The Jovian Planets and the Trans-Neptunian Objects

As recently as the 1990s, not a lot was known about the outer solar system, the region beyond Neptune, in comparison with the rest of the solar system. Pluto had been discovered in 1930 by Clyde Tombaugh. Pluto was odd. It was, is, a dwarf planet with a big moon, so far away its surface can't be seen from Earth. It's now known to have several small moons too. The Kuiper belt of objects resident beyond Neptune had been postulated as the source of short period comets, and some long period asteroids have come from the outer solar system. Remember the maxim from the very first lecture of this course – the farther you go from Earth, the bigger objects have to be to be seen. It's a sobering comparison that we are struggling with a good telescope to see a planet in our own solar system that is less than 6 light hours away whereas we can see with our naked eye bright stars over 100 light years away. However, that's the case. The mind-set for most of the twentieth century was that we couldn't see much solar system beyond Pluto, therefore there was not much to take an interest in.

All that is changing, almost as I write. The outer solar system is a place that astronomers are zooming in on, for several reasons. First, new observational technology is allowing them to do that for the first time ever, not with space probes, which are incredibly expensive to send to Pluto and beyond, but with Earth-based telescopes. (Only one space probe has been sent to Pluto, NASA's New Horizons probe launched in January 2006 that flew past Pluto in July 2015 taking stunning pictures and many measurements). Suddenly with new technology we're seeing what we couldn't see before and it's clear that there is a lot more beyond Neptune than Pluto. Secondly, people are realising that what lies beyond Neptune may have seriously influenced the inner solar system. Perturbed matter from the outer solar system sent towards the Sun may, for example, have been the cause of mass extinctions on Earth. We want to know about such things. It could be as important as life and death. Thirdly, now we have firm evidence that planetary systems are common in the universe, there is tremendous interest in modelling the process that gives rise to planetary systems. We want to make sure that we understand the science behind the formation of our own solar system, and others. What is out there beyond Neptune is primordial stuff formed when the solar system as a whole was formed. It is evidence of our birth process and well worth finding out about. If you reflect on it, frozen landscapes are the norm in the solar system. Planets and moons beyond the frost line are what most of the solar system is about. We really want to know about them. Expect to hear more about the outer solar system in the next ten years and beyond.

Meanwhile, between Mars and Pluto are many wonders of the solar system: Jupiter, Saturn, Uranus, Neptune and all their moons and rings. We'll work our way out.

Jupiter

Jupiter can be seen brightly in many an evening sky with your naked eye, distinguished from the bright stars by its steady light that doesn't twinkle. It's therefore easily spotted as a planet. A pair of binoculars reveals the sight that Galileo discovered, the four big moons of Jupiter in a line close to the planet. The line lies along the ecliptic and is therefore tilted so it follows the path the Sun follows in that part of the sky. Sometimes one or more of the moons are hidden by the planet. Since they orbit in times from just less than a couple of days for *Io*, the innermost, to just over a fortnight for the outer one, *Callisto*, their pattern changes by the day. Jupiter's four big moons are big. The inner two, *Io* and *Europa*, are about the size of our Moon; the outer two, *Ganymede* and *Callisto* are about the size of the planet Mercury. The initial letters of the four names are the same as the initial letters of the sentence *I eat green carrots*. How could you now forget the order of Jupiter's moons?

Jupiter's moons

Jupiter has many more moons than the big four. There are 4 much smaller moons even closer than Io. There are two other groups of 4 moons, shown in the textbook diagram, outside Callisto. In recent years many further moons have been announced, discovered within the Hill radius by the latest generation of imaging techniques. In 2003 the count passed 50 moons and updating this note with 2019 data, Jupiter has 79 moons. We are truly living in an age of discovery. Many of the outer moons are only a few km in diameter and in retrograde orbit, sometimes quite eccentric and inclined to the ecliptic.

Jupiter from Earth

- Orbital period 11.86 years, giving the orbital size from Kepler's 3rd law.
- Size calculated from angular diameter: 142,000 km diameter (11.2 Earth diameters).
- Mass found from applying Kepler's law to one of Jupiter's moons. The result is 318 × M_{earth} (twice the mass of all the other planets beside Jupiter put together). Its large mass perturbs orbits of planetary debris (comets, asteroids etc.) and, over millions of years, hoovers up a lot of debris. Over the lifetime of the solar system Jupiter has shielded the Earth from many serious impacts by interplanetary debris. Some consider that without this protection, life wouldn't have evolved as far as it has on Earth but would have been set back by far more mass extinctions.
- Jupiter rotates rapidly, equatorially in 9 hr 50 min; near the poles in 9 hr 56 min. Hence the observed planet is not solid. However, buried deep within is a solid core.
- Jupiter's atmosphere is conspicuously banded with clouds and contains a notable red spot that has been there since it was first seen in mid 1600s. Jupiter has a distinctive equatorial bulge, giving it an elliptical cross-section with a major axis 6% larger than the minor axis. A calculation using the relationship between major axis, minor axis and eccentricity of an ellipse shows that the eccentricity of this shape is a large 0.35.
- The Hubble Space Telescope follows the weather systems of Jupiter (and other planets), uninterrupted by Earth's atmosphere.

