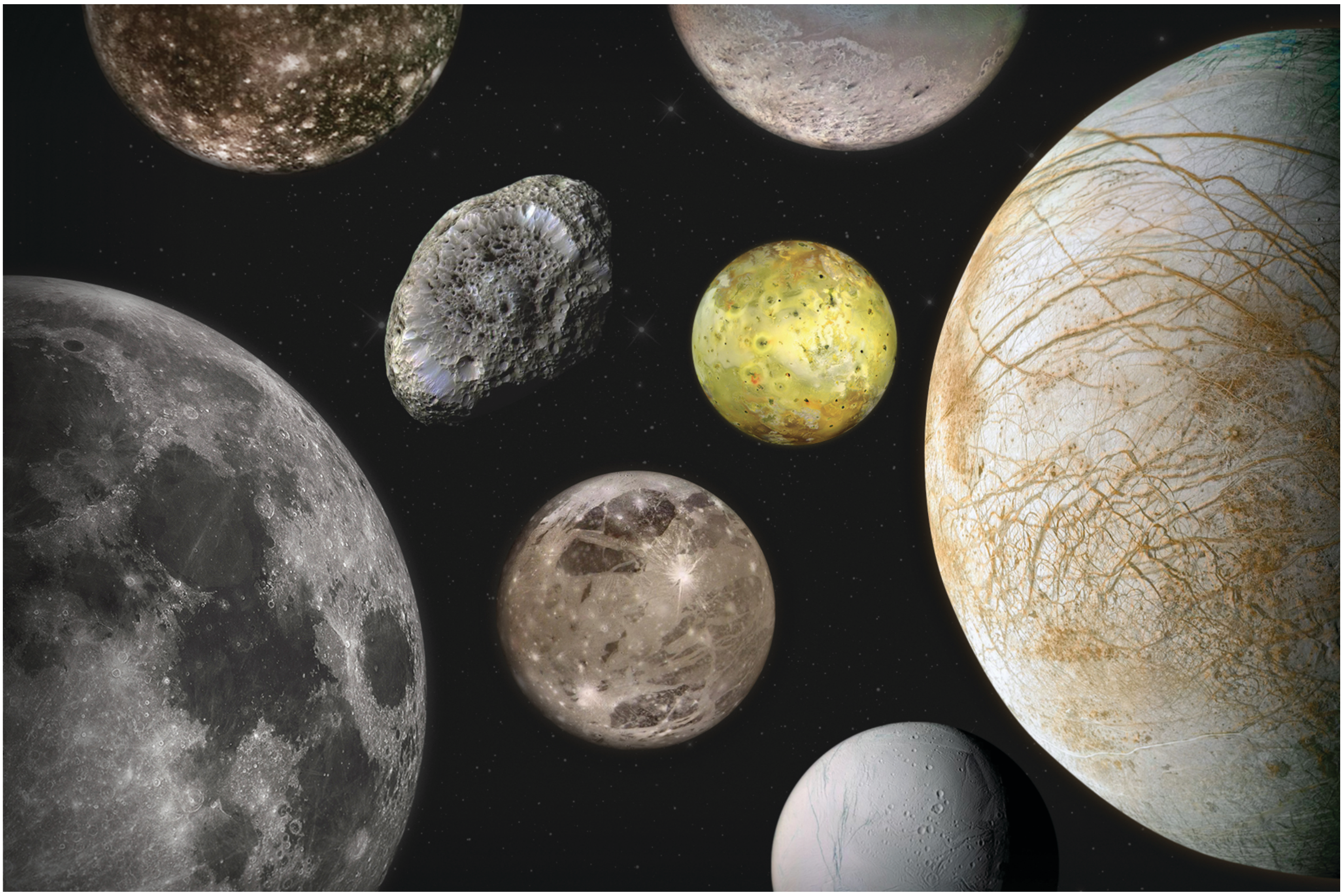
Moons of our Solar System



About this free course

This version of the content may include video, images and interactive content that may not be optimised for your device.

You can experience this free course as it was originally designed on OpenLearn, the home of free learning from The Open University –
https://www.open.edu/openlearn/science-maths-technology/moons-our-solar-system/content-section-overview

There you'll also be able to track your progress via your activity record, which you can use to demonstrate your learning.

Contents

Introduction and guidance

Introduction and guidance

Welcome to this free course, *Moons of our Solar System*.

The course lasts 8 weeks with approximately 3 hours of study time each week. You can work through the course at your own pace, so if you have more time one week there is no problem with pushing on to complete another week. The eight weeks consist of the following:

1. What are moons?
2. Looking at moons
3. Looking closer
4. Our Moon
5. What we learned from the Moon
6. Water on the Moon
7. Exploring moons
8. Moons and the future

There are lots of opportunities to check your learning. This includes interactive quizzes; Weeks 4 and 8 will provide you with an opportunity to earn a badge to demonstrate your new skills. You can read more on how to study the course and about badges in the next sections.

After completing this course, you will be able to:

- develop an awareness of the nature and diversity of moons in our Solar System, and their significance
- describe the compositions and nature of the surfaces and interiors of moons
- describe the nature and history of volcanic activity on several moons, assess and be aware of which moons may have subsurface oceans, and the implications for hosting native life
- describe and be aware of the history of discovery and exploration of moons, and of future prospects
- reflect and suggest ways in which resources from the Moon may help future space exploration.

Moons Facebook group

There is no official online forum for this course. However, learners who completed a previous version of this course, and want to maintain their connection with moons have

Introduction and guidance

set up a Moons Facebook group. Feel free to drop in, to swap experiences with, or seek advice from, your predecessors.

Moving around the course

In the 'Summary' at the end of each week, you can find a link to the next one. If at any time you want to return to the start of the course, click on 'Course content'. From here you can navigate to any part of the course. Alternatively, use the week links at the top of every page of the course.

It's also good practice, if you access a link from within a course page (including links to the quizzes), to open it in a new window or tab. That way you can easily return to where you've come from without having to use the back button on your browser.

What is a badged course?

While studying *Moons of our Solar System* you have the option to work towards gaining a digital badge.

Badged courses are a key part of The Open University's mission *to promote the educational well-being of the community*. The courses also provide another way of helping you to progress from informal to formal learning.

To complete a course you need to be able to find about 24 hours of study time, over a period of about 8 weeks. However, it is possible to study them at any time, and at a pace to suit you.

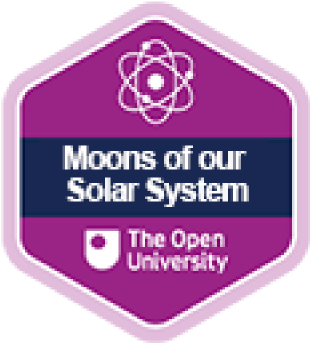
Badged courses are all available on The Open University's OpenLearn website and do not cost anything to study. They differ from Open University courses because you do not receive support from a tutor. But you do get useful feedback from the interactive quizzes.

What is a badge?

Digital badges are a new way of demonstrating online that you have gained a skill. Schools, colleges and universities are working with employers and other organisations to develop open badges that help learners gain recognition for their skills, and support employers to identify the right candidate for a job.

Badges demonstrate your work and achievement on the course. You can share your achievement with friends, family and employers, and on social media. Badges are a great motivation, helping you to reach the end of the course. Gaining a badge often boosts confidence in the skills and abilities that underpin successful study. So, completing this course should encourage you to think about taking other courses.

Introduction and guidance



How to get a badge

Getting a badge is straightforward! Here's what you have to do:

- read each week of the course
- score 50% or more in the two badge quizzes in Week 4 and Week 8.

For all the quizzes, you can have three attempts at most of the questions (for true or false type questions you usually only get one attempt). If you get the answer right first time you will get more marks than for a correct answer the second or third time. If one of your answers is incorrect you will often receive helpful feedback and suggestions about how to work out the correct answer.

For the badge quizzes, if you're not successful in getting 50% the first time, after 24 hours you can attempt the whole quiz, and come back as many times as you like.

We hope that as many people as possible will gain an Open University badge – so you should see getting a badge as an opportunity to reflect on what you have learned rather than as a test.

If you need more guidance on getting a badge and what you can do with it, take a look at the OpenLearn FAQs. When you gain your badge you will receive an email to notify you and you will be able to view and manage all your badges in My OpenLearn within 24 hours of completing the criteria to gain a badge.

Get started with Week 1.

Introduction and guidance

Week 1: What are moons?

Introduction

Meet scientists describing their fascination with moons, discuss the implications of finding life on a moon and meet Jessica, your course guide. Take a tour through the Solar System and find out how much you already know about moons.

