Lifting Titan's Veil

Exploring the giant moon of Saturn

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CHAPTER 1

The landscape seems alien. The few clouds that burned a garish red as the Sun set have flitted away and the sky is clear. Strange and unfamiliar life-forms, deprived of water, struggle to survive in the harsh conditions. This is no extraterrestrial scene though, but Tucson, Arizona. Arizona's commendably dark and clear skies are a magnetic attraction for astronomers.

High above, Jupiter gleams brilliantly. Through even a small telescope, an entourage of four moons circling this giant planet and its cloud bands alternating light and dark are obvious. A short distance to the east there is another planet, not as bright as Jupiter. It's Saturn. Through the telescope it is an altogether different object, with its rings tilted tastefully – as though a jeweller had set it there. A little to one side of the rings is a dim, unprepossessing dot, looking a little reddish maybe. This dot is the focus of our attention – Saturn's moon, Titan, a world as intriguing as any in the solar system.

On the 15th of October 1997, another Titan roared into the sky. To be precise, it was a Titan IVB/Centaur launch vehicle. Just before 5 o'clock in the morning local time the appropriately named rocket blasted off from Cape Canaveral Air Force Station, Florida, bearing a 5.8-tonne spacecraft bound for Saturn and Titan. It was the start of a seven-year journey for the *Cassini–Huygens* mission and of a tantalising seven-year wait for the anxious scientists on the ground. *Cassini* was destined to enter orbit around Saturn on the 1st of July 2004. Seven months later, if all goes according to plan, the *Huygens* probe will detach itself, cruise towards Titan for about three weeks, then parachute down onto Titan's surface. Instruments on board the *Cassini* orbiter will gather data about Saturn and its moons, espe-

Figure 1.1. The launch of the *Cassini–Huygens* mission on the 15th of October 1997 at 4.43 a.m. EDT, from Cape Canaveral Air Station in Florida. The launch vehicle was a Titan IVB/Centaur. NASA image. (In colour as Plate 1.)

cially Titan, over a four-year period. Then Titan will become the most distant world by far to have a human artefact land upon it. The enormous effort dedicated to achieving this feat is a testament to the growth in our fascination with Titan as world of unique significance in the quest to understand our own planet.

To see how Titan became the centre of such attention we must first turn the calendar back to the middle of the seventeenth century.

Galileo and the Saturn enigma

When Galileo Galilei turned a crude, low-powered telescope to the sky he opened a new era in astronomical discovery. News of the Dutch invention had spread through Europe like wildfire in the early part of 1609. Telescopes constructed from badly made spectacle lenses were being offered for sale at fabulous prices, even though the views through them were blurred. At the University of Padua, where he was professor, Galileo had set up a workshop for making scientific instruments and had acquired a deserved reputation for skilled craftsmanship. In the space of a few weeks, Galileo carefully ground lenses from the finest Venetian glass and built the best telescope in the world. It brought him instant international fame and was the first of many to be manufactured by his workshop.

Galileo began a survey of the heavens in 1609 using a telescope that gave him a magnification of 30 times. He was the first person to direct a telescope skywards and make a record of what he saw. Wherever he turned his gaze, new and amazing sights greeted him. A family of moons belonging to the planet Jupiter was one of the most significant. With a series of observations made between January and March 1610, Galileo demonstrated that four bright 'stars' near to Jupiter were not stars at all but moons orbiting around the planet. This discovery was not merely of scientific interest. It was political dynamite! It was a powerful piece of evidence in favour of a Sun-centred planetary system, which contradicted the religious dogma of the time. Nicolas Copernicus's heliocentric theory had been in circulation since 1543 but had not been generally accepted. Its lack of appeal was partly because it undermined the authority of the church and partly because it did not square with actual observations of the planets and the philosophical reasoning prevailing at the time. One of the arguments against Copernicus claimed that the Moon would be left behind if Earth moved. Newton's theory of gravity would not be published until 1684, so the concept of an attractive force to keep moons tied to their planets was some years off. Now here was Jupiter, indisputably going around the Sun, with moons that did not get left behind.

