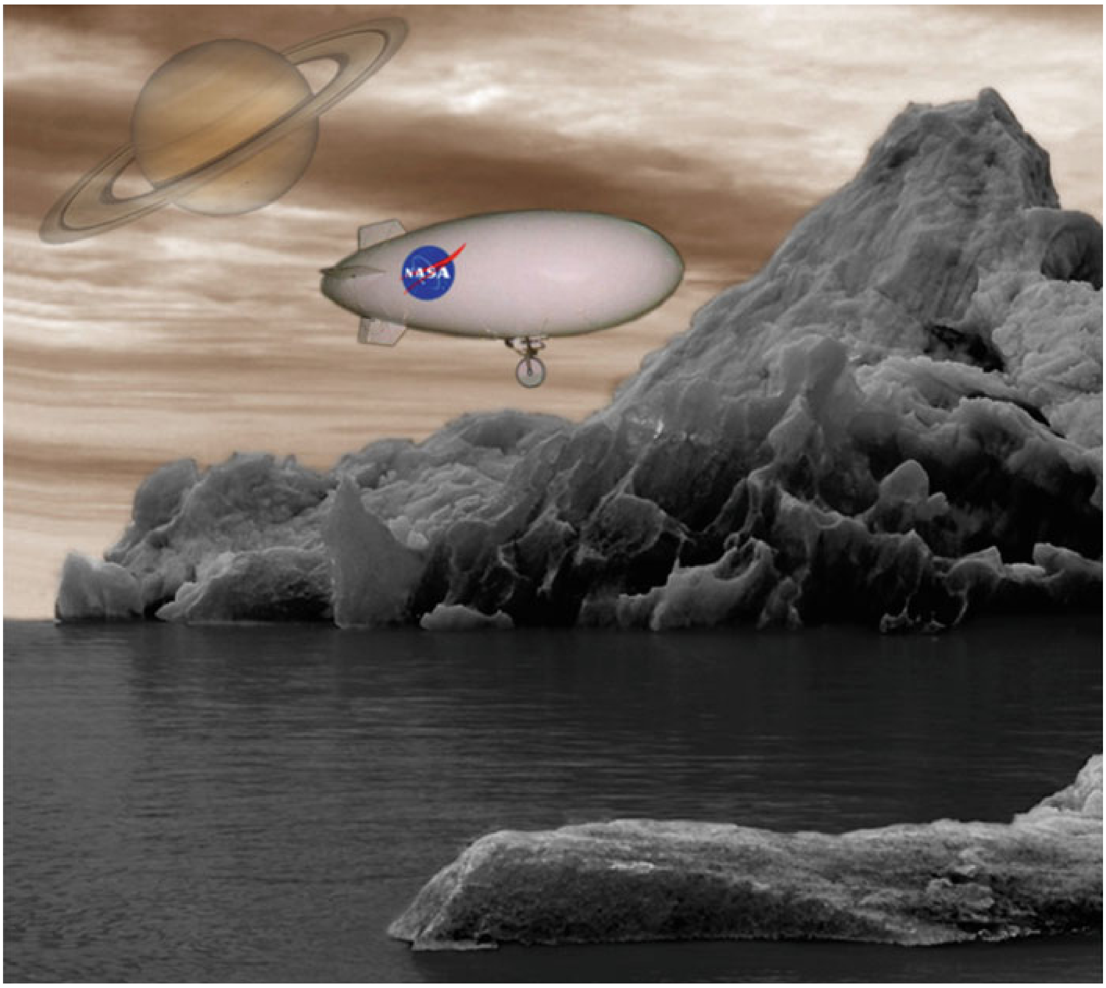
Chapter 4

Titan



Titan is the second largest moon in the Solar System, after Ganymede, which is Jupiter's largest moon. With a diameter of 5,150 kilometres (3,200 miles), compared to 3,470 kilometres (2,156 miles) for our Moon, Titan is even larger than the planet Mercury. Uniquely amongst moons, Titan possesses an atmosphere. From the outside, it looks like a yellow-orange, featureless globe, because its thick, hazy atmosphere entirely conceals its surface.