Jess Barnes is your guide through the course. She was a PhD student when these guide videos were filmed, then became a post-doctoral researcher at The Open University with a specialist interest in water inside the Earth's Moon, and in June 2016 moved on to a position at the Johnson Space Center in Houston. Jess pops up at the start of each week to tip you off about highlights and challenges, to remind you what you've learned and to help you make the most of these eight weeks of scientific discovery.

Video content is not available in this format.

By the end of this week, you should be able to:

- understand the nature of orbits and how the Earth's orbit is responsible for its phases
- understand how tidal heating occurs as a result of the Moon's rotation and orbit
- describe various theories to explain the Moon's origin.

The Open University would really appreciate a few minutes of your time to tell us about yourself and your expectations for the course before you begin, in our optional start-of-course survey. Participation will be completely confidential and we will not pass on your details to others.

1 Fascinating bodies

To make this video, we gathered comments about moons from scientists attending the 2013 Lunar and Planetary Science Conference in Houston, Texas. Christine Shupla, who will appear again in later videos, spoke about different kinds of moons. The single thing that they all have in common is that each of them orbits a larger body. This larger body is usually a planet, but there are many bodies too small to be classified as planets that also have their own moons.

The giant planets Jupiter, Saturn, Uranus and Neptune each have some large moons, comparable in size to our own Moon. Most of these moons probably formed around their planet. But each giant planet also has numerous smaller moons, which are irregular in shape because the moon's own gravity is too weak to pull it into a sphere. Some of these irregular moons are in orbits very close to their planets and are probably debris from bigger moons destroyed by collisions or ripped apart by tides. These are sometimes called 'inner moonlets'. Other irregular moons orbit much further from their planet and are probably wanderers such as comets (mostly ice) or asteroids (mostly rocky) that became captured after straying too close by chance.

Video content is not available in this format.

At the 2014 Lunar and Planetary Science Conference, Professor David Rothery managed to grab this bonus video message for learners from an Apollo astronaut, Harrison (Jack) Schmitt. His good wishes were addressed to learners on a different course, but they apply to you too.

View at: youtube:iorisXarvg4

1.1 Getting started with moons

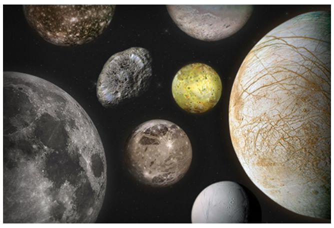


Figure 1 moons

In the first of the two previous videos, Keri Bean mentioned that the two moons of Mars are small and that these are probably captured asteroids, whose orbits are still changing significantly. Others then spoke about the moons that show the most obvious signs of present-day activity:

- Io, a moon of Jupiter, which is a rocky body with active volcanoes that colour its surface with sulfur
- Europa, another moon of Jupiter, with a rocky interior but an outer layer of ice and probably a global ocean sandwiched between the two
- Enceladus, a small icy moon of Saturn with a young, fractured surface and jets of ice crystals vented into space
- Titan, Saturn's largest satellite, which has a dense atmosphere shrouding an icy surface that has rivers and lakes of liquid methane.

One important point that is not clearly mentioned is the low temperatures prevailing in the outer part of the Solar System. Out at Jupiter, whose distance from the Sun is five times the Earth's, the average surface temperature on a moon is minus 170 degrees centigrade. The further from the Sun, the colder it gets: minus 200 degrees centigrade for Saturn's moons, minus 210 degrees at Uranus, and minus 235 degrees at Neptune. This means that except where there is an internal heat source, the ice that forms the outer layers of all large moons (except the Moon and Io) is so cold, strong and rigid that it behaves exactly like rock does on the Earth or on the Moon.

Attention was also drawn to the Pluto–Charon system (which had not yet been visited when the video was made). Pluto is a dwarf planet made of ice. It is no longer counted as a true planet, but as one of the largest and nearest Kuiper Belt objects. Its major moon, Charon, has a diameter that is slightly more than half that of Pluto. Pluto and Charon are so close to each other that tidal forces have locked their rotations so that each keeps the same face permanently towards its partner. If you like, you can think of Pluto–Charon as a double object, rather than a main body plus a moon.

The video then turned to the Moon, meaning the moon that orbits the Earth. You will learn much more about the Moon later on, but the scientists gave you some hints about why this is an important body.

The video concluded by speculating about moons that could host life and about how resources from the Moon could open up the way for future exploration of the Solar System.

There is also a Moons infographic documenting the known moons of six planets (Venus and Mercury have no moons) and three dwarf planets in our Solar System. Note: since this infographic was made, a 4th dwarf planet (Makemake) has been shown to have a moon.

1.2 Thinking about Europa

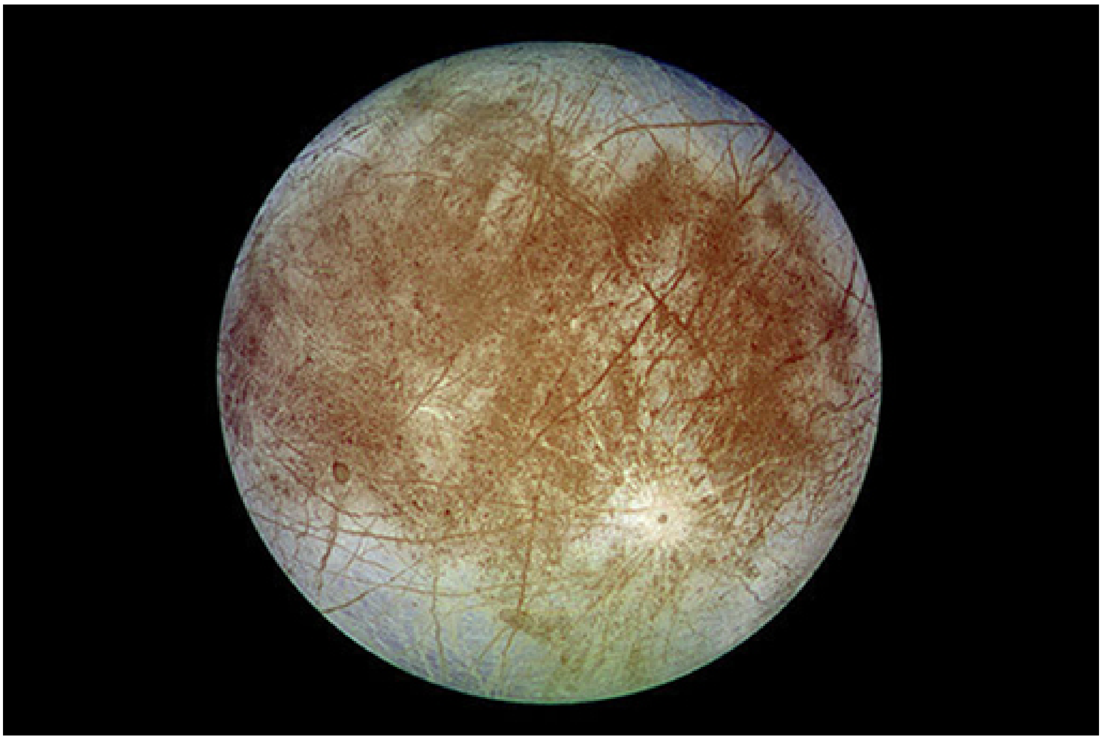


Figure 2 Europa

If there is life in Europa's ocean, it may be nothing more than simple microbes living off chemical energy supplied by hot springs on the ocean floor, or snatching brief glimpses of sunlight as tidal cracks open and close in Europa's icy shell.

What do you think would be the significance of finding life on Europa? Should precautions be taken to prevent contaminating Europa with life from Earth?

You'll learn more about Europa (Figure 2) later, and you'll explore the issues relating to life in the Solar System in your final week.

1.3 Mythbusting moons

It's only planets that have moons, right? So where exactly is the dark side of the Moon? Supermoons are special but they can cause natural disasters, can't they? Is it true that without the Moon there would be no tides in our seas, and no advanced life on earth?

Let's pause for a moment and get some facts straight.

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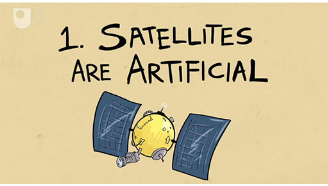

1.4 The first picture show

You saw glimpses of several moons in the first video and you'll find out more about many of them later. In the meantime, work your way through this image gallery to get a taste of some of what's to come. We start by giving you a sense of scale (Figures 3 and 4), then you look at some of Saturn's moons, which are a particularly spectacular and varied family, and then you whizz past just a few of the other moons in our Solar System.

The top of Figure 3 has a view of the Solar System looking obliquely across. The planets move anticlockwise in near-circular orbits, whose shapes are foreshortened in this perspective. So do the asteroids (concentrated between the orbits of Mars and Jupiter) and Kuiper Belt objects (mostly beyond Neptune). The Earth's orbit is 150 million km from the Sun; Neptune is thirty times further out. The bottom of Figure 3 has the Sun, the eight planets and Pluto drawn with diameters (but not distances) to the scale shown.