Galileo recorded his first observations of Saturn in July 1610. Having found four moons in orbit around Jupiter, he must surely have been on the lookout for satellites of Saturn. But either he failed to detect Titan, or he did not recognise it as a moon of Saturn. His telescopes may not have been good enough to discern the dim reddish

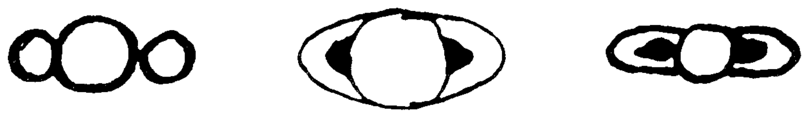

Figure 1.2. Three sketches of Saturn made by Galileo in 1612. He thought that the appendages he could see on either side of the planet might be stationary moons of some kind and never realised that Saturn was surrounded by a ring system.

speck, or he may have been led into a blind alley by the puzzling appearance of the ringed Saturn. Galileo thought that the appendages he detected on either side of Saturn were moons of some kind, though they were clearly different in character from Jupiter's moons. Galileo remained baffled throughout his life. He never realised that his apparently triple Saturn was in reality a planet surrounded by a set of rings. The privilege of discovering Saturn's largest moon was to fall to a gifted young Dutchman who would ultimately earn a reputation as one of the greatest scientists of the seventeenth century. His find was no quirk of chance but the reward for a major advance in telescope making.

Luna Saturni

Christiaan Huygens discovered the moon we now know as Titan on the 25th of March 1655. He announced the find publicly a year later, in a pamphlet called *De Saturni luna observatio nova.* The telescope he used was cumbersome by modern standards but in 1655 it was a technical breakthrough. In collaboration with his brother Constantyn, Christiaan Huygens developed a machine for grinding and polishing lenses that made use of gears. Until the Huygens' invention, lenses were all ground and polished by hand. The process was laborious and it had proved very difficult to make the gently curved long-focus lenses that gave the least distortion in a telescope. Using their new machine, the Huygens brothers experienced little difficulty in producing long-focus lenses. The first to be incorporated as the main lens of a telescope had a focal length of about 3.6 m. This meant the telescope had to be almost 4 m long. A closed tube was out of the question and the main lens was mounted high up on a pole (Figure 1.4). A lens giving a magnification of 50 times served as an eyepiece. When Huygens turned his lanky telescope on Saturn, he noted a small point of light close enough to the planet to raise suspicions of an association

Figure 1.3. Christiaan Huygens (1629–1695), who discovered Titan in 1655.

between the two. Observing on subsequent nights, he saw the speck of light complete a circuit around Saturn over a period of 16 days. Innovation had paid off.

Englishman Christopher Wren, better known as an architect than for his early research in astronomy, and the German Johannes Hevelius both testified later that they had observed Titan through their telescopes before Huygens did but had never suspected it was anything other than a background star. The history of astronomy is full of such sorry tales of 'pre-discovery' observations by individuals who have lived to regret their lack of perception, or died without ever knowing what they missed. Indeed, Galileo never knew he had seen the planet Neptune.

Huygens had a rare combination of talents. Like Galileo, he was a practical inventor and skilled craftsman as well as being a brilliant mathematician and prolific writer. One of his greatest achievements was developing the wave theory of light but, in the late 1650s, between observations of Saturn, he was busy inventing and perfecting the pendulum clock. All the same, he found time to write *Systema Saturnium*, which was published in 1659. Saturn's mysterious appendages had remained unexplained since Galileo first reported them in 1610.