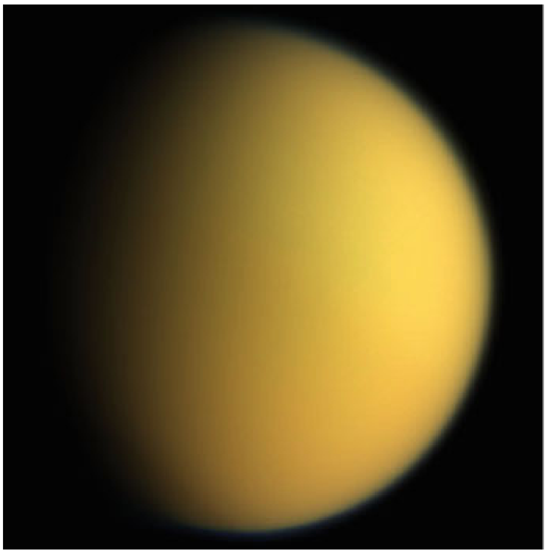


Fig. 4.1 Titan. Image credit: NASA

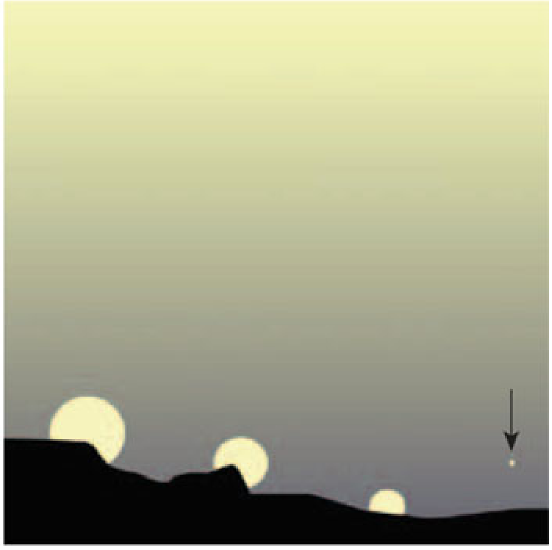


Fig. 4.2 The Sun seen from Titan (right), compared to its size from Earth, Venus and Mars (from left).

Seen from Titan – at almost ten times the Sun-Earth distance – the Sun is only a weak spotlight in the sky, and the temperature is correspondingly colder, around two hundred degrees Celsius below zero.

The main component of Titan's atmosphere is nitrogen, the same gas that dominates our atmosphere. The rest is methane (CH_4), hydrogen (H_2), and ethane (C_2H_6), another component of natural gas, with methane. At these low temperatures, heavier molecules like water and carbon dioxide freeze and form blocks of ice on the ground. The whole planet's crust is actually dominated by water ice, with maybe a buried liquid ocean, deep underneath.

The atmospheres of Earth and Titan are similar in several ways. They are the only two known atmospheres which are dominated by nitrogen. The pressure at the surface is slightly higher than here, at 1.54 atmospheres, a pressure we could adapt to (equal to the pressure under about six metres of water). The main difference is that Titan is so much colder.

Surface features

On 14 January 2005, the small Huygens probe pierced the haze of Titan and plummeted towards the surface. While parachutes were starting to slow down its fall, it took the first snapshots of the surface of Titan, never seen before by human eyes. The results were breath-taking.

The first images from Titan were more Earth-like than anything ever seen before. Titan may be a frozen, sterile world, but from the air it looked strangely familiar.

What did Huygens see? Rivers, streams, quiet shaded valleys, light morning fog. In the suggestive shadows of the first images one could almost imagine sloping forests, scattered juniper bushes or a fishing village.

The rivers are not made of water. Water is always rock hard on Titan because of the extremely low temperatures. What is flowing there, even forming lakes (that most

Earth-like feature) is liquid methane. Indeed, Titan is the only known place with liquid on its surface apart from our planet.

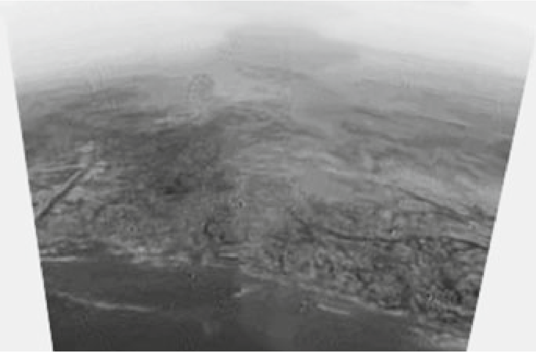


Fig. 4.3 Titan's "shoreline", visible on an early image from the Huygens descent. Image credit: NASA

During its fall, the Huygens probe swayed wildly because of its parachute; as a result its camera covered a good fraction of the landscape, if in a rather haphazard manner. Once on the ground the probe took a more detailed picture of its surroundings, showing it had landed in a somewhat disappointing spot – the usual Atacama-desert-style plain of rubble, not unlike Mars, the Moon, or Venus. No methane waterfalls in sight; no tungsten tree or cryogenic sheep.

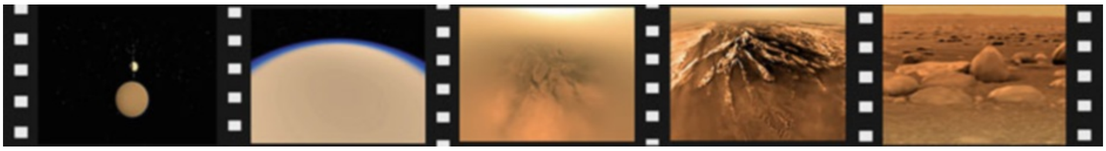


Fig. 4.4 Stills from the movie of the Huygens descent. Image credit: NASA

The planetary explorers

The engineers of the Huygens project had an interesting challenge to face: the presence of lakes or seas of liquid methane were expected on Titan, and they had to devise a probe that could either land on solid ice or splash into a sea of methane. Building a lander that can travel across the Solar System and parachute into an alien atmosphere is hard enough, but this was the first time the vehicle had to be amphibious.