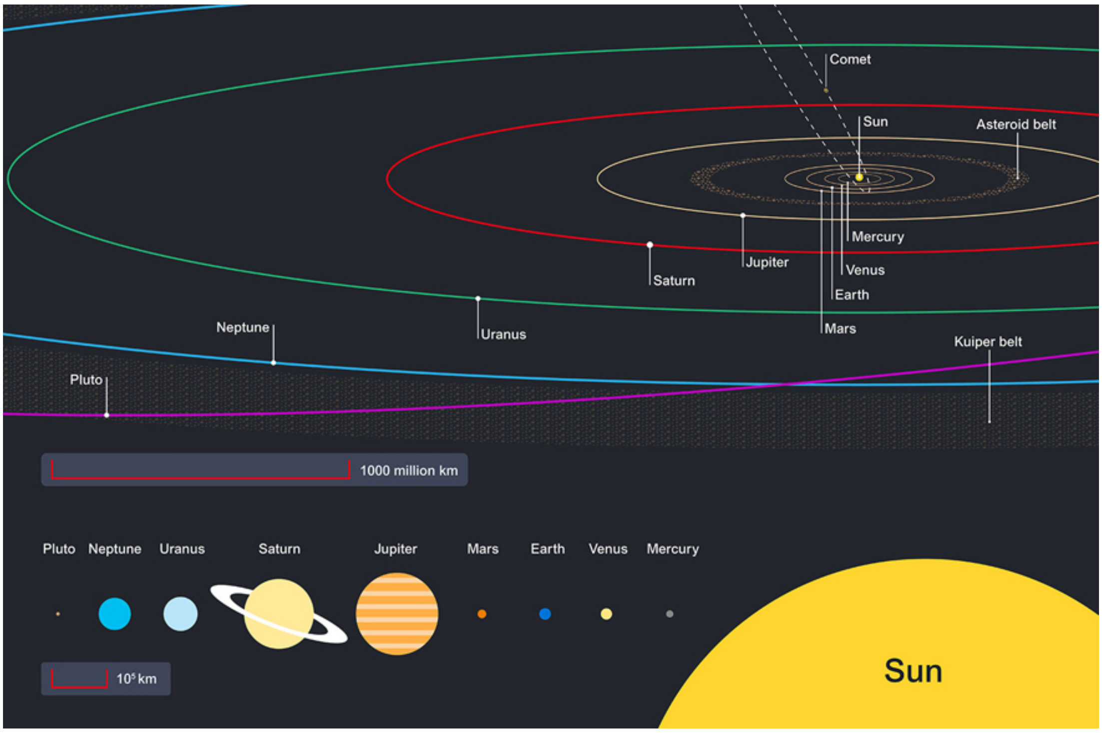

Figure 3 Two ways of looking at the Solar System

Figure 4 shows the largest solid bodies in the Solar System, colour-coded according to how recently there has been significant internal geological activity (known or likely). This shows all the large moons on the same scale as the Earth-like (terrestrial) planets. You can see that Ganymede is slightly bigger than the planet Mercury; however, it is made partly of ice whereas Mercury has a large, dense, iron core and so has more than twice the mass of Ganymede.

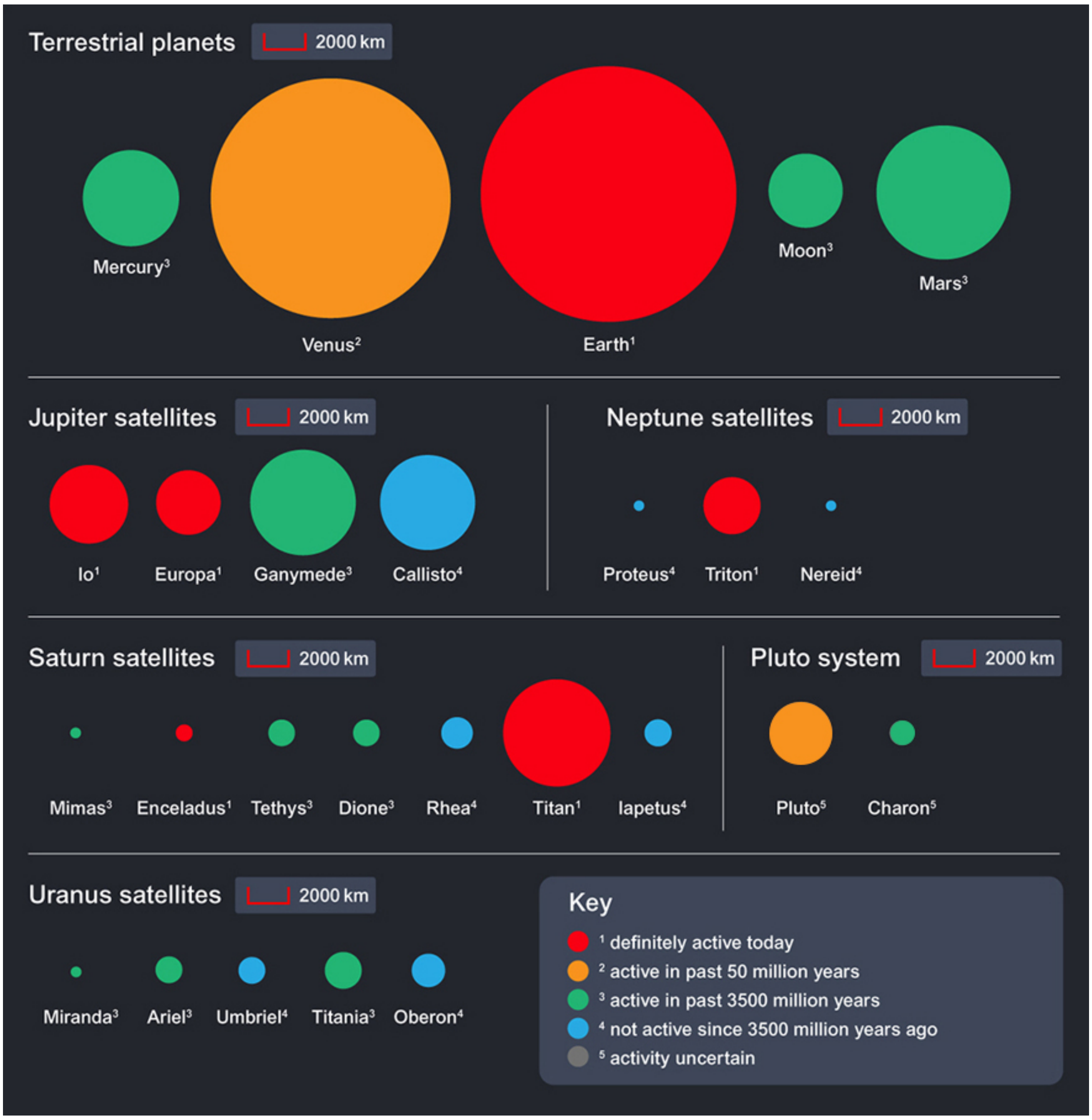

Figure 4 The largest solid bodies in the Solar System

Saturn's rings are made of myriads of brick-sized lumps of ice, individually too small to be regarded as moons. However, there are some genuine moons among the rings. In Figure 5, captured by the Cassini orbiter in 2013, you can see Pan, a 28-km long 'shepherd moon' whose orbit lies in a 325-km wide gap in the rings.

