smoothly that we could build a house of cards on the tray in front of us, and suddenly the whole plane jumps and rocks as if hit by sandbags from all sides at once. Outside there is not a cloud in sight, and nothing in the air looks different. The plane has just crossed from a laminar to a turbulent section of the sky.

Turbulent flow is one of the most intractable problems in physics. As Hungarian mathematician Theodore von Karman put it: “There are two great unexplained mysteries in our understanding of the universe. One is the nature of a unified generalised theory to explain both gravity and electromagnetism. The other is an understanding of the nature of turbulence. After I die, I expect God to clarify the general field theory to me. I have no such hope for turbulence”.

What makes turbulence so intractable is related to the science of “chaos”, phenomena that are fundamentally unpredictable, as often illustrated by the possibility that a butterfly flapping its wings in Brazil can, in principle, trigger a hurricane in Russia. Turbulent flow is chaotic, not in the sense of total disorder, but in the mathematical sense that small causes can produce immense effects.

Not all butterflies provoke storms, but the connection of large effects with potentially tiny causes makes it very difficult to study such processes with the usual tools of physics. The science of chaotic behaviour, sometimes also called complexity theory, is used to investigate the causes of avalanches and earthquakes, another field of study where it is possible to identify danger spots and likely events, but not to predict when and where anything will actually happen.

In a planetary atmosphere, turbulence means that large-scale properties, such as the red spot on Jupiter, or the speed of the global winds, will depend on the smallest scales, the weak interactions between particles in the tiniest of swirls, or a local knot in the magnetic field. It also means that there is really no way to predict in detail what the swirls and eddies will look like, or how they evolve.

Sometimes the best we can do is sit back and enjoy the view.

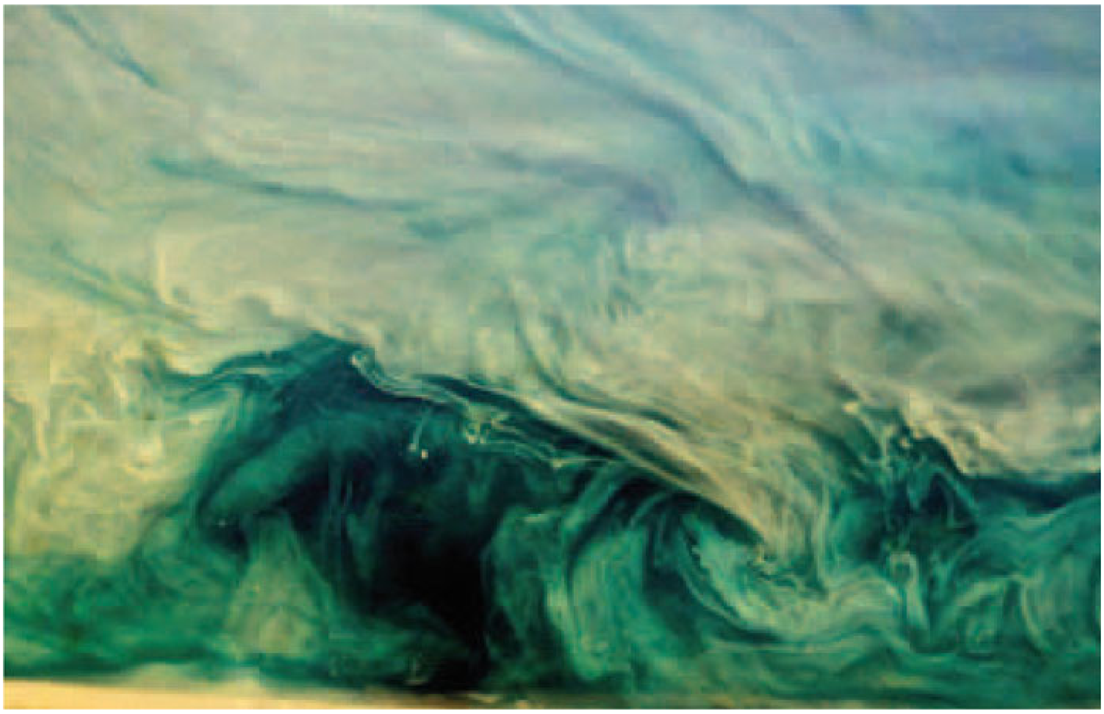

Fig. 5.18 Turbulence in a fluid-dynamics lab tank. Image credit: P. Burge