The Huygens probe was equipped to float on an ocean of liquid methane. It would have frozen fast in such a situation, lasting no more than a few minutes. In the event, it landed on hard ground and was able to send data for about 90 minutes.

Upto 2012, some 14 vehicles have managed to print their little podmarks under alien skies: five on Venus, seven on Mars, and one on Titan.

The main obstacle for a probe to arrive alive and well on another planet is the speed of its fall. Different atmospheres pose different problems. On Mars the thin air does not provide much breaking and large parachutes and retro-rockets are used to slow down the fall. In some cases an airbag system was used to cushion the impact of contact with the ground, which can still be rather violent. In the thick, viscous air of Venus, slowing down the fall is not a problem, and the probe can gently sink below the clouds under a small parachute. The problem there is posed by the intense pressure and temperature, which pressure-cook the instruments in a few minutes. The central part of the Venera probes is a sphere of metal, similar to submersibles like the Bathyscaphe that reached the deepest parts of the oceans on Earth.

On Jupiter, in 1995 the Galileo probe fell through an increasingly thick atmosphere with no solid ground in sight, until it entered gas layers so dense that contact with Earth was lost. Since its metal components remained denser than the surrounding hydrogen at any pressure, the probe will have continued sinking, ever more slowly as the density increased, until the components were melted by the high temperature and crushed by the high pressure, and carried around in the planet's huge convective motions. Over time, the scattered pieces of metal will have reached regions deep inside the planet where the temperature is high enough to melt and vaporise them and combine their individual atoms in the general mix of Jupiter's composition.

On each planet, the fate of the landers gives an indication of the atmosphere. Vulnerable parts of the Venera probes softened and buckled under the stifling Venusian conditions, while the metallic parts were slowly corroded by the acidic atmosphere until the whole craft was reduced to lumps of metallic oxides blending with the local rock landscape, its exotic composition the only reminder of its alien nature. The Martian landers on the other hand will remain in shape for millennia, like the vestiges of the Pharaohs preserved in the arid Egyptian desert, the oxidising air and tiny dust particles very slowly chipping their metal plates away. They may end up covered by their own little sand dunes before disintegrating.

Contrast these with the pieces of equipment that the Apollo astronauts left on the Moon, which are expected to remain in pristine condition for millions of years. These may well be the last human artefacts left in the Solar System long after the disappearance of any trace of human occupation on Earth.

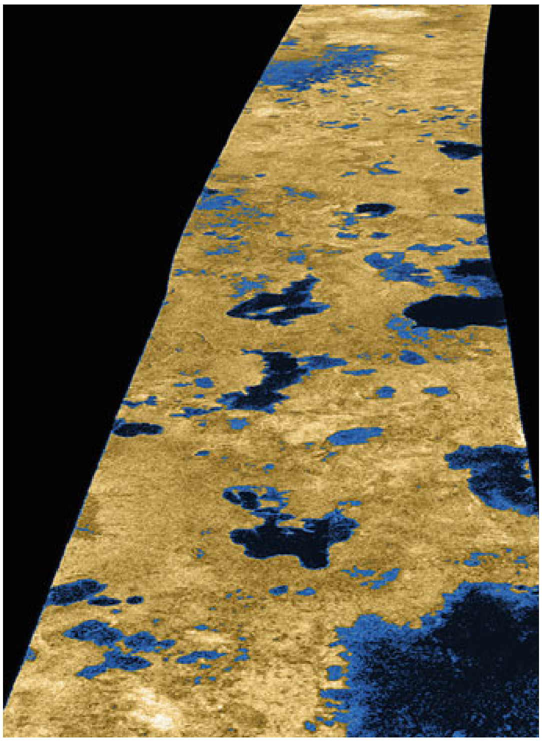


Fig. 4.5 Titan methane lakes, reconstructed from measurements of the smoothness of the surface. Image credit: NASA

Lakes of methane

Instruments aboard the Cassini spacecraft (which launched the Huygens probe in 2005 and has aproached Titan several times since then) have revealed how smooth or rough the surface is on various parts of the planet. It is thought that especially smooth patches are lakes of methane.

Close observation of one of these lakes, Ontario Lacus, has even shown the shoreline of the lake receding with time, a sign of the passing seasons on Titan.