Jupiter from Space

Voyagers 1 & 2 flew past in 1979 and produced astonishing pictures of Jupiter's upper atmosphere, ring system and very diverse four large moons. The Voyagers measured Jupiter's magnetic field, the broad chemical composition of the visible surface (the outer atmosphere) and more besides. The images sent back by the Voyagers astonished everyone who saw them with the detail they contained and the shear unexpected nature of what they showed. Carl Sagan in a TV program at the time summed it up with the words "*in the late 20th century we are for the first time learning the realities not the myths of our little swimming hole in space*". In the 1990s, the *Galileo* probe added significantly more detail, both visually and in terms of remote sensing measurements. The Cassini-Huygens probe on its way to Saturn passed Jupiter by and recorded further images and data. In fact any probe heading to the outer solar system is likely to have its orbit planned to pass close to Jupiter so that it can get some additional energy and hence speed from the so-called 'sling-shot' effect of Jupiter. This is explained in our *Space Science* course PX2011 and also in the blue panel piece on "*Orbits of satellites and planets*". Updating these notes in 2016, the *Juno* probe has been inserted successfully into polar orbit close to Jupiter. If it works as intended, it will provide much more in depth knowledge of the most important planet in the solar system after Earth. "In depth" physically as well as metaphorically, for the probe is instrumented to find much more of how Jupiter is layered beneath the surface and how its dynamics work. We should be able to infer more from this of how the solar system at large was formed. Watch for Juno news.

Jupiter's conspicuous red spot was imaged for extended periods by earlier missions and seen to be a stable rotating high-pressure storm, that goes around counter-clockwise about once every 6 days. It sheds highly visible eddies from its NW corner. Jupiter has a very strong magnetic field whose influence extends out well beyond the orbit of Callisto and even the next set of moons at about 11 million km distant.

Jupiter's banded atmosphere

There is a transparent atmosphere, mostly of H_2 and He above the clouds we see, which are mainly ammonia crystals (NH_3) with small quantities of other materials produced by action of sunlight or electrical discharges. There is at least one layer of warmer (-50°C) lower clouds.

Most elements on Jupiter are present in their hydrogenated form. Examples given in the slide include methane (CH_4), ammonia (NH_3), water (H_2O) and phosphine (PH_3). As with the Sun, hydrogen is by far the most common element on Jupiter. The clouds are varying colours due to varying chemical composition, not all of which is known. There is indeed some liquid water cloud at higher pressures lower in the atmosphere so the possibility that organic chemistry has evolved is certainly present, though no signature has been seen yet.

Jupiter's structure

- transparent - few 100 km
- clouds - few 1000 km in an atmosphere of hydrogen and some helium.
- liquid H_2 is created by pressure. The thickness of this layer is about 20,000 km
- speculation based on our understanding of inter-atomic forces, but never yet observed in a lab, that below this there is liquid metallic H_2 for about 40,000 km
- 10,000 km of rocky core

Jupiter's large magnetic field (about 10,000 as big as the Earth's) is considered to be due to currents in enormously thick layer of conducting liquid metallic H_2. Currents are also generated in a plasma moving through a magnetic field and the Voyager craft found a current of 0.5×10^6 amps flowing between Io and Jupiter. Jupiter also emits radio waves, which is not surprising when there are large numbers of electrons circulating around magnetic field lines.

Jupiter's own energy

Jupiter may look a constant beacon of reflected light in the sky but close-up it is quite a violent place. Jupiter emits twice the energy it takes in from Sun. It was once thought that this might be due to nuclear fusion in the core but the pressure and the temperature there are not high enough. Nor is there enough energy from slow gravitational collapse to explain the energy output of Jupiter. Today's story is that the energy output is the residue of the energy of formation, slowly flowing out through the blanket of the enormous liquid layer.