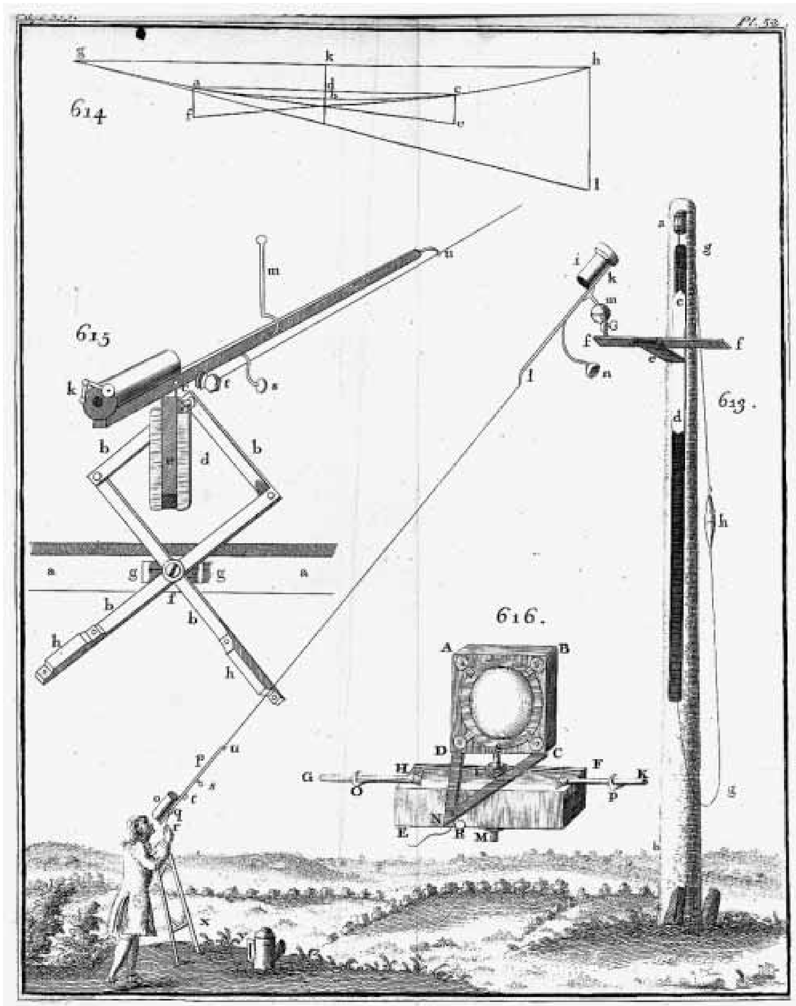

Figure 1.4. The 'aerial' telescope that Huygens was using when he discovered Titan, as illustrated in a treatise of 1738, *Compleat System of Optics* by R. Smith. Photograph courtesy of the Royal Astronomical Society.

Struggling with telescopes that were not up to the job, the handful of observers who tried simply could not make sense of what they were seeing. With the advantage of the superior telescopes he made for himself, and a brilliant mind, Huygens resolved the mystery once and for all. A thin flat ring around Saturn's equator could explain every feature of the telescopic observations recorded in the previous 39 years. The discovery of Titan orbiting Saturn in line with the 'appendages', Huygens said, was the key that led him to his correct conclusion. It was to be 198 years before another great physicist, James Clerk Maxwell, proved that the rings must themselves consist of countless miniature moonlets.

To Huygens, the world he discovered was both faceless and nameless. His seventeenth century telescopes were not remotely capable of seeing Titan as a disk and the idea of giving moons individual names didn't catch on until the middle of the nineteenth century. Huygens referred to the moving point of light simply as Luna Saturni – Latin for 'Saturn's moon'.

Over the next 30 years, the tally of moons was raised to Jupiter 4, Saturn 5. But for a long time that was it. No more moons were discovered anywhere in the solar system until 1787 and the question of names never arose. For over 100 years, the four moons of Jupiter and the five moons of Saturn were designated by Roman numerals, in order of distance from their parent planet. The system was practical enough, if unimaginative. Then in 1787, William Herschel spotted the satellites of Uranus we now call Oberon and Titania. Two years later he followed them up with two more moons of Saturn. Inconveniently, they were nearer to Saturn then the other five. What was to be done? Numbering them VI and VII would play havoc with the ordering system but re-numbering all the moons would lead to worse confusion. Not surprisingly, confusion reigned.

William Herschel's son John came up with the solution. Give moons names. Then whatever numbering system is finally adopted, at least each world is individually identified. The discovery in 1848 of Saturn's eighth moon, also out of keeping with the original order, clinched the matter. The astronomical world gratefully accepted John Herschel's names. Drawing on Greek mythology for names connected with the god Saturn – or Cronus as his equivalent deity was known in Greek – Herschel gave us Mimas, Enceladus, Tethys, Dione, Rhea, Titan, Hyperion and Iapetus. In some ways, Titan was a strange choice. Unlike the others, it was not the name of an individual but the collective name for six of the male offspring of Uranus and Gaia. Cronus, Hyperion and Iapetus were Titans. Mimas and Enceladus were two of 24 giants who were also brothers to Cronus. The female deities Tethys, Dione and Rhea were his sisters.

Dark ages

Titan's existence was known and its period of revolution around Saturn roughly determined but that was virtually the state of knowledge about Titan for more than 200 years. While increasingly powerful telescopes opened up unimagined vistas on the universe at large, the moons circling the planets of the solar system – Titan included – remained as diminutive points of light, stubbornly beyond reach. Astronomers largely turned their attention to other things, while research on moons was forced to endure long dark ages. Enlightenment would not really arrive until the space era.

Even building the list of saturnian moons proved to be a tedious process. Huygens discontinued his search after finding Titan in 1655. A quaint belief in numerology apparently led him to conclude that the inventory of the solar system must be complete. Unscientific reasoning of that kind by someone of such ability seems extraordinary from our perspective in the twenty-first century but this was an era when people ardently looked for divine harmony in the construction of the heavens. In the event, Huygens' subsequent lack of interest left the way clear for Giovanni Domenico Cassini.