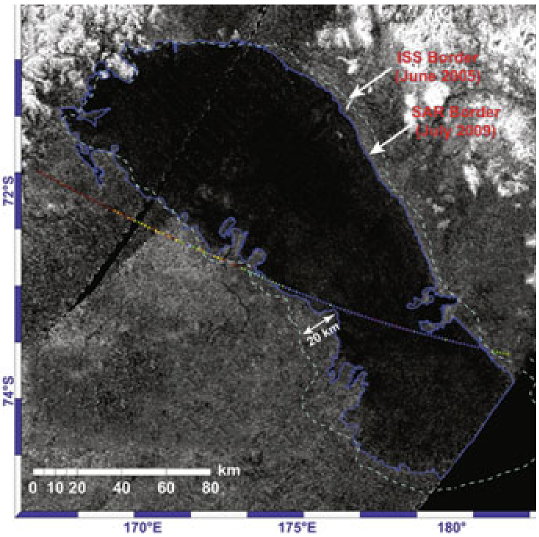


Fig. 4.6 Receding shoreline of the methane lake Ontario Lacus on Titan. Image credit: NASA

Methane cycle

There are clouds, rivers and lakes on Titan for the same reason as on Earth – because a substance changes between its solid, liquid and gas forms with changes in temperature. On Earth this substance is water, on Titan it is methane. Methane melts at –182 degrees Celsius and boils at –162 degrees Celsius (compared with water's 0 and 100 degrees Celsius).

Such cycles are often what make a planetary atmosphere interesting. We have encountered the water and carbon cycles on Earth, the CO_2 cycle on Mars and the two sulphur cycles on Venus. Carbon dioxide on Mars moves from its ice form in the polar caps, to being a gas in atmosphere, where it form clouds, then snows down in winter and regulates seasonal temperature changes. Sulphur on Venus forms droplets of sulphuric acid that shroud the whole planet in thick clouds.

On Earth, a large fraction of the energy from sunlight is used to evaporate water from oceans, lakes and forests rather than being turned into heat, so that the water cycle acts as a giant temperature regulator. In the same way that sweating is an efficient way of cooling a human body, evaporation prevents oceans and landmasses from overheating. Running water is the major factor in land erosion, shaping continents and returning sediment to the sea. Less visibly for us, the water cycle also plays a key role in regulating the amount of carbon dioxide and the warming in the atmosphere through the greenhouse effect.