Io

In this course we'll concentrate on the 'big four' of Jupiter's moons, the ones discovered by Galileo. Io is only three times Jupiter's diameter from the planet. If our Moon were that close to the Earth you'd get the same naked eye view as you now get through a pair of ×10 binoculars. Io exhibits spin-orbit coupling, keeping a constant face towards Jupiter, like our Moon does to the Earth. Io has a volcanic sulphurous outer layer, dry, probably largely rock, heated by strong tidal friction. Its volcanoes are the hottest in the solar system, including Earth's. Why are they so hot when the moon is too small to have retained its primordial heat? Its heating is caused by the variation in tidal effect resulting from the eccentricity of orbit. The planet is effectively kneaded by the tidal action as it goes around a complete orbit and the heat generated is stupendous. Ultimately the energy comes from the rotational energy of Jupiter itself and there is plenty there. Io is surrounded by a halo of sodium atoms and it orbits within the magnetic field of Jupiter, resulting in huge electric currents flowing between the planet and the moon. You can hear the radio emission produced by these currents from Earth.

Europa

The 3 large inner moons of Jupiter are locked in orbital synchronism, with periods in the ratio 1:2:4.

Europa is mainly rock covered by a frozen ocean of water, giving the moon the appearance of a badly scarred billiard ball. Europa has enough turn-over of its surface to hide craters; tidal flexing has induced cracks and water beneath is liquid, taking meteoric matter beneath the ice. Models of Europa's internal constitution all predict that it has a substantial ocean of liquid water under its surface, probably planetary wide, that could support life, probably primitive, life that has developed quite independently from life on Earth.

I was going to insert here a short table showing that the name of a feature on planets and moons is usually given a Latin word describing the nature of the feature (like *fossa* for a long, narrow, shallow depression, from the Latin for a ditch) and a proper name derived from some particular set of names from science, literature or mythology. Proper names on Europa are usually derived from Celtic mythology, hence the reason for inclusion here. However, there is a much more comprehensive set of names on Wikipedia than I could put in a short table so see https://en.wikipedia.org/wiki/Planetary_nomenclature, valid at the time of updating these notes.

Ganymede

The largest moon in solar system (5262 km in diameter) whose surface is cratered ice, covered by meteoric dust and debris. Ganymede's surface shows a few cracks, filled with welled-up icy slush. The *Galileo* probe has found a remnant magnetic field. Ganymede, and even Callisto, may have a watery ocean deep beneath the surface. Whether life could have evolved there is a question that will take more technology to answer than exists at the moment. Below the watery ocean lies a planet-like rocky mantle and an iron-nickel core.

Callisto

White spots on the surface are considered to be clean ice exposed by meteorite impact. Callisto shows the largest impact crater in the solar system (Valhalla). The decreasing density of satellites as you look further from Jupiter is taken to signify an increasing ratio of ice/rock.

Big missions are even now being planned as sequels to the Galileo mission to Jupiter and the Cassini-Huygens mission to Saturn. The particular aim of future missions will be to look for biologically interesting molecules on at least Jupiter’s moons Europa and Ganymede, and on Saturn’s moons Enceladus and Titan. Missions like these, though, take a lot of development, a lot of money, a lot of time to get there and a lot of patience. Don’t expect much in the way of results before 2030, a bit later for the Titan Saturn System Mission. The huge timescale involved (I’m writing this in 2009) emphasises how lucky we are now to have all the results available from past missions, the fruits of decades of vision, planning, development, launches, measurements and data processing. A 2012 update is that ESA have approved the Jupiter Icy Moons Explorer (JUICE) that will cost over a billion Euro but even at this stage the scheduled arrival time is 2030 and it will take some time after that for the varied results to come, all being well!

Saturn

The planet itself is like a smaller version of Jupiter (with a diameter 9.5 times that of the Earth), not so red but with a banded cloud system and sometimes with a similar huge storm spot, seen as a white area in the Hubble telescope photo, that is temporary and not permanent. The general composition and structure of Saturn is similar to that of Jupiter. A composition like Jupiter’s is similar to that of the Sun, which is perhaps not surprising given our current thinking that both were formed almost together during the collapse of an interstellar nebula. Saturn has a smaller magnetic field than that of Jupiter (~1/20th). Saturn, too, has some extra radiant energy but this is believed to be due not to residual heat of formation but to gravitational shrinkage. The 'story' on this is not settled.

Saturn does look much paler than Jupiter, due on the whole to some of the chemical components of its clouds. It has a convective troposphere like the Earth and a non-convective stratosphere above. Most of the atmosphere is hydrogen and helium, with the addition of methane, water, ammonia, hydrogen sulphide and phosphine. In the Earth’s atmosphere, the only substance that condenses out to form clouds is water. On Saturn, it’s cold enough for the condensation of constituents other than hydrogen, helium and methane. Banded layers of clouds of dissimilar materials are formed and looking in we see the top of this structure only. Infrared and microwave sensors can penetrate lower. Photochemistry on the aerosol particles in the atmosphere generates a soup of hydrocarbons and other particles, creating a smog that is quite effective at preventing us seeing the lower layers. Saturn’s golden yellow appearance is provided by this smog and upper level cloud.