Cassini came from Italy but in 1669 he was lured to Paris by King Louis XIV to direct the first observatory there. He became a French citizen in 1673 and was known afterwards as Jean-Dominique Cassini. With a relatively modest telescope he discovered Iapetus in 1671 and

Figure 1.5. Giovanni Domenico Cassini (1625–1712). He discovered the moons of Saturn now known as Iapetus, Rhea, Dione and Tethys, and the Cassini division in the ring system. After becoming a French citizen in 1673 he was known as Jean-Dominique Cassini.

Rhea in 1672. Using a more powerful instrument, he brought the total of known saturnian moons to five with his 1684 discovery of Dione and Tethys. Cassini was also the first to draw attention to the dark gap in Saturn's rings now universally known as the Cassini Division.

Next to add to the slowly growing catalogue of Saturn's satellites was William Herschel. Few celestial targets escaped the attention of this eagle-eyed musician-turned-astronomer from Hanover, who became internationally famous after discovering Uranus in 1781. In 1789, Saturn's rings appeared edge-on as viewed from Earth. In effect, they virtually disappear from view for several weeks. This made it easier for Herschel to detect for the first time two faint inner satellites that would be known as Mimas and Enceladus. But that was not all. Herschel made numerous observations of all seven of the moons he was aware of, computing the time each one took to make a revolution around Saturn. With further refinements from other observers, Titan's period of revolution was pretty well determined by the 1840s. The German astronomer Friedrich Wilhelm Bessell quoted 15 days 22 hours 41 minutes 24.86 seconds, only about half a second out from the modern accepted time.

In the nineteenth century, the study of how heavenly bodies move – the science of celestial mechanics – became highly sophisticated. Minute variations in the courses of the planets and their moons could be explained when the small gravitational tugs they each give the others were taken into account. John Couch Adams in England and Urbain J. J. Leverrier in France predicted that there was a planet beyond Uranus by assuming that its gravitational influence was responsible for pulling the errant Uranus off course. Not only that, they pinpointed where the unknown planet would be found. The discovery of Neptune in 1846, just as predicted, was a triumph for the mathematicians. In similar fashion, there were data to be gleaned about Titan's mass from the way it pulled its fellow moons around.

Saturn's eighth moon, Hyperion, proved to be the vital key in this ingenious exercise. Hyperion was discovered independently by William C. Bond at Harvard University and the noted English amateur, William Lassell, in September 1848. By an amazing coincidence, both became satisfied that they had found a new saturnian satellite on the night of the 19th. Hyperion turned out to be Titan's nearest neighbour in the saturnian family and it soon materialised that the pair interact in a remarkable way. To explain how, we should take a closer look at their orbits.

The orbits of all planets and moons are elliptical but some are a great deal more elliptical than others. Although Titan's orbit is close to being circular, Hyperion's is noticeably elongated. Saturn sits off centre, so Hyperion's distance constantly changes, swinging between 1.33 million km at one end of its orbit and 1.64 million km at the other. Titan meanwhile ranges between 1.11 and 1.26 million km from Saturn. The two orbits are not tilted to each other. Titan's is nested inside Hyperion's, like rings on a target.

Now imagine lining up Titan and Hyperion on the same side of Saturn. We put them where Hyperion is at its greatest distance from Saturn, so they are both on the long axis of Hyperion's orbit. The starting gun fires and the two take off like athletes racing around a track, except that this is an unfair competition. According to the laws of planetary motion, the more distant a moon lies from its planet the slower it's forced to go. Titan will lap Hyperion sooner or later. In fact, Titan catches Hyperion when it's made exactly four circuits, about 64 days later. What's particularly interesting is the fact that the pair are virtually back at the starting blocks, because Hyperion has done three laps in the same interval of time. Astronomers have a technical expression for this phenomenon. Hyperion and Titan are said to be in a 3:4 resonance.

Real life situations are rarely simple. In the case of Hyperion and Titan, the catch-up position isn't exactly where the two started on the long ('major') axis of Hyperion's orbit. But it's a welcome complexity for astronomers who would like to estimate Titan's mass. Titan's pull on Hyperion wants to bring the line-up back to the starting position. Over time, the interaction between Titan and Hyperion causes the Saturn–Titan–Hyperion line to swing from one side of Hyperion's major axis to the other, like a pendulum. The most it deviates is 36° and the time for a complete swing is 640 days. Crucially, the time-scale of this pendulum-like action in the line-up of the two moons is set by the mass of Titan. Several mathematicians worked on the motion of Hyperion in the 1880s, including the American George W. Hill. Hill determined that Titan's mass was 1/4714 that of Saturn. The 'modern' value is 1/4262, so Hill was about 20% off – not bad at all.