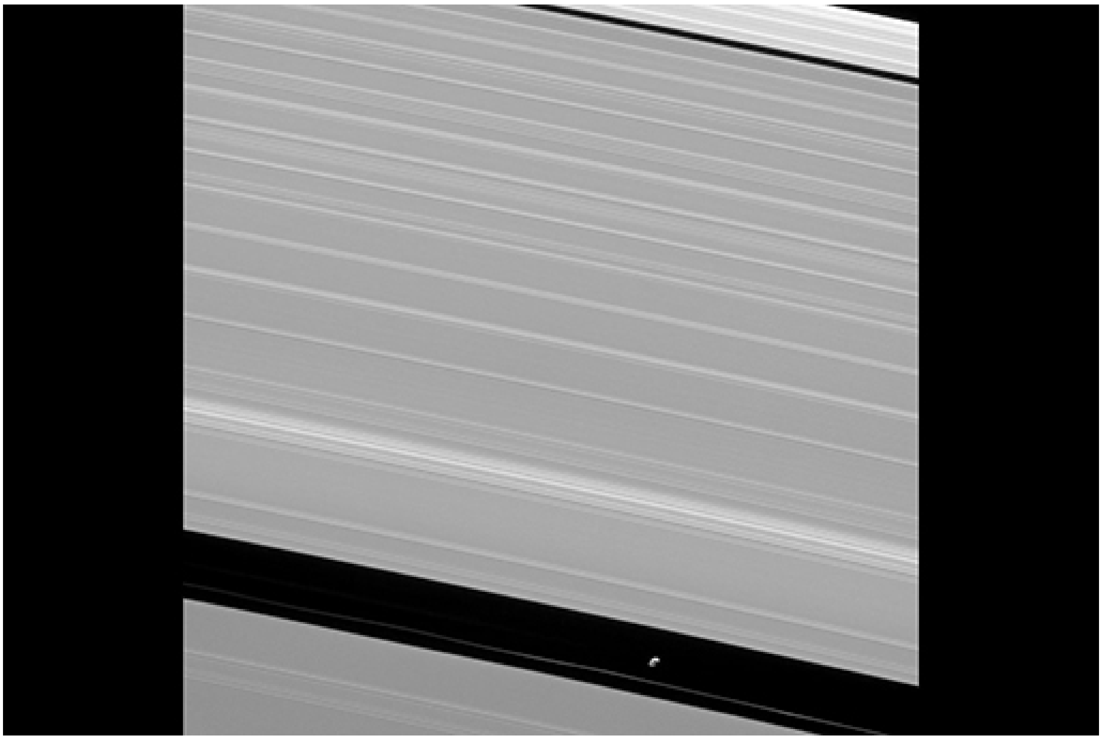

Figure 5 Pan orbiting among Saturn’s rings

Figure 6 was captured looking south onto Saturn’s rings by the Cassini orbiter in 2009, when Saturn’s ring-plane was almost exactly edge-on to the Sun. It shows the 86-km long moon Prometheus and its very elongated shadow cast onto the rings to its right (faint thin line crossing the wide grey ring about halfway up the image). To its left, you can see the disturbances in a narrow ring (called the F-ring) caused by the gravitational attraction of Prometheus which is orbiting anticlockwise, faster than the particles in the F-ring.

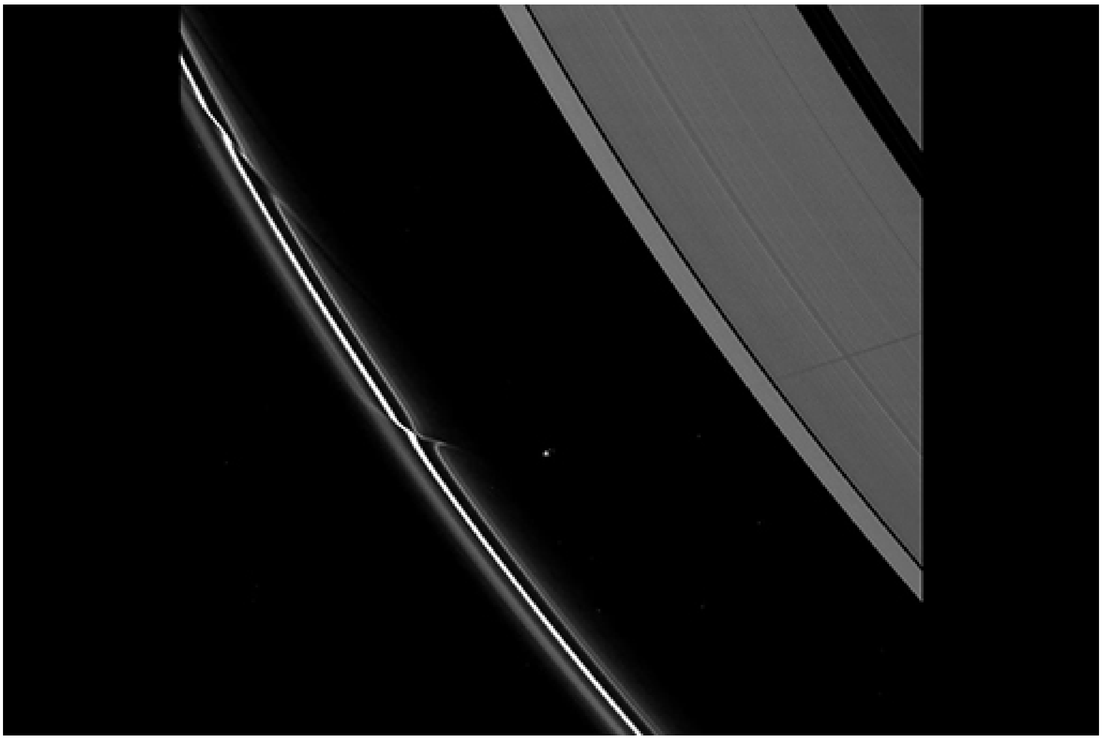

Figure 6 Prometheus perturbing Saturn’s F-ring

A few moons actually swap orbits. Figure 7 shows Janus (right) and Epimetheus (left) as seen in 2006 by the Cassini orbiter. Janus is 203 km long and Epimetheus is 130 km long. They look similar in size because in this view Janus was further away (492 000 km, whereas Epimetheus was only 452 000 km away). One orbits slightly closer to Saturn than the other, but about every four years they swap over.

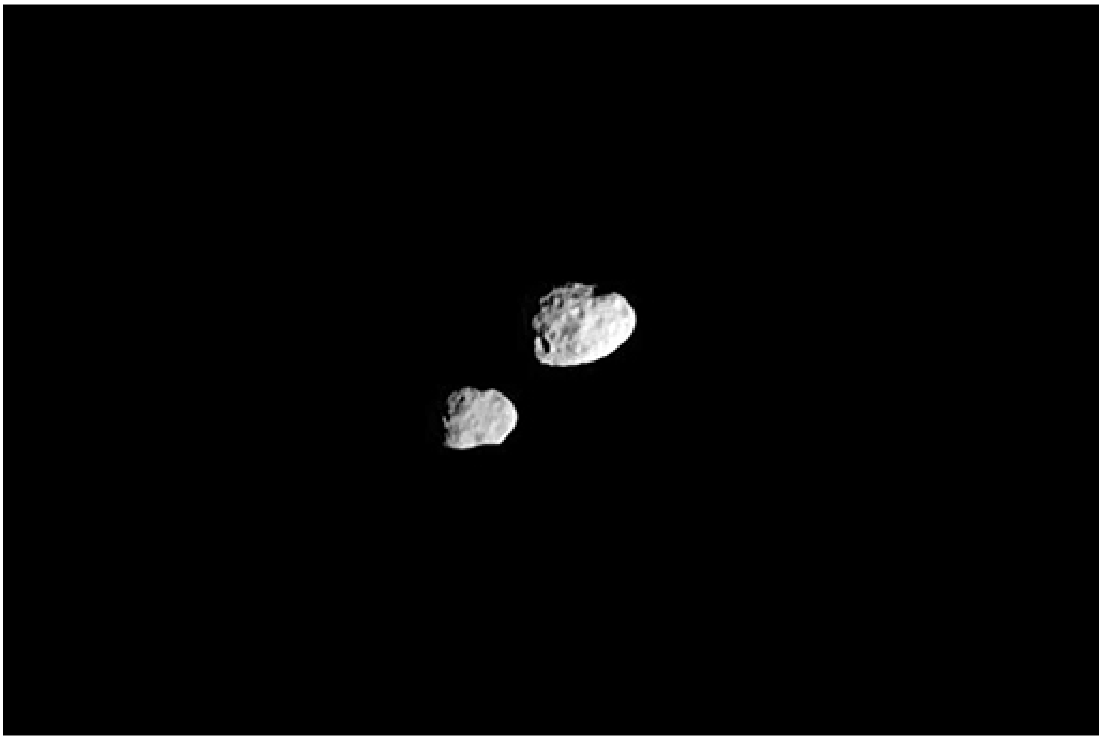

Figure 7 Janus and Epimetheus

Figure 8 is a close-up colour view of Epimetheus, imaged by the Cassini orbiter from a range of 74 600 km. The large crater in the lower centre, Hilairea, is 33 km across.