Saturn’s appearance & rings

In the early days of telescopic astronomy, the great Dutch scientist Christiaan Huygens discovered that Saturn’s rings were separate from the planet. Saturn’s ring system is inclined at 27^o to the orbital plane of Saturn and is in the equatorial plane of the planet. The rings stay in a fixed orientation in space so we see them at different angles depending where Saturn is in its 29 year orbit. In 2009, the rings disappeared from Earth view, edge-on. See the lecture animation. Giovanni Domenico Cassini (1625-1712, born in Nice and astronomer at Bologna before becoming the first director of the Paris Observatory in the last quarter of the 17th century) discovered the main dark division in Saturn's rings.

James Clerk Maxwell showed while he was Professor at Aberdeen that on grounds of mechanical stability the rings of Saturn must be a myriad of small chunks of materials, rock or ice, circulating in orbits close to the planet. Indeed, the rings are now thought to be mainly icy chunks (perhaps including ammonia (NH_3) ice and other non-water ices). The ring system is less than 100 m thick, too thin to be seen edge on from the Earth. It is an astonishingly big, flat structure: some tens of metres thick and a third of a million km wide. The total mass within the giant ring structure is only a few times the mass of the moon Mimas that is just outside the rings, a moon about 400 km in diameter.

The Cassini-Huygens probe

The Cassini-Huygens probe was the last of NASA-ESA's big multi-purpose missions. After a 7-year trip to Saturn it has already more than fulfilled expectations of adding a great deal of detail to our knowledge of the planet and its moons. The ESA component involved parachuting a probe onto the mysterious, hazy Titan. Let's look first at Saturn's spectacular rings.

The rings stretch from ~ 1.2 Saturn radii to 2.3 times the radius. The Voyager spacecrafts first showed how highly complex the ring system structure is. The detail isn't static either, for some detail changes in a matter of months. The Cassini-Huygens craft that orbited Saturn showed even more of the stunning complex detail of the rings. Some images are shown in the presentation. The final image in this sequence "A view from Cassini" is not a composite but a genuine view showing part of the main A ring and the thin F ring, seen in front of the hazy enshrouded giant moon Titan (over 5000 km in diameter; more on Titan in a minute) and the small moon Epimetheus, which is just over 100 km across.

The most obvious detail in the rings that can be seen even from Earth is the occurrence of two dark bands. The largest gap is called the Cassini division (see above). It was created by 'orbit coupling' between Saturn's largest close moon outside the rings, Mimas, and any chunks within the division that orbit at exactly one half the period of Mimas. How this happens and the gap in the ring system is created is described in the next two slides.

Orbital resonance

The strongest **outward** pull on the rocky particle occurs when the particle is closest to Mimas, by virtue of the inverse square law of gravity. One period of the particle later and the pull is **inward** but substantially less. When the particle and Mimas next line up, the strongest pull is in exactly the same direction as before because of the 2:1 relationship between the orbital periods of Mimas and the particle.

Forces on a rock

The next slide shows in detail the forces on a rock due to the gravitational attraction of Mimas, taking both the orbit of Mimas and the rock as circular. The forces are calculated for all positions of Mimas and the rock, for 6 orbits of Mimas, which correspond to 12 of the rock. More advanced students in the class could easily work out the physics themselves. What is plotted is the **radial component** of the force, i.e. the force pulling on the rock directly outward (shown in blue), and the **tangential component**, i.e. the force in the direction of the orbit (shown in pink). The tangential component averages to zero when Mimas goes around once but the radial component doesn't. Moreover, the radial component peaks regularly in the same direction. In a way, it is like pushing a swing regularly to disturb the occupant. If you push at random then the swing won't move much. If you push with the right period in the same direction, the swing does its business and moves a lot. The phenomenon is called *resonance.*

The repetitive directed pull of Mimas shifts chunks that get into the main Cassini division so that they soon move out, creating a visible gap.

[On a different scale, a similar effect happens in the asteroid belt between Mars and Jupiter. The Kirkwood gaps are created by resonances between the asteroid periods and that of Jupiter]. In Saturn's rings, other gaps are caused by a shepherding effect of smaller moons within the ring system itself.

Roche limit

Why hasn't the ring material coalesced into a Moon? The material is too close to Saturn, within what is called the ''Roche limit'. Inside this distance from a planet, orbiting particles won't stick together for the following reason. Think of a large moon orbiting very close to a planet. Remember that the further from a planet a particle is, the slower the particle travels in its Keplerian orbit. Hence particles at the front and rear of a moon would naturally go round at different speeds, if allowed to do so. If they are prevented from doing so by some connection, then that connection will be in tension. Larger moons are held together by their own gravity (not by the strength of their constituent rock or ice) and if this is not large enough to counteract the tension between the front and back of the moon created by the central planet, the moon will fly apart. The difference in force between front and back increases as you get closer to the planet and the limit at which a moon will hold together by its own gravity is called the Roche limit. This is illustrated in more detail on the second slide.