Methane lasts only one or two decades in the atmosphere of Titan, after which it

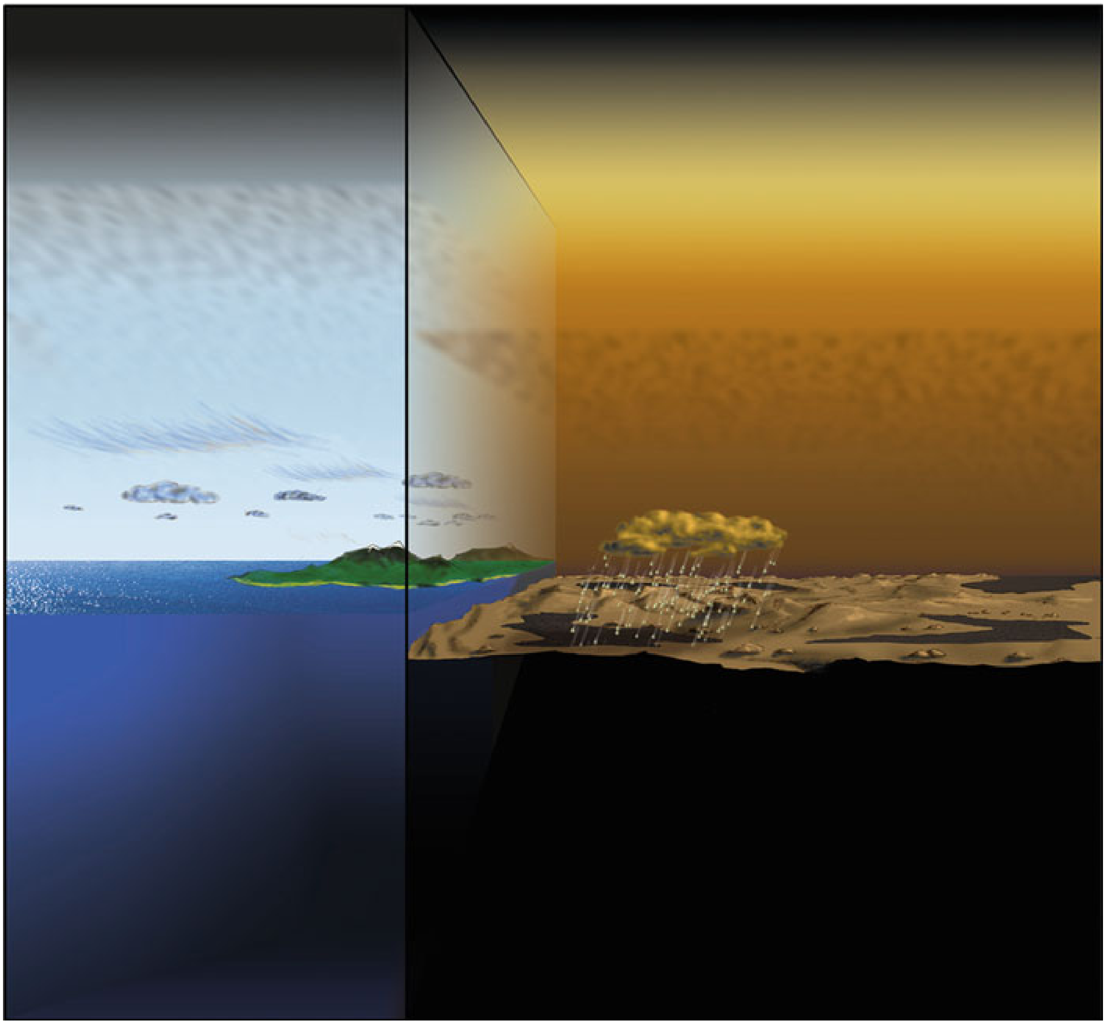


Fig. 4.7 Profile of the atmosphere of Titan, on the same pressure scale as Earth.

is modified by interacting with the rocks or the sunlight, forming for instance acetylene (H_2C_2), ethane (C_2H_6) or more complex molecules like polymers or aromatics. It must therefore be constantly replenished by a cycle. Compared to the Earth's cycles, the water cycle with timescales of hours, and the rock-carbon cycle with timescales of millennia, the methane cycle occupies an intermediate position.

The driving force of the water cycle on Earth is the evaporation of vapour from the surface of the ocean, occurring most intensely over the few hottest hours in the equatorial region. The driving force of the rock-carbon cycle is the volcanic production of CO_2, a slow and episodic process related to the secular motion of the tectonic plates and the convection of the mantle of the Earth over millions of years. The driving process for the methane cycle of Titan is the chemical reaction of the methane molecules with other substances in the atmosphere or on the ground, or with sunlight above the haze.

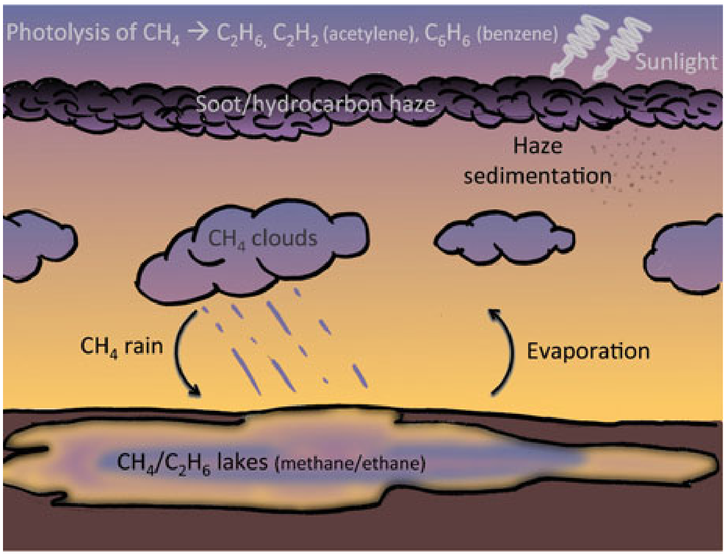


Fig. 4.8 The role of methane in the atmosphere of Titan. Image credit: Joanna Barstow

Iceball Titan

Methane is essential to Titan's atmosphere in another respect. It is a powerful greenhouse gas, transparent in visible light but very opaque towards infrared light. Even the tiny amount of methane that we have in Earth's atmosphere makes an important contribution to the greenhouse effect here, so with methane being the most abundant component after nitrogen on Titan, the greenhouse effect is large. Although the temperature is only –180 degrees Celsius, it would be much lower without methane. So low, in fact, that the temperature would dip below the condensation temperature of nitrogen (–196 degrees Celsius), leading to the collapse of the whole atmosphere. Liquid nitrogen would start flowing and freezing out of the sky, until the whole planet became a frozen, airless body like the other satellites of Jupiter and Saturn.

Maybe one day the methane content of Titan's air will drop below a critical value that will lead to the collapse of its atmosphere. Would Titan then be able to kick itself out of its frozen state and raise the temperature enough for the nitrogen to evaporate and re-form the atmosphere? This is possible, because volcanism keeps injecting methane and other gases into the atmosphere.

In fact this tells us that higher gravity is not the only thing that enables Titan to maintain a thick atmosphere while other slightly smaller satellites of Saturn and Jupiter cannot. Its larger size means that it is also able to keep more internal heat, and therefore maintain more volcanoes to regularly eject gases and replenish its atmosphere.