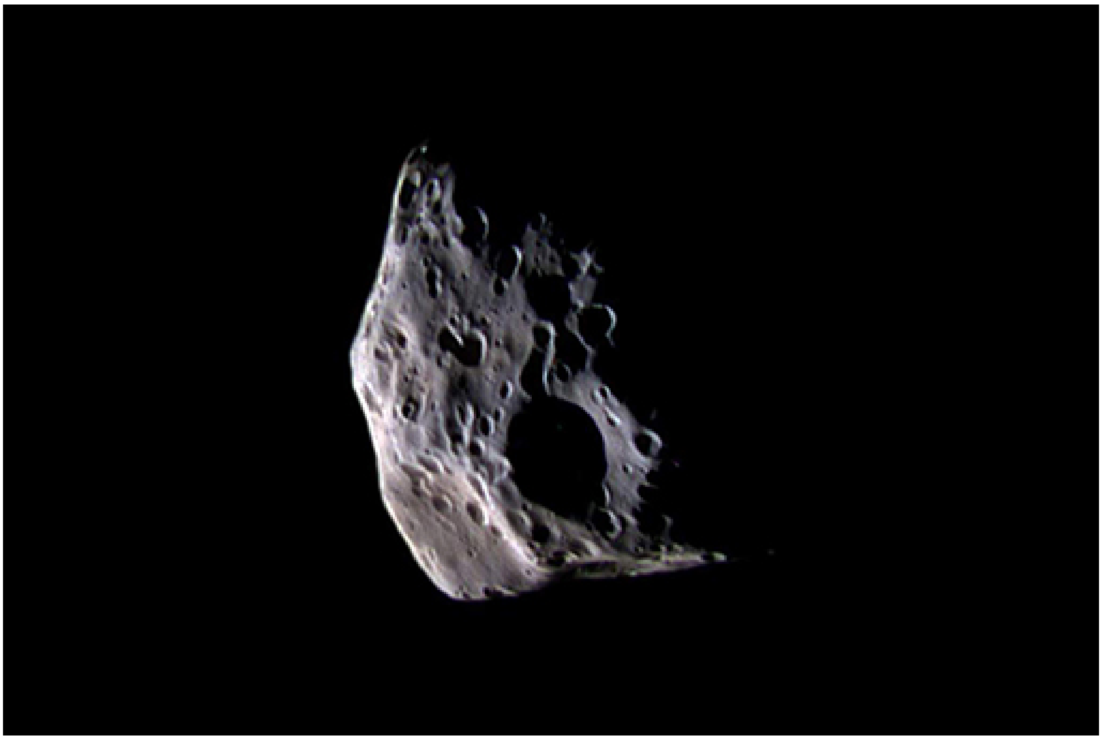

Figure 8 Epimetheus: Up-close and colourful

Figure 9 is a Cassini orbiter image with the south polar region of Saturn's second-largest moon Rhea (1527 km in diameter and heavily cratered) in the foreground. Beyond it is a foreshortened view of part of Saturn's rings (the planet itself is out of shot to the left) and beyond them Dione (1123 km in diameter). Rhea and Dione are large enough for their own gravity to pull them into spherical shapes, unlike the smaller moons in the earlier images.

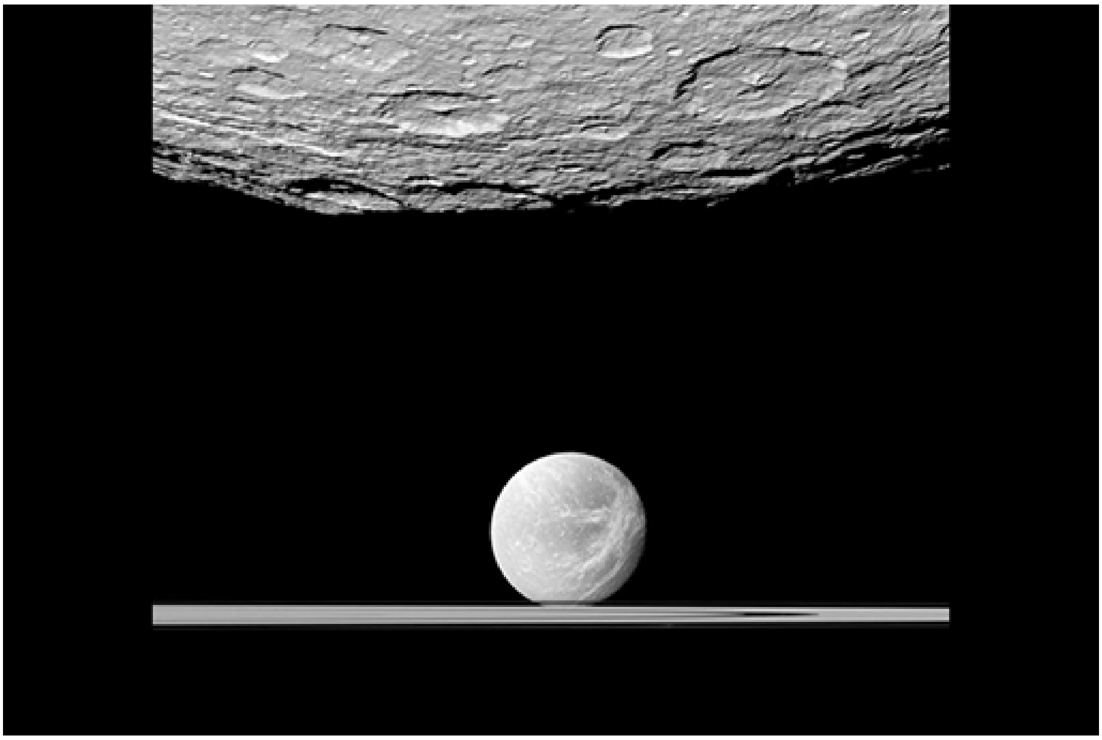

Figure 9 Rhea and Dione

Figure 10 is a colour close-up of part of Enceladus, one of the smallest spherical moons of Saturn. The largest crater in this view is about 20 km across. Many of the craters have been cut by fractures and at the upper right is a region so heavily fractured that no traces of craters remain.

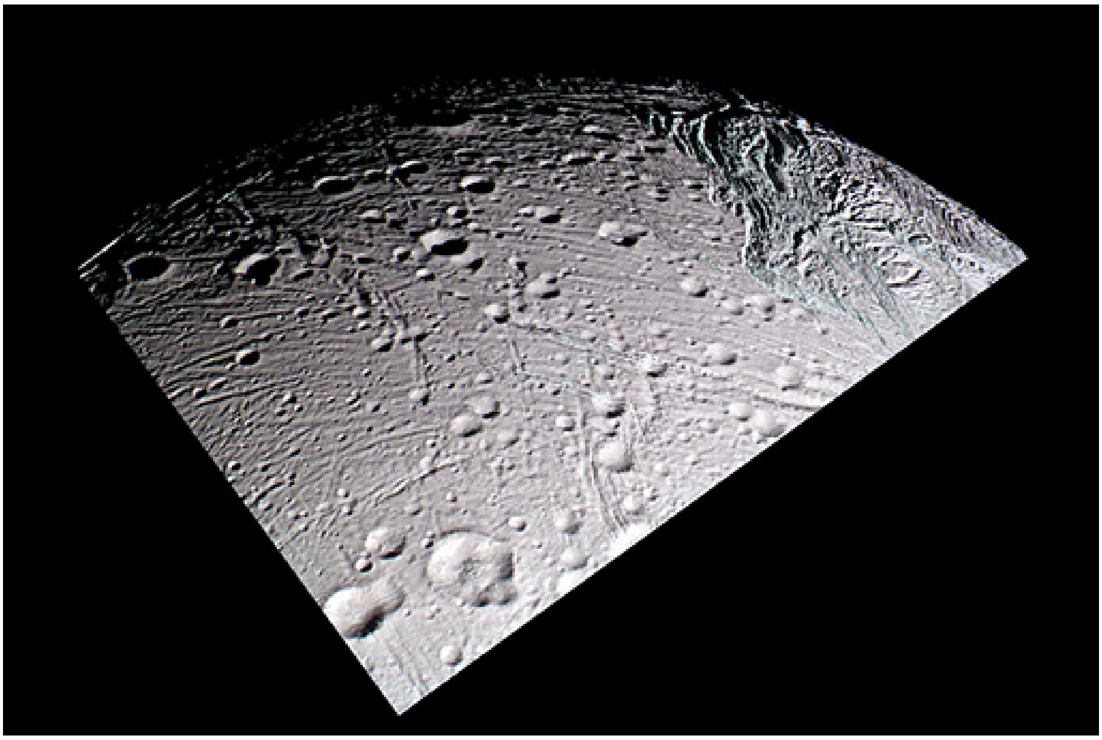

Figure 10 Contrasting terrains on Enceladus

Figure 11 is a Cassini image looking at the night side of Enceladus, at the bottom. Jets of ice particles spout from cracks near the moon's south pole and catch the sunlight as they rise above the surface.