Saturn's rings are inside the Roche limit for Saturn. To re-iterate, because the consequence is not immediately obvious, if you stand on the Earth or Moon and break a rock in two with a hammer and let the pieces go, they fall back to the surface, joining the rest of the body. For bodies as large as the Earth or Moon, the strength of the rock is not holding all the material together as one planet or moon - it is mutual gravitational attraction of all the particles. If some catastrophe pushed the Moon so that it orbited only 10,000 km above the Earth's surface, then the gravity of the Moon wouldn't be able to hold it together any longer and it would crumble into billions of pieces, creating a ring around the Earth. 10,000 km is within the Roche limit for the Earth.

Titan and Saturn Moons

Updating the count of Saturn's moons in 2019, the planet now has 82 named moons. Remembering that the 4 planets Mercury, Venus, Earth and Mars have only 3 moons between them, it's clear that the outer solar system is of an unconventional character to the inner solar system. The majority of named moons are beyond the ring systems. Many have surfaces of ice. NASA's portfolio diagram summarises the succession of the better known moons orbiting Saturn.

Huygens found Saturn's giant moon *Titan.* That was the start. Cassini the astronomer followed up by discovering the moons Iapetus, Rhea, Tethys & Dione. Close-up pictures of several of Saturn's moons are shown in the following slides. These were all taken by the Cassini-Huygens mission. You get some idea from the slides that they are a diverse lot. Some are heavily cratered rocks; others comparatively smooth and ice-covered. Mimas, already mentioned, has a distinctive crater one third the diameter of the moon. Hyperion doesn't rotate regularly but tumbles chaotically under the influence of the other moons.

I'll single out Enceladus for special mention. It's about 500 km in diameter, quite a small fry but it has cryo-volcanic activity. Plumes of material have been seen jetting out from near its South Pole, sufficiently vehemently that material has escaped from the gravitational pull of the moon and joined the thin E ring of Saturn. Cryo-volcanism is propelled by internal heat, enough in Enceladus's case to generate liquid water close beneath the frozen surface of the moon. The heat comes from tidal heating, both from Saturn (Enceladus orbits in just 1.4 days) and probably from Dione outside it, which is in a 2:1 orbital resonance. That water, according to Cassini's sensors, contains carbon compounds. In October 2015 Cassini flew through the plume within 50 km of the surface. Cassini seems to have found yet another candidate location in the solar system where there could be primitive life. Maybe not life as we know it, but still self-replicating life. On Mars we may first discover death in the solar system but in more distant locations like Europa, Ganymede, Titan and Enceladus, we may find active life. Since the water is close to the surface, unlike Europa, then Enceladus may be a better bet to send a life-seeking probe to.

You might have thought that Jupiter's varied moons covered every possible kind of moon we were going to find in the solar system. It's not so. Enceladus is one example of something different. Iapetus is another example. Iapetus is pretty far out from Saturn but always keeps one face towards the planet; it is about 1500 km in diameter, a goodly chunk, and half black with carboniferous deposits - not nice ones like coal but cyanide and hydrated minerals - half white with ice. What's going on here? I'll leave you to look on the web for the latest ideas.

Titan on one page

Titan is second largest moon in solar system, only slightly smaller than Ganymede. Like Ganymede, it is larger than the planet Mercury. Voyager 1 was diverted from its grand tour of the outer planets to photograph Titan reasonably close-up but the photographs were disappointing because the moon turned out to have total cloud and haze cover. The Huygens probe launched in 1997 landed on Titan in January 2005 amid great excitement. No life was found, less firm evidence of liquid on the surface than was expected as the first pictures of Titan's icy landscape and surface were relayed back. Search through our web pages for the latest offerings.

Titan is the only moon with an atmosphere – indeed a higher pressure atmosphere than the Earth possesses. Like the Earth, the atmosphere is mainly nitrogen, in fact about 98.5% nitrogen and 1.5% methane. Relatively light winds blow over a landscape with lows highlands. There is weather but it's a very peculiar place. The temperature is only 95K, close to -180°C. The rain is liquid methane, the rivers seem to flow only intermittently like those in the deserts of the Earth, the surface 'rocks' seem to be made of ice, and the atmosphere contains enormous quantities of organic chemicals, organic in that they are compounds containing carbon. It is believed these were created by the action of UV on the indigenous hydrocarbons.

Continued remote sensing from the Cassini mission has revealed increasing detail of this mysterious world, the largest known unexplored object in the solar system before the arrival of the Cassini-Huygens probe. (Titan is more than twice the diameter, 10 times the volume, of Pluto).