Cryovolcanism

The volcanoes on Titan are rather different from what we have on Earth. What is spewing out of the frozen ground is not lava and sulphuric gases, but water vapour, methane, ammonia and nitrogen. Because of the extremely low temperatures, in the outer parts of the Solar System, ice plays the role of rocks. Water is a very solid material at –200 degrees Celsius and only far hotter temperatures rising from deep inside the planet can make it evaporate, and explosively escape towards the surface. This is aptly termed *cryovolcanism*.

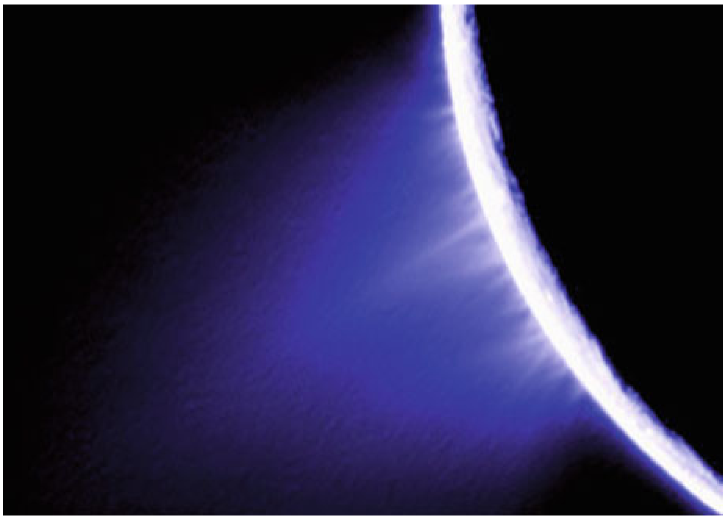


Fig. 4.9 Enceladus "geyser" spraying water vapour directly into space. Image credit: NASA

Cryovolcanism is common on the satellites of Jupiter and Saturn. Enceladus, one of Saturn's smaller moons, regularly emits jets of water vapour and other cold gases into space. In this case the gravity is too low to keep the volcanic plume on the moon, and the gases from volcanoes disperse in space to form a trail of gas around Saturn.

Hot volcanism affects the inner circle of planets (Mars, Earth, Venus and Mercury), and cryovolcanism planets of the outer solar system, but there is one exception: Io, the first satellite of Jupiter, has a rocky surface and hot volcanoes. The reason is that Io is so close to Jupiter that its interior is churned up by its tidal pull to such an extent that it is heated from inside and has become warmer than Titan; so warm in fact that ice has entirely disappeared from the planet. Earth-type volcanoes regularly spit out sulphur, CO_2 and water vapour. Io's gravity is too weak for it to be able to cling onto its gases, so it has no atmosphere and most of the volcanic smoke drifts straight out into space. Only the sulphur compounds, being heavier, fall back onto the surface.

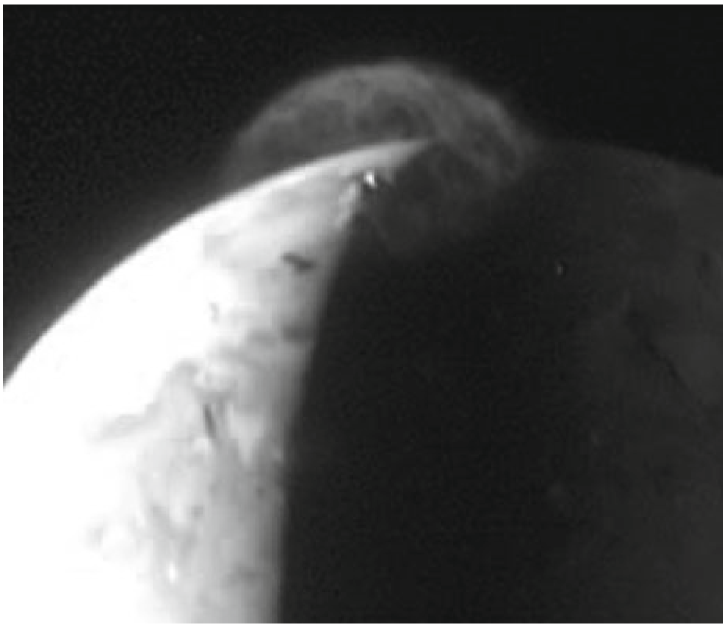


Fig. 4.10 A volcanic erruption on Io. Image credit: NASA

Titan's haze

From space, Titan looks like a smooth orange sphere with fuzzy edges, because of the thick haze that shrouds the whole planet. The haze on Titan is mainly composed of the product of the photochemistry of methane and ethane. Several of these carbon-based molecules have been detected on Titan by the Huygens probe. Strangely enough, many of these are constituents of oil and gas fields on Earth: propane, acetylene, benzene, etc… Titan's weather is a constant "oily drizzle".