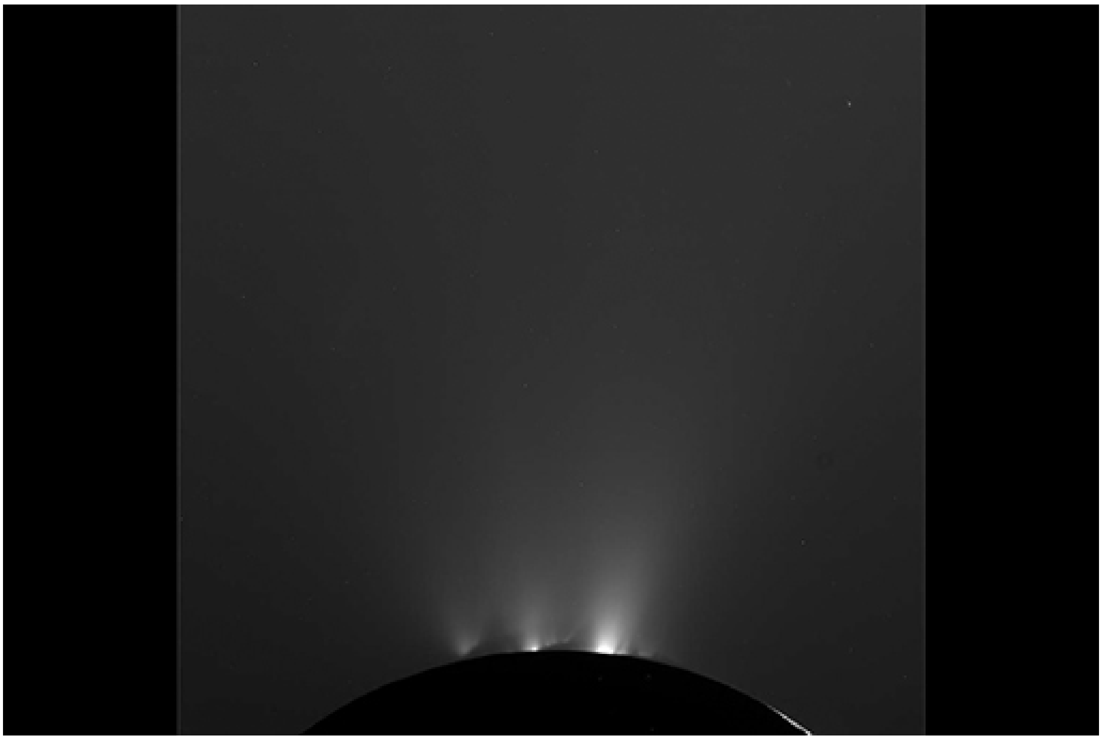

Figure 11 Erupting plumes on Enceladus

Titan is Saturn's largest moon, 5151 km in diameter and the only moon in the Solar System to have a dense atmosphere. This natural-colour image from the Cassini orbiter (Figure 12) shows the dense orange hydrocarbon smog with a blue haze layer above. A vortex pattern lies above the south pole. To see the surface of Titan, either special filters are used to accept only the wavelengths of light that the smog does not affect, or radar is used to penetrate to the surface.

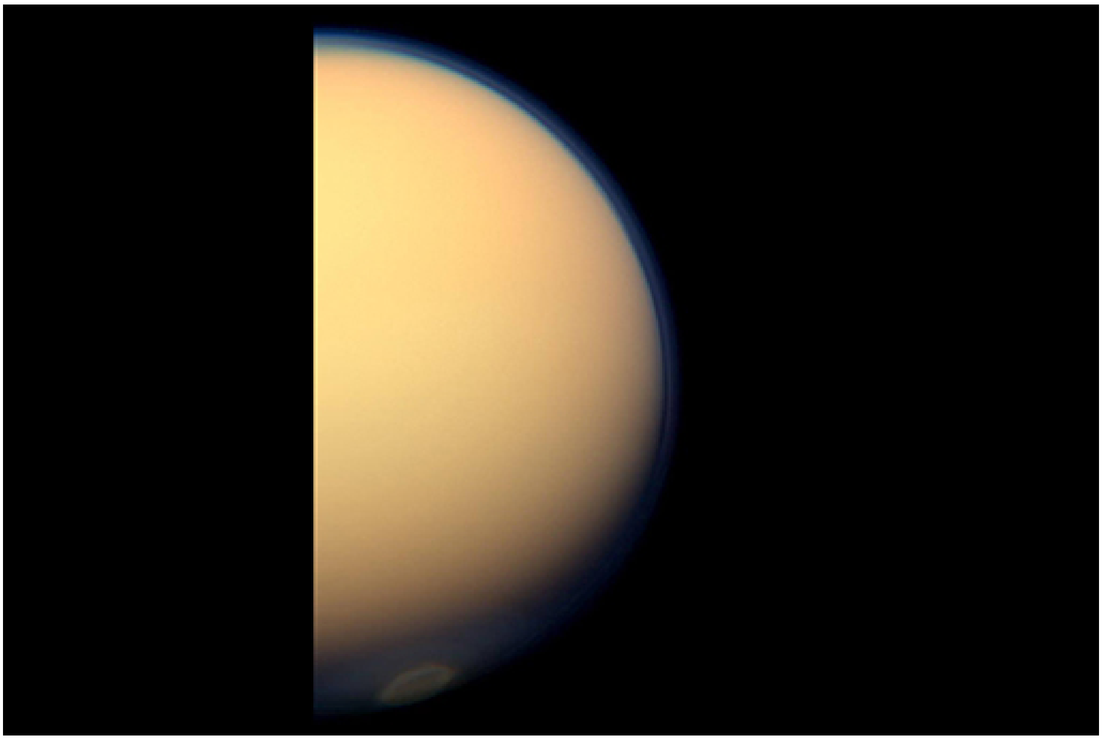

Figure 12 Natural colour view of Titan

And here (Figure 13) is what radar shows through all Titan's haze – rugged terrain with rivers feeding into large lakes. This one, named Ligeia Mare, is in Titan's north polar region. The lake is probably mostly liquid methane. The rugged terrain is water-ice, behaving like rock.

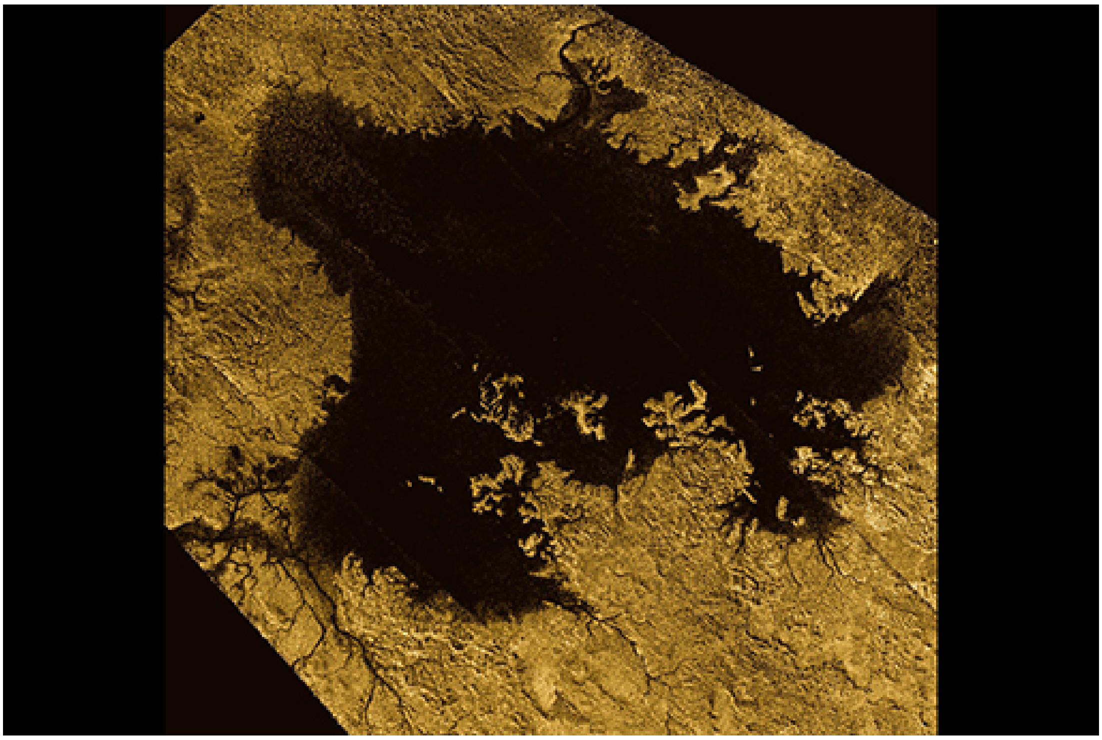

Figure 13 Radar view of a lake on Titan

Figure 14 is the best sort of view you can get of Titan's surface from a distance without using radar. Cassini recorded this using a narrow-band near-infrared filter to accept light at 938 nanometres wavelength, which is just about able to penetrate the haze. The dark patch near the north is a large lake called Kraken Mare that has been imaged by radar. The equatorial dark patches may be dry sea-beds, but have no liquid at present.