The incident of the Spanish eyes

There is no doubt that some individuals are gifted with exceptionally acute eyesight. Their problem is convincing everyone else – ordinary mortals with normal vision – that they really see what they claim. If no-one else is capable of seeing what you see, who is to say whether your description is genuine or not? Even if you are later proved correct, your interpretation could be put down to a lucky guess. If you seem to be claiming a feat of visual acuity way beyond most people's capability, you can expect some healthy scepticism.

In the early twentieth century, many astronomical observations were still made by eye. Observers would look through their telescopes and sketch what they saw. This is a technique still widely favoured over photography by amateur observers of the planets, and for good reason. Incessant motion within the atmosphere causes images to squirm like jellyfish. It is rather like looking at a coin on the bottom of pool stirred by the wind or swimmers. Expose the dancing image to a camera for more than a fraction of a second and you have a blur. By comparison, the trained human eye, with its fast link to the brain, is capable of capturing in memory fleeting moments of clarity. Nature has its moments of benevolence too, donating periods of relatively steady 'seeing' from time to time.

José Comas Solà observed Titan with a 38-cm telescope at the Fabra Observatory in Barcelona, Spain, on the 13th of August 1907. He wrote:

> . . . with a clear image and using a magnification of 750, I observed Titan with very darkened edges (somewhat similar to those one observes on the disk of Neptune), while on the central part, much brighter, one sees two round, whiter patches, which give the appearance of a blurred

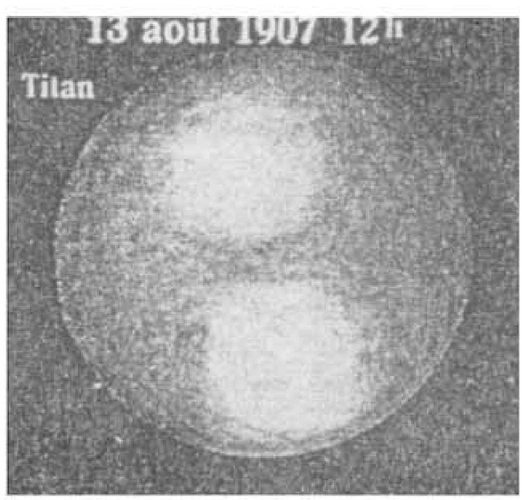

Figure 1.6. The sketch of Titan made by José Comas Solà in 1907 and published in 1908 in the *Astronomische Nachrichten* (Nr 4290, p. 287). The darkening around the periphery of the disk is believable but the two bright spots are hard to explain.

> double star. We may suppose reasonably, that the darkening of the edges demonstrates the existence of a strongly absorbing atmosphere around Titan.

It is the first hint that Titan has an atmosphere. But could he have genuinely made such an observation? The claim certainly stretches credibility to its limits. At the time it was not generally taken seriously and it was never repeated. But it was there in print. Thirty-six years later, indisputable evidence of an atmosphere around Titan would raise the intriguing question of whether Comas Solà was the first to discover it. By then the Spaniard had been dead for seven years. With hindsight, how convincing was his evidence? Would it convince a jury in a court of law, beyond reasonable doubt?

What Comas Solà claimed to have observed was a disk fading off in brightness between the centre and the edge, making it substantially darker all around its periphery. A solid planet or moon without an atmosphere, such as our own Moon, does not look like this. Its disk is bright all over, with a hard edge. We can say today that this edge darkening certainly affects Titan's appearance but it is difficult to detect even with the best of modern telescopes. Was it technically possible for Comas Solà to see it by eye with his modest telescope?

We have to bear in mind the apparent size of Titan's disk. Titan is 5150 km across, say 5400 km when we add the substantial thickness of its hazy atmosphere. But Saturn is typically ten times farther from the Sun than Earth. When Comas Solà observed Titan in August 1907 it was more than 1.3 billion km away. Its disk is so small that 2000 Titans in a row would just stretch from one side of the Moon to the other. It was rather like looking at a golf ball 15 km away.

Even with perfect conditions in the atmosphere (or no atmosphere at all), the level of detail someone with normally good eyesight can distinguish is still limited – by the physical dimensions of the telescope. A telescope with a large main collecting mirror or lens can resolve finer details than a smaller telescope. A simple mathematical formula gives the size of the smallest features a particular telescope can separate. The calculation for Comas Solà's telescope says the smallest things it can distinguish are half or three-quarters the apparent size of Titan. In other words, Comas Solà was operating at the absolute limit of what his telescope could do when he spotted lighter and darker areas on Titan. Even under the best of conditions he shouldn't have been able to see much.