If Venus is eerily reminiscent of the medieval image of hell, and Mars is a frozen arctic wasteland (the hell of some Nordic mythologies), then Titan is a more modern kind of hell, a super-cold industrial nightmare.

Photochemical haze vs condensation clouds

Clouds form when part of the atmosphere rises up and cools below the condensation temperature of one of its components. Water, sulphuric acid or ammonia forms grains or droplets when condensing. Because of the requirement of rising currents and temperature changes, clouds are usually associated with atmospheric motions, hence their wonderfully varied shapes and structures.

The haze above Titan is not made up of droplets that condense because of the low temperature, it forms following chemical reactions triggered by the light of the Sun. Chemical reactions that use sunlight are a key element of atmospheric physics that is very remote from our daily experience. They are instances of what is called *photochemistry*, photo being Greek for light.

In ordinary chemistry, as when cooking a stew, boiling an egg, or making aspirin in industrial tanks, some molecules can interact with others to swap atoms and electrons and turn into other molecules. These reactions are generally controlled by temperature. Temperature – random motions of atoms and molecules – is needed so that molecules bump into each other with sufficient velocity to overcome some of the initial repulsion of electrons, until the outer electrons can feel the positive charge of the protons in the nucleus of the other atoms. That's why many reactions have to be started with the heat of a flame, like the combustion of natural gas or wood, until they produce their own heat to keep it going. At absolute zero or –273 degrees Celsius (the temperature at which all atoms stand still) no chemical reaction can happen.

Heat is not the only way to bring enough energy to initiate a chemical reaction, however, sometimes the energy can come directly in the form of light. In photochemistry, an atom or molecule absorbs light to trigger a chemical change.

This happens in photosynthesis, which allows plants to draw energy directly from sunlight. One particle of light, a photon, gets captured by the chlorophyll molecule. It modifies its structure so that it will be able to transmit energy through electron-swapping to a long chain of molecules, to provide useable power for the plant.

The retina in our eye is also able to capture light directly, in reactions that ultimately produce electric currents in nerve cells to inform the brain about the layout of our surroundings.

We have already encountered two instances of photochemistry in planetary atmosphere. The ozone layer on Earth is caused by the reaction of oxygen with sunlight.

On Venus, sunlight dissociates the sulphur dioxide in the atmosphere into more active molecules, which then react to form the grains and droplets that make up the clouds of the planet.

At ground level on Earth, photochemistry can act on some chemical pollutants to form larger compounds, which can aggregate into particles and give a perceptible brownish hue to the air – the industrial smog that can form over cities on windless summer days.

On Titan, the photochemical haze contains dozens of carbon compounds. Why don't these complex carbon molecules form in Earth's atmosphere? After all, there is much more sunlight on Earth, and at least as much carbon.

The key difference is a spectacular feature of our atmosphere that we have encountered in Chapter 1: with 20 percent oxygen, our atmosphere is so reactive that complex carbon compounds cannot last long in the air. Their carbon chains get ripped apart and carbon atoms are captured by oxygen to form CO_2. In everyday language, they burn. Our atmosphere is so thick with reactive oxygen that anything that can react with oxygen will do so, given time.

Life in liquid methane

With such a rich, carbon-based chemistry and the most Earth-like weather system we know of, could Titan possibly harbour life?

Not our kind of life; life on Earth requires liquid water, and on Titan all the water is frozen. Water is essential to life as we know it, as a solvent and a matrix in which all the molecules of life can interact and go about their business. A liquid solvent is thought to be essential to the chemistry of life, because chemical reactions in solid material tend to be slow and difficult, while in gases they are too random and scattered. Water provides the gentle but firm continuum that proteins, nucleic acids, sugars and lipids require to prosper.

Could liquid methane do the trick? This is a very difficult question, since nobody knows how a methane-based life system would work. It is difficult enough to understand life on Earth, and with only one example of life having appeared, it is even harder to distinguish the essential from the accidental. Nevertheless, using our present understanding, some people have tried.

As a solvent, methane is weaker than water. Because of its lower temperature and weaker electric properties, methane can dissolve smaller molecules than water can. The kinds of sugar that we use as a source of energy, for instance, would be too large for methane, and would simply sink. There are, however, a good number of carbon compounds that can dissolve in methane, including some phosphate molecules that would be too fragile at our kind of temperatures.

How many molecules would be enough to sustain life? One attempt to address this question is to consider how many different molecules are used in the basic operations of a living cell on Earth. Present estimates put this number around 700. Many more carbon compounds dissolve in water, so life on Earth has a comfortable selection of molecules to choose from. In methane the total number of molecules that can dissolve is only a few hundred, which may be sufficient, but barely.

At present I think most specialists would say that methane-based life is not entirely excluded, but requires stretching the chemical possibilities to their limits.