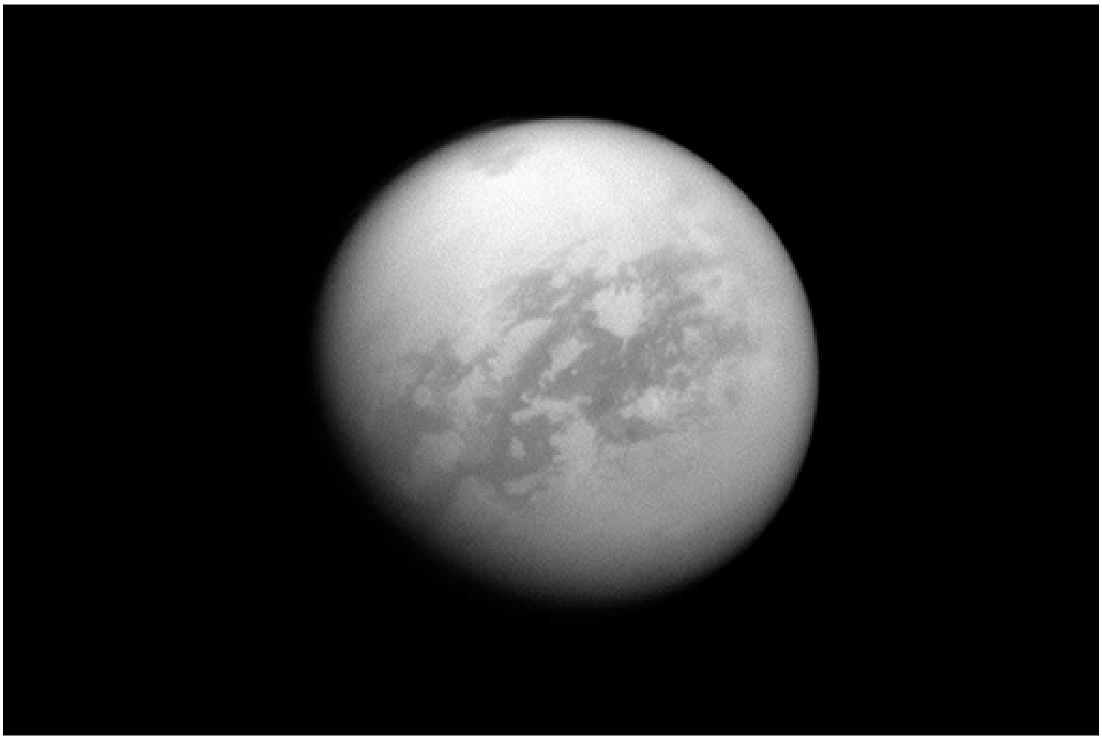

Figure 14 Peering through Titan's haze

This is Iapetus (Figure 15), 1470 km in diameter. It is Saturn's outermost large satellite and was discovered in 1671 by Giovanni Domenico Cassini (after whom the Cassini orbiter spacecraft is named). All Cassini could see of Iapetus through his telescope was a tiny speck of light, but he noted that it is always much fainter when on one side of Saturn than when on the other. From this simple observation, he correctly surmised that Iapetus keeps the same face towards Saturn throughout its orbit and that its leading hemisphere must be much darker than its trailing hemisphere. You will soon discover that most moons do keep the same face towards the object they are orbiting. However, Iapetus' asymmetric brightness is unusual. The side that always faces forward as Iapetus moves round its orbit (its leading hemisphere) has become coated in dark, reddish dust collected from space. The other side is highly reflective ice.

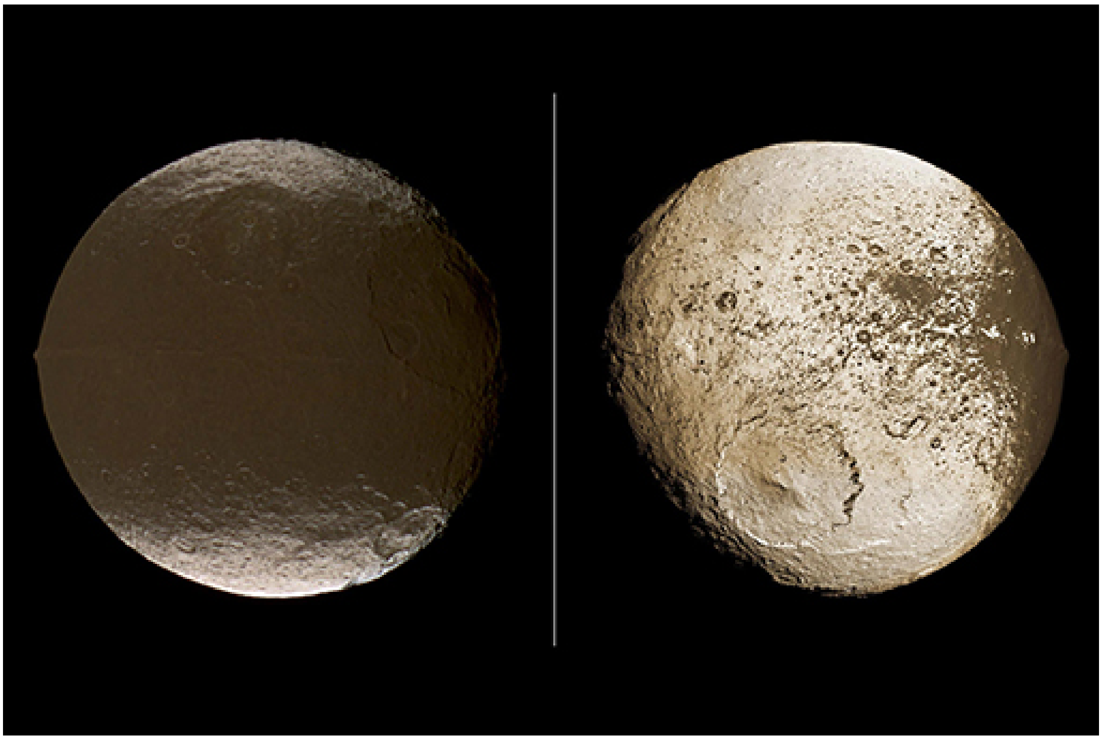

Figure 15 Iapetus' two contrasting hemispheres

This is arguably the place in the Solar System, beyond the Earth, most likely to host life. It is not Mars, but a moon of Jupiter called Europa (Figure 16). It is only slightly smaller than our Moon and it is probably made of similar stuff except that it has an outer layer of ice. The way the icy surface has become cracked and shunted around suggests that there is a liquid water layer between the solid icy shell and the rocky interior. The images used here were recorded by NASA's Galileo orbiter in 1996 and 1997.

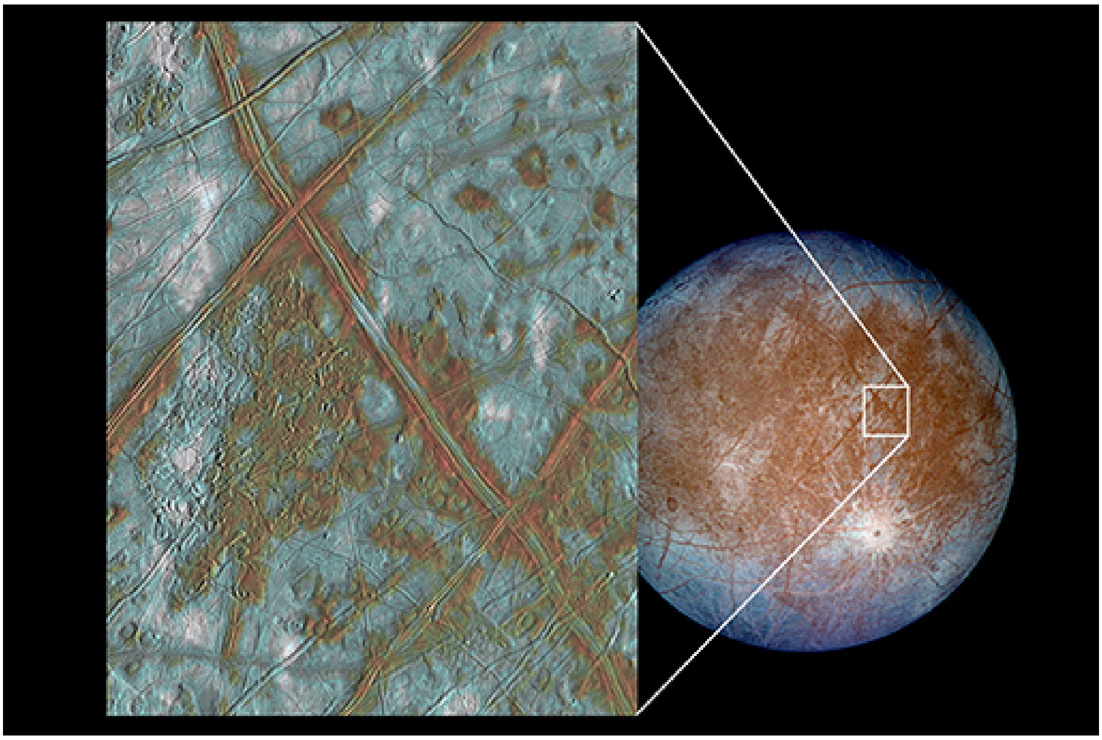

Figure 16 Europa's disrupted icy surface

The most volcanically active body in the Solar System is Jupiter's moon Io (Figure 17). It is a fraction bigger than our Moon and is the only other large moon to have a rocky, rather than icy, surface. It is coloured yellow by sulfur compounds. The two views here were recorded by NASA's Galileo orbiter in April and September 1997. The large orange ring is fall-out from a previous eruption of the volcano Pele Patera. Note the grey deposit to its right, erupted from the volcano Pillan Patera between the dates of the two images.