However, there is some persuasive evidence that Comas Solà's visual powers did verge on the superhuman. In the report that contains the Titan observations, he presents drawings of Jupiter's satellites Callisto and Ganymede. The broad features he sketched compare reasonably well with what we now know about the surfaces of these moons. He also suggested that Jupiter's closest large satellite, Io, looked flattened, pulled, he supposed, into a lemon shape by Jupiter's gravity. Although Jupiter's gravity has overwhelming consequences for Io, driving violent volcanism, Io isn't deformed nearly enough to see by eye. However, Io's polar regions are darker than the rest of its surface, so it may well have looked distorted to Comas Solà. Does this prove that all his observations were genuine? No-one can be certain what the verdict should be but the evidence for the defence cannot be ignored. In science, though, being right often isn't enough: you have to be right in such a way that other scientists can check that you're right. Since no-one else could verify the observation it is difficult to argue that Comas Solà 'discovered' the atmosphere.

Nevertheless, at least one person whose opinion counted regarded the report as credible. He was the distinguished British astrophysicist Sir James Jeans. Jeans's first book, *Dynamical Theory of Gases*, was initially published in 1904, before Comas Solà's observation but, in an edition published in 1925, Jeans applied the theory to Titan.

The dynamical (or kinetic) theory of gases says that many aspects of the behaviour of a gas are predictable if one imagines it as a collection of molecules whizzing about at speed, constantly colliding and bouncing off each other in a manner resembling a fantastic game of three-dimensional snooker. The hotter the gas, the faster the molecules go.

Without something to confine it – a box for example – a gas will quickly disperse as the molecules shoot off in every direction. In an atmosphere around a planetary body, the gas molecules are pulled towards the planet by gravity. Gravity acts rather like a box, but a leaky one without a lid. If any of the molecules near the top of the atmosphere gather enough speed to exceed the escape velocity, they can disappear into space and be lost from the atmosphere for ever. So there's a balancing act between the gas's natural tendency to spread out in all directions and the restraining force of gravity. A body has the best chance of hanging on to its atmosphere if (a) it's massive – so its gravity is strong, (b) the gas molecules are themselves relatively heavy, and (c) it's cold – so the molecules generally move slowly and don't reach escape velocity.

Jeans noted that, in the frigid depths of the solar system where Saturn and its moons orbit the Sun, Titan's gravity would be strong enough to retain an atmosphere for as long as the solar system has existed. His decision to introduce the case of Titan was no coincidence. Here was a splendid opportunity to put the kinetic theory of gases to work. Though Jeans says that an atmosphere has been discovered, frustratingly, he does not give his source of information, but it's fair to presume it must have been Comas Solà. Jeans's calculations showed that light gases, such as hydrogen and helium, would easily escape. If Titan was proved to have an atmosphere, it was going to consist of heavier molecules. Leading candidates included argon, neon, nitrogen and methane.

The methane fingerprint

With rare exceptions, astronomers can never hope get their hands on material from the objects they study. But even though samples of matter are out of the question, energy samples arrive unsolicited. Light and its invisible relatives – ultraviolet and infrared radiation and radio waves, for example – are there for the taking with the right telescopes and instruments. Fortunately, many of the substances in stars, planets, or indeed anything that shines, indelibly impress their unique fingerprints on the energy they radiate away.

Extracting the tell-tale fingerprints from a beam of light is achieved by spectroscopy – a process rather like disentangling a vast skein of multicoloured yarn of various lengths. Each colour corresponds to a different wavelength and the length of thread represents the intensity of the light in that individual colour. The signature of a particular chemical is a unique combination of threads with certain lengths and colours.

For scientific analysis, a spectrum has to be transformed into a trace, displaying the ups and downs of light intensity with wavelength. Common features in such spectrum traces have their own descriptive expressions in the scientific jargon. A series of closely spaced narrow dips, which may appear to be merged together to make a single broad dip, is an 'absorption band', for example. The fingerprints of molecules typically take the guise of absorption bands.

In the winter of 1943–44, the Dutch–American astronomer Gerard P. Kuiper used the 82-inch (2.08-m) telescope at the McDonald Observatory in Texas to record the spectra of the ten largest moons in

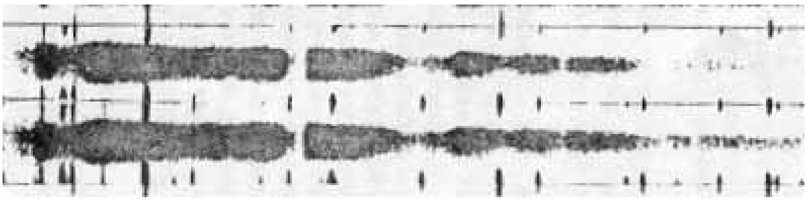

Figure 1.7. Two of Gerard Kuiper's photographic spectra of Titan, taken in the winter of 1943–44 with the 82-inch (2.08-m) telescope at the McDonald Observatory in Texas. They were published in the *Astrophysical Journal* in 1944 (vol. **100**, p. 378). Wavelength increases from left to right. They are negatives, so the methane absorption bands, which disclosed the presence of an atmosphere on Titan, appear as light gaps in the broad, dark, horizontal strips. The short vertical lines are wavelength reference marks.

the solar system in both visible light and the near infrared. This exercise was challenging at that time and had not been attempted before. The telescope was still relatively new, having been completed in 1938.