Huygens ahoy

The Huygens probe, shown sitting on Titan's surface in the artist's view based on actual pictures, revealed a pebble strewn world bathed in orange light filtered by the haze. The 'pebbles' though may be chunks of water ice, not rock. On Titan the liquid is methane, a pure hydro-carbon with chemical symbol CH_4. Radar imaging that penetrates the haze has shown river systems, lakes, dunes and uplands. Might there be anything that could be called life? The chemical ingredients are all there. Sunlight is about 1/90th of the amount that hits the Earth, which is still quite considerable but it is perishingly cold and perishing is not an adjective that suggests life as we know it. There may be hot spots and there has been an exceedingly long time for something to happen, over 4 billion years in fact, so my money would be on finding some primitive development that merited the description 'life'. Titan, though, is still largely unknown. In so much as it's like anywhere we can think of, it resembles a frozen version of what early Earth may have been like. Life did start early on Earth and it's worth remembering that it started in conditions that would kill much of present day life. Nevertheless, it will take many missions to such a strange place before we know a lot about it. Missions to a world 1500 million km away aren't cheap.

Titan revealed

Titan revealed but still mysterious. The Huygens probe revealed a landscape that at first looked difficult to interpret. We interpret pictures with reference to the known. Titan seemed so different from anywhere in the inner solar system that there were few reference points. The Cassini probe that was orbiting around the moons of Saturn has taken radar pictures of selected areas on Titan. These are still being interpreted years later, along with infrared images. There are very few craters on Titan but one substantial crater is shown here. Also shown is one of several radar pictures that show lakes, particularly in the northern hemisphere, but not lakes as we know them. Lakes at -180°C, lakes of liquid hydrocarbon. The largest lake is known as Kraken Mare, a real sea of liquid methane over 1000 km in extent near Titan's North Pole. It appears to be as smooth as a mirror and perhaps 150 m deep. Strange place on a strange world. One study (Nov. 2019) summarising the topography describes the landscape as *labyrinth terrains and lakes at the poles, plains at mid-latitudes and dunes at the equator*.

Tumbling through Titan's atmosphere

ESA have released the composite picture on the final slide of Titan that shows views of the landscape obtained by the Huygens probe as it parachuted down through Titan's thick atmosphere.

Saturn's irregular moons

As has been found around Jupiter, the space more distant from Saturn but still close enough to harbour moons (within the Hill radius) has been found to have a collection of small moons, some in retrograde motion, some in inclined orbits. These are relics of the early solar system. More will undoubtedly be found.

Uranus

The more we discover planets around other stars, the more we see that planets the size of our 'ice giants' Uranus and Neptune are very common. In a way that makes it even more important that we understand our own large planets but in fact we've hardly scratched the surface, as the saying goes. The last probe to Uranus was Voyager 2's flyby in 1986, over a third of a century ago. We know little about Uranus's internal structure or even its composition; little about its asymmetric magnetic field, its internal energy, its weather patterns, the reason for the tilt of its axis, unique on the solar system. Given the cost of a mission to the icy giants, it's pretty unlikely that any probe will get there in the next quarter of a century. Indeed, ESA's possible *Uranus Pathfinder* mission that would have arrived in 2037 has not been funded. We'll have to make do with information from Voyager 2 and improved technology observations from Earth, or close to it. Still, we know a lot more about Uranus than we used to when it was simply a little white dot on a photographic plate.

Uranus is a blue cold world not seen by naked eye except in most favourable circumstances. The blue is due to methane absorption of light scattered back by clouds. Overall, Uranus' composition is broadly like Jupiter's, but without the exotic red chemicals.

Uranus has its rotation axis 98° to the ecliptic, i.e. the planet is on its 'side'. Infra-red observations from the largest telescopes have now revealed a system of banded weather patterns in the outer atmosphere not seen in the visible images and reminiscent of the patterns on Jupiter and Saturn. They are swirling around the canted rotation axis. Uranus's magnetic field poles are 55° from the rotation axis, with the effective centre of the magnet well away from centre of planet. It has a well-developed ring system with 10 dusty, narrow rings and many ringlets - seen only by probe.

How Uranus formed and evolved leading to its present condition and appearance is an outstanding question relevant to our understanding of planetary systems at large. There isn't yet a convincing story. All in all, we know Uranus is different from Jupiter, different from Saturn, and as we'll see it's different from Neptune. Unfortunately I'm not likely to be around when the next probe reaches Uranus and helps to give us the kind of knowledge we now have for closer bodies in the solar system.

Uranus has 5 moons over 100 km in diameter (Miranda, Ariel, Umbriel, Titania and Oberon) and at least 9 others. The photograph of Miranda shows that solar system continues to surprise.