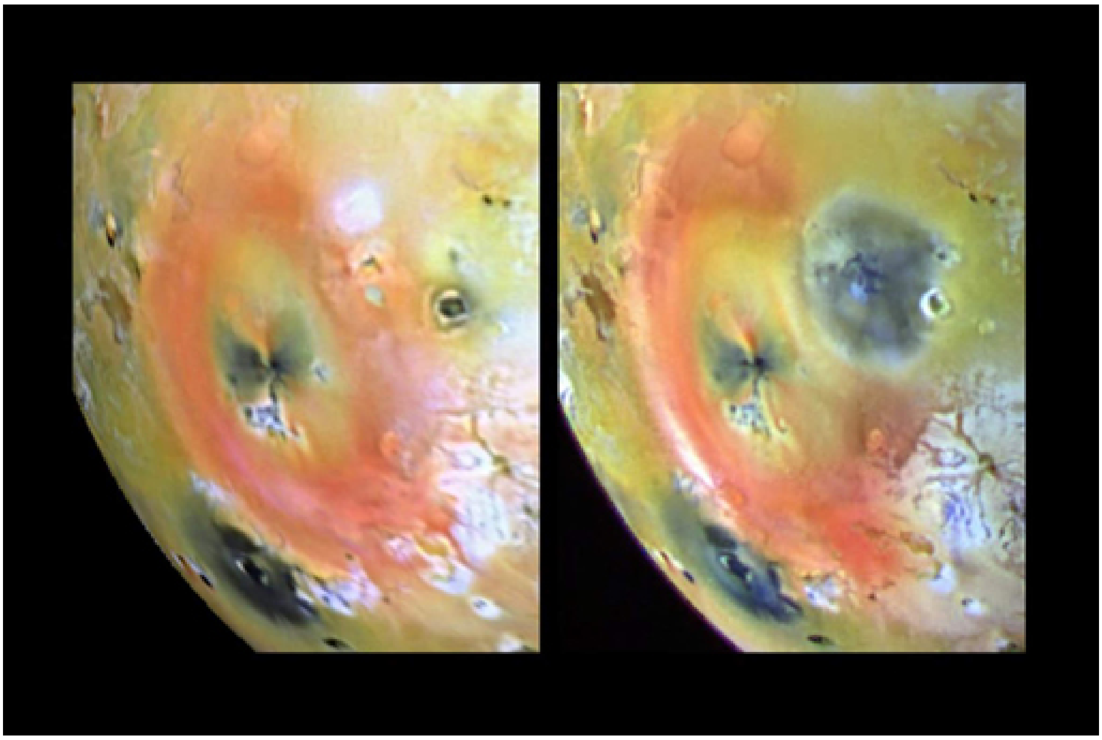

Figure 17 Changes on Io

Figure 18 might look like an artist's impression for a science fiction story, but it is a genuine image sent back by a Japanese lunar orbiter called Kaguya (also known as SELENE) in December 2007. The view is across the lunar south pole and consequently the Earth is upside down too, with its South Pole towards the top. The shadow-filled crater below right of the Earth is named Shackleton and is 21 km in diameter. The lunar south pole is inside Shackleton, and the shadow within it, and inside some neighbouring craters, is permanent. There is good evidence that quantities of water-ice are mixed among the lunar soil (or regolith) in these permanently cold sites.

Figure 18 Earth on the lunar horizon

Figure 19 is one from the glory days of Apollo in 1971. Apollo 15 commander Dave Scott is seen beside the Lunar Roving Vehicle on the rim of a lunar valley, Hadley Rille, believed to have been formed by flowing lava. The rille snakes away northwards into the distance.

Figure 19 On the Moon's surface

No one should be in any doubt that the Apollo landings were real. Figure 20 is the Apollo 15 landing site imaged from lunar orbit in March 2010 by the Lunar Reconnaissance Orbiter. Spacecraft from other nations have imaged the landing site too. Near the centre is the Apollo 15 ‘descent stage’, casting a shadow to its right. This was designed to be left on the surface when the ascent stage took off. Trails of scuffed-up regolith made by the astronauts on foot are dark lines. The twin wheel-tracks of the Lunar Roving Vehicle are harder to make out. The area shown is about 400 m across.

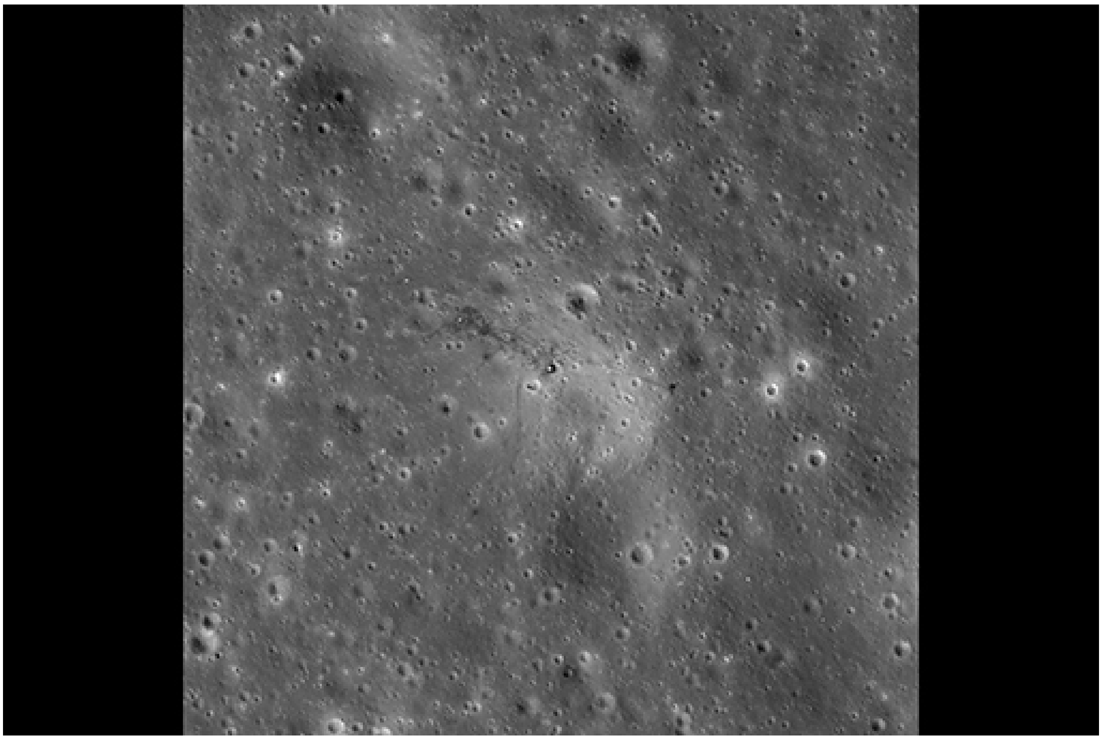

Figure 20 Apollo 15 landing site

Figure 21 is Phobos, the larger of the two small moons of Mars. It is only 22 km long and is almost certainly an asteroid captured into orbit about Mars. Several sets of grooves cut across the surface and are thought to be the trails made when Phobos passed through hails of debris thrown up by impacts on Mars, only about 6000 km away.

Figure 21 Phobos seen by NASA's Mars Reconnaissance Orbiter

This was an unexpected discovery. When the Jupiter-bound Galileo probe flew past the 54-km long asteroid 243 Ida in September 1993 it recorded a series of images. It was not until some of the last were downloaded five months later that Ida's 1.6-km wide moon, now named Dactyl, was noticed. Figure 22 is an image of Ida and Dactyl, with a higher resolution enlarged view of Dactyl shown in the upper right. In the twenty years since then, about 150 moons of asteroids have been discovered and seven asteroids are known to have two moons each.