Kuiper's spectrum of Titan immediately stood out from the rest. Uniquely, it contained absorption bands identified with methane gas. Titan's orange hue was also apparent in the data, confirming what many an observer had noted by eye. Though a link with the atmosphere was an obvious connection to make, Kuiper could not know at that time whether the surface of Titan or the atmosphere itself was responsible for Titan's distinctive colour. Kuiper published his results in a paper under the title *Titan: A satellite with an atmosphere.* While James Jeans had shown decades earlier that physics and chemistry allowed Titan to have an atmosphere, the proof of its existence was still for many a startling revelation.

Unlike Comas Solà's obscure and unrepeated observation, Kuiper's evidence was clear and indisputable: Titan was no run-of-the-mill satellite. Yet the strong signature of methane was far from the last word on Titan's atmosphere. The bigger story would have to wait until 1980 and the arrival the *Voyager 1* spacecraft. Now we know that methane, which trumpets its presence with a strong spectral signature, accounts for a mere few per cent of Titan's atmosphere at most. Its publicity-shy but more abundant partner turned out to be nitrogen. As in Earth's atmosphere, the nitrogen atoms pair up to form molecules, N_2. Together, nitrogen and methane weigh down on Titan with a pressure one and half times greater than atmospheric pressure on Earth.

Voyager 1 reached Saturn in November 1980 after a journey lasting just over 13 years. Its encounter with Titan was brief but intimate.

The craft closed in to a mere 4394 km from the surface at nearest approach, its camera and full arsenal of instruments trained on the mysterious moon. In the 1970s, before *Voyager 1*'s arrival, astronomers began to suspect that Titan's atmosphere contains clouds and haze. Yet they held out the hope of gaps – a glimpse perhaps of the surface below. But it was not to be. *Voyager*'s camera, sensitive to visible light, returned images of a moon comprehensively swathed in a global blanket of orange smog. It was a disappointment but not so great a surprise. Ultraviolet light from the Sun breaks up the molecules of methane and nitrogen in Titan's upper atmosphere, releasing the ingredients to cook up a soup of complex chemicals. Some of the new substances created from the dismembered fragments are probably polymers – large, chain-like molecules. According to *Voyager 1* data, the dark particles suspended high above Titan's surface are about 0.2 to 1.0 micron across. No-one knows the details of their chemistry for sure. Whatever their nature, they are guilty of concealment and of provoking intrigue on another world a billion miles away.

A singular satellite

Titan's atmosphere is distinctive, fascinating and unique in the solar system, imbuing its owner with the qualities of a true planetary world according to all our preconceptions of what moons and planets should be like. Reinforcing this notion of planetary status, the composition of Titan's nitrogen-rich atmosphere is beguilingly similar to Earth's and unlike every other substantial atmosphere in the solar system. Not only that, the pressure and density of the atmospheres surrounding Earth and Titan are similar. No other world's atmosphere matches Earth's so closely in this respect. But there the similarities between Earth and Titan end. The trace gases in the two atmospheres are very different, largely because of the low temperature on Titan.

As a moon of Saturn, Titan is firmly in the 'outer' solar system. This means that it is cold – very cold. Its surface is 180 °C below zero – or 94 K on the absolute temperature scale preferred by scientists. It means also that Titan is made of a mix of ingredients different from those familiar on Earth and the other terrestrial planets, which are made almost entirely of rock and metal. Titan, like most of the other bodies in the outer solar system, is composed mainly of ice. Carbon dioxide and water vapour, minor but significant gases in Earth's atmosphere, are frozen solid on Titan. Instead, Titan's atmosphere boasts a cocktail of carbon-based chemicals, including ethane, acetylene and carbon monoxide.