Neptune

Neptune can be seen from Earth but the best views have been obtained by Voyager 2 when it passed in 1989, sending back many pictures. Neptune has been described as 'Earth-like' for having a blue appearance with white clouds but like the other three giants it has no land above its liquid layers. The blue appearance is atmospheric methane and the white clouds are frozen ammonia so it really has little resemblance to the Earth. It, too, has a storm system, a great black spot, and it also radiates more internal heat than Uranus. The internal heat drives its clouds at over 1000 km hr^{-1}. It's astonishing to find such activity in a place so cold and far away from the Sun.

Neptune's magnetic field rotates in 16 hrs 3 mins, faster than clouds at the equator (18 hrs) but slower than clouds at poles (12 hrs). This suggests an internal fairly rigid body. Neptune is at a pretty uniform temperature of about - 216°C (57K). Neptune has a couple of thin lumpy rings.

Neptune has 1 large Moon called Triton (2760 km in diameter, bigger than Pluto) and in retrograde motion – and 7 smaller moons.

Pluto – what's visible?

Pluto appears to astronomers on Earth as a mere pin-prick of light. In round numbers there are some 50 million objects in the sky brighter than Pluto, almost all of them stars. Imagine looking for one small pebble among 50 million larger ones. It's not easily found. Even if you know where to look with quite a decent amateur telescope, say 250 mm in diameter, then you will be hard pressed to see Pluto in the eyepiece. You should have no trouble capturing it on a photograph, though you still have to identify it among the hundreds of other stellar images on your screen. The slide shows some basic information about Pluto that was discovered from Earth. The thumbnail illustration is Clyde Tombaugh's discovery photograph. Pluto's quite elliptical orbit actually intersects that of Neptune and comes inside it. Pluto retreated from being closer to the Sun than Neptune in 1999. However, the two bodies will not crash because their orbits are in synchronism, 3 periods of Neptune equalling 2 periods of Pluto. In 2006 Pluto was demoted from a full planet to a 'dwarf planet'. It is by a whisker the largest body recognised as dwarf planet (in 2016) but Eris is the most massive. Ceres, the biggest asteroid, is also now called a dwarf planet and there are two others at the moment that will be mentioned later.

Pluto – what's there?

It was the Hubble Space Telescope during its first 25 years of operation that told us more about Pluto than had been found in the previous decades. From these images Pluto was deduced to have a temperature of about 44 K and be covered with assorted ices of water (H_2O), methane (CH_4), carbon monoxide (CO) and lots of nitrogen (N_2). Pluto is still, though, a tiny dot in a Hubble image. It was the New Horizons probe that had been 10 years on its journey to Pluto that suddenly gave us a clear view of the planet in July 2015 when it approached, flew close by and hastened onward to the outer reaches of the solar system. The New Horizons images may well be the best you will see in your lifetime. It will take over a year to download all the New Horizons data but it was instantly clear that far from being a dull ball of rocky ice it is a very varied planet with large highlands, apparently of ice, expansive plains, possibly the icy surface of cryo-convection, and some processes that are reforming the surface to the extent that most craters have been wiped out. Pluto is also streaming nitrogen gas into space and onto its largest moon, Charon. The Pluto story will unfold over the next few years.

Pluto's moons

Pluto's large moon Charon was discovered as recently as 1978. How could a large moon in the solar system, bigger than the dwarf planet Ceres and just over half the diameter of its parent planet, have been discovered only so recently? In short, because it's so far away, absolutely at the limit of visibility of 'old fashioned' telescopes and photographic plates. New Horizons, though, took stunningly detailed images of Charon in 2015. It is a world in itself, almost as varied as Pluto, with huge canyons as well.

It's a mark of the development of astronomical observing in the early 21st century that two very much smaller moons, Nix and Hydra, were discovered in 2005 using the Hubble Space Telescope. They are only several tens of km in diameter, very faint indeed from Earth. Atmospheric degradation of the images of Earth-based instruments limits these instruments' ability to see very faint objects. In one sense we shouldn't be surprised that Nix and Hydra were missed but amazed that a faintly illuminated object of about 60 km in diameter can be seen at all at a distance away of some 6000 million km. Imagine someone holding up a dirty tennis ball, shining a torch on it and then asking you to see it from a distance of 6000 km away. You've got the challenge of seeing Nix and Hydra.

There's more around Pluto too, for in July 2011 a 4th moon was discovered in Hubble images. When I updated these notes in 2012 it was just called P4 but now has a 'proper' name, Kerberos, after the dog that guarded the gates of Hades. It lies between Hydra and Nix and is smaller than either of them. The story doesn't end here. A year later, P5 was discovered, another moon about 15-20 km across in the same plane. It's now called Styx, after the river that souls were imagined to cross to enter the underworld. Styx is at least the size of Mars' moon Deimos. So Pluto has at least 5 moons. All the small moons orbit outside the Pluto-Charon duo. No more were seen by the New Horizons probe.