How would we detect methane-based life on Titan? Short of spotting a methanoid moose crossing the field of vision of a probe's camera, the best way is to analyse the composition of the atmosphere and look for the kind of disequilibrium that life has created on Earth. In the same way that life on Earth has given itself away by poisoning the atmosphere with 20 percent of reactive oxygen, the methane life of Titan could be producing unstable compounds which we could detect in its atmosphere.

The big question when pondering the possibility of life outside Earth is to assess how earth-centered we are in our assumptions about life in general.

Living atmospheres

There is probably no life on Titan. Nevertheless, there is another way, more metaphorical, in which it can be helpful to consider some atmospheres as a living system.

Sometimes, when some systems become complex enough, they start behaving like more than the sum of their parts. Think of an *ecosystem* on Earth for instance. It may be made up of living creatures, but the ecosystem as a whole is not a living creature. Scientists have found that complex ecosystems can be very resilient. The intricate relationships between their constituents makes then able to deal with circumstances in a much better way than simple systems.

An important feature of the properties of complex systems, that makes them seem alive in a certain sense, is the presence of cycles. Feedback loops allow regulation. Cycles like the methane cycle or rock-carbon cycle introduce such loops into planetary atmospheres, and some researchers have suggested that the analogy with living systems may be useful.

At the extreme, the "Gaia" view of the Earth posits that the atmosphere of our planet has now reached such a state of intricacy that it functions more like a living system than a physical system. Feedback loops allow it to control its temperature and the composition of the atmosphere, maintaining the optimal conditions for life.

An early example of how this kind of system could work was given by the imaginary *Daisy world* planet. This is a simple model of a planet covered with plants. When the temperature gets too hot, some plants die. This makes the surface of the planet brighter, because deserts and rocks are lighter in colour than forests and vegetation. As a result, more sunlight gets reflected into space, and the temperature cools. In Daisy world, life regulates the temperature of its planet through a simple feedback mechanism.

Living organisms use this kind of regulating mechanism very often; there are many examples in our own body, control loops that allow us not only to maintain a constant temperature, but also fight off infections and keep track of time.

The atmospheres on Earth and on Titan seem complex enough for such system-level properties to be present.

Is this true for all atmospheres? Probably not. For instance, the atmosphere of Mars is so light that it doesn't seem to have the capacity to control its own fate. In summer, intense sunlight can send the whole planet into a dust storm. In winter, the atmosphere collapses onto the poles.

Whether complex planetary atmospheres – and that of Earth in particular – can be well understood as physical systems, or whether they can also be likened to living systems, have important consequences for us as we try to come to terms with the issue of climate change.

In the first case, climate models tell us that an increase in the carbon-dioxide content of the atmosphere will heat the climate catastrophically. In the second case, however, the Earth's climate is much more resilient than we think, and feedback mechanisms will react to keep the climate around its present state. This is not necessarily as good news as it sounds, because resilient systems tend to absorb strain up to a certain point, then "snap" abruptly (not unlike the way the human brain deals with trauma). In that case, our atmosphere may succeed in handling the changes for some time, but there may be a snap lurking just behind the corner.

At present, the balance of evidence is rather against the existence of a "Gaia" condition for Earth, at least from the point of view of global warming. The best evidence is provided by an event that happened at the dawn of the age of mammals, in the Eocene some 60 million years ago. This event and its consequences on the climate have been recorded in detail by rocks and sediments.

A huge volcanic eruption at that time briefly doubled the concentration of CO_2 in the atmosphere. Global temperatures then spiked by 4–5 degrees Celsius for a few thousand years, as measured by indicators such as the concentration of oxygen isotopes in sea shells. This is as expected if the climate was reacting passively to the added greenhouse effect, without any feedback mechanism to mitigate the change.

Another indication is the occurrence of planet-wide ice ages, or "snowball episodes", in the history of the Earth. In this case the feedback goes in the wrong direction: colder temperatures increase the ice cover, which makes the planet more reflective and reduces the amount of sunlight absorbed. It seems that life and the atmosphere were not able to do anything about it in the past. The planet was brought back to a milder climate only by volcanoes, not by any sophisticated resilience mechanism.

Being there

What would it be like to stand on Titan? The cold would be terrible, but we could shelter in sophisticated heated habitats like those of the Concordia research station in Antarctica. The air is mainly made of nitrogen like on Earth, which is nice, and the atmospheric pressure is bearable. Neither methane nor ethane are toxic, and they are not flammable on Titan because of the lack of oxygen. We would need oxygen to breathe of course, but light oxygen masks like in hospitals or airplanes could do the trick.

Outside everything would be rather dark, because the Sun is so far away. The sky would be a pale, uniform glow. Days last for 15 Earth days, so there would be one week of darkness every fortnight.

One detail that we may notice outside is that sound travels much more slowly in very cold air. The horn of the returning exploration vehicle would sound much lower than normal (the opposite of the "funny voice" effect of Helium gas), and the noise of construction machines in the distance would seem to take forever to reach us.