In some respects Titan is like the planet Venus. Both have atmospheres that are thick and opaque to sunlight and both rotate slowly. This combination appears to lead to fast winds in the upper atmosphere, which zip around from east to west. In another sense, Titan is faintly reminiscent of Mars, in that the tilt of its equator results in pronounced seasons and the movement of atmospheric gas from the summer hemisphere to the winter one. On Mars, where the atmosphere is thin, the effect is huge: carbon dioxide frost evaporates in the summer hemisphere and snows out on the winter hemisphere. Atmospheric pressure changes by around 30%. On Titan, with its much thicker atmosphere, the effect is much more subtle. The haze high in Titan's atmosphere seems to be driven from the summer hemisphere to the winter one – changing Titan's brightness quite dramatically as it moves.

The magnificent seven

Larger than Mercury and Pluto, Titan was thought for a long time to be the most sizeable satellite in the solar system but *Voyager 1* set the record straight. As it turned out, Titan's solid globe, with a radius of

Figure 1.8. A montage of the seven largest planetary satellites in the solar system (see Table 1.1). From left to right, top row: the Galilean moons of Jupiter, Ganymede, Callisto, Io, Europa; bottom row: the Moon, Titan, Triton. NASA images. (In colour as Plate 2.)

Table 1.1. *The 'magnificent seven', Mercury and Pluto*

Name	Moon of	radius (km)
Ganymede	Jupiter	2634
Titan	Saturn	2575
Callisto	Jupiter	2403
Io	Jupiter	1821
The Moon	Earth	1738
Europa	Jupiter	1565
Triton	Neptune	1353
Mercury	—	2439
Pluto	—	1150

2575 km, is fractionally smaller than Jupiter's moon Ganymede. Titan appears superficially larger than Ganymede because of its thick atmosphere rendered opaque with haze.

A total of seven satellites in the solar system surpass Pluto in size. Ganymede and Titan head the list of this 'magnificent seven'. The remaining Galilean moons of Jupiter – Io, Europa and Callisto – account for a further three. The other two in the club are our own Moon and Neptune's satellite, Triton. Size sets these seven in a class on their own above the other 60-odd (a number that increases year on year). Their nearest challengers come in with radii under 800 km.

The four large planets of the outer solar system each play host to a substantial swarm of satellites. Many of these moons are small irregularly shaped chunks, their dimensions reckoned in tens of kilometres at the most. A proportion, we can be sure, are captured asteroids, trapped by gravity after some chance close encounter aeons ago. But others, Titan included, most likely came into being where we observed them today, condensing out of a disk-like nebula surrounding their nascent parent planet. Each of these systems of satellites is like a solar system in microcosm.

In the very early solar system, as now, temperature declined with increasing distance from the Sun. The local temperature had a profound effect on the final composition and structure of the different planets. Nearest the Sun, scorching Mercury is dense rock and metal, and bone dry. Farther out, Earth has more rock and less metal and its surface is awash with vast oceans of water. In the much cooler environment of the outer solar system, the giant planets accumulated great atmospheres of light, volatile gas.

When Jupiter and Saturn first condensed out of the solar nebula, they were hot. As sources of heat, these bodies had an effect on their developing satellite systems similar to the Sun's on its emerging planets. That effect is very obviously reflected in the bulk composition of the four Galilean moons of Jupiter.

Closest to Jupiter, Io seems largely bereft of water. From what we can see, Io is made of rock and sulphur, although its density implies that it has a core of iron. Next out is Europa. Although this is the brightest of the Galileans , its icy crust is a thin veneer: its density requires that most of its interior is rock and that only the outer 170 km or so is water in solid or liquid form. Because many compounds we are familiar with on Earth as volatile gases are frozen solid in the cold outer solar system, we call them ices – methane ice, ammonia ice and so on. Accordingly, planetary scientists often specify 'water ice' when they mean frozen water, since the simple word 'ice' is ambiguous. The surface of Europa is water ice but there is a lot of evidence to suggest that, a few kilometres down, the water is liquid. There seems to be a global subsurface ocean on which the ice crust floats and grinds. Certainly there are places where it looks as if water has welled up through the ice and areas where rafts of broken ice have moved around. We can see how, in principle, many of the pieces could be reassembled like a jigsaw puzzle. Tidal energy supplies the heat to power Io's volcanism and melt Europa's ice.

By contrast with Europa, both Ganymede and Callisto have more ice. The proportions of rock and ice are reflected by average density: more ice and less rock and metal means a lower density.

Unexpectedly, magnetic measurements made by the *Galileo* spacecraft suggest that Callisto also has a subsurface water layer deep below its icy crust. Ganymede probably has one too, although its signature is hidden by Ganymede's own magnetic field. This came as something of a surprise; while Europa is close to Jupiter and is kneaded by tidal forces, Ganymede and Callisto are much further out, so should experience much less tidal heating. If Callisto has an internal ocean, then it raises the possibility that Titan might have one too. Titan also has the likely advantage of abundant ammonia acting as an antifreeze in its interior.