Varuna

Varuna was one of the first large TNOs (Trans-Neptunian Objects) discovered with 'new technology' equipment. It is named after the Hindu lord of the cosmos. Varuna is, apparently, a dark body with comparatively little surface frost.

Quaoar

Quaoar was described at its discovery as the largest solar system object found since Pluto. Unfortunately this same description has been rightly applied to several bodies found after Quaoar. Like Varuna, it has an orbit a bit larger than Pluto's and is the only one of the large trans-Neptunian objects so far discovered with an orbital inclination of less than 10°.

Sedna

A new candidate for the largest body found since Pluto. Sedna's orbit is unlike any other large TNO so far discovered in being strongly elliptical with its closest distance of approach not even as close as Pluto.

Orcus

Are we running out of Gods of the underworld? By convention large outer solar system bodies are given names associated with the underworld. If we haven't run out quite yet we shall do. Modern estimates suggest there are at least several hundred bodies in the outer solar system that fit the definition of a dwarf planet. It's just a matter of coming up with the observational proof. Several candidates that have already been observed in some detail are sitting at the top of the list but it's not been easy to provide sufficient proof that they are large enough and round to satisfy the naming committee of the IAU (International Astronomical Union).

Haumea, Make-make, Eris & Dysnomia

This slide shows 3 objects that have been named as dwarf planets (in addition to Ceres and Pluto). Haumea (with moons Hi'aka and Namaka) is the name of Polynesian origin now accepted by the International Astronomical Union (the IAU) for a weird body discovered in 2003. Haumea is a large elliptically shaped object as big as Pluto in its biggest dimension, rotating incredibly quickly, every 4 hours, with two moons and a number of other objects in its wake. Haumea can be deduced to be a rocky body with an icy crust that has likely suffered a major impact.

Eris is bigger than Pluto – by the old rules almost a 10th planet but now another dwarf planet. How did Clyde Tombaugh miss it? Partly because its orbit is so inclined that it appears in parts of the sky you would never expect to find planets in. Eris has a moon, named after Eris's daughter Dysnomia. These are minor Greek goddesses, closely associated with the dark art of sowing discord. Eris is less bright than Pluto but Make-make (another Polynesian name) is almost 5 times brighter. At the time Tombaugh was looking for other planets, Make-make was only visible in the direction of the Milky Way and easily overlooked within the mass of visible stars. Make-make is unusual for such a large trans-Neptunian object in having no moon. It's also very cold, at only about 30 K, and has a surface that is largely solid methane and ethane, unlike Pluto's surface that is largely nitrogen.

TNOs in summary

Slowly we are finding that there is diversity in the outer solar system that was never before appreciated. It's as if a door to a mysterious world has just been opened and we are seeing for the first time that our solar system is not the homely place we were just getting accustomed to. To make another analogy, we are finding a very peculiar collection of relatives in our family of planets that we thought we were getting to know quite well. Some are dark objects, some very bright. Some have odd orbits, some don't. Some have moons, others don't. Some are pretty spherical, others apparently not so. Whatever next? Since I wrote these words another development has been glimpsed through the gloom. Now that more and more Kuiper Belt objects are being measured they are being found to have peculiar orbits. How these orbits came to be is investigated by computer simulation and the computer simulations that do the job best seem to need an as yet unseen planet-sized object in the belt – Planet Nine, quite a bit larger than the Earth. Other simulations trying to figure the past history of the known planets from Neptune to Mercury that would lead to their planetary orbits we now see work best if there was at one time another planet that has been ejected from the visible solar system as a result of past movement of the big planets. Of course, scientists don't particularly like explanations that invoke invisible objects but modern computer-based analyses are sufficiently detailed to make predictions as to where in the sky Planet Nine might be. So watch the scientific magazines and you should find "what's next".

Arrokoth

Updating these notes in 2019 allows me to mention 486958 Arrokoth, the Trans-Neptunian object visited by the New Horizon's probe long after it left Pluto. Arrokoth is just one of a myriad of small TNOs. It is a double object, less than 40 km long, formed when two mutually orbiting objects coalesced as they came together. It says something for the Hubble Telescope that the search for an object near the New Horizon's orbit found this tiny object at a distance of some 6.5 billion km. Its apparent size would be the same as a golf ball 7000 km away. Impressive telescope! New Horizon's imaging taken at a few thousand km distance from Arrokoth shows that it has a red surface fairly free from craters, which is not surprising since TNOs are very far apart so collisions will be extremely rare. The red colour is due to tholins, produced over the eons by the photosynthesis of surface chemicals. You can find a lot more detail and images on the web but I think it's fair to say you will never in your life see any more images of Arrokoth than those already taken.

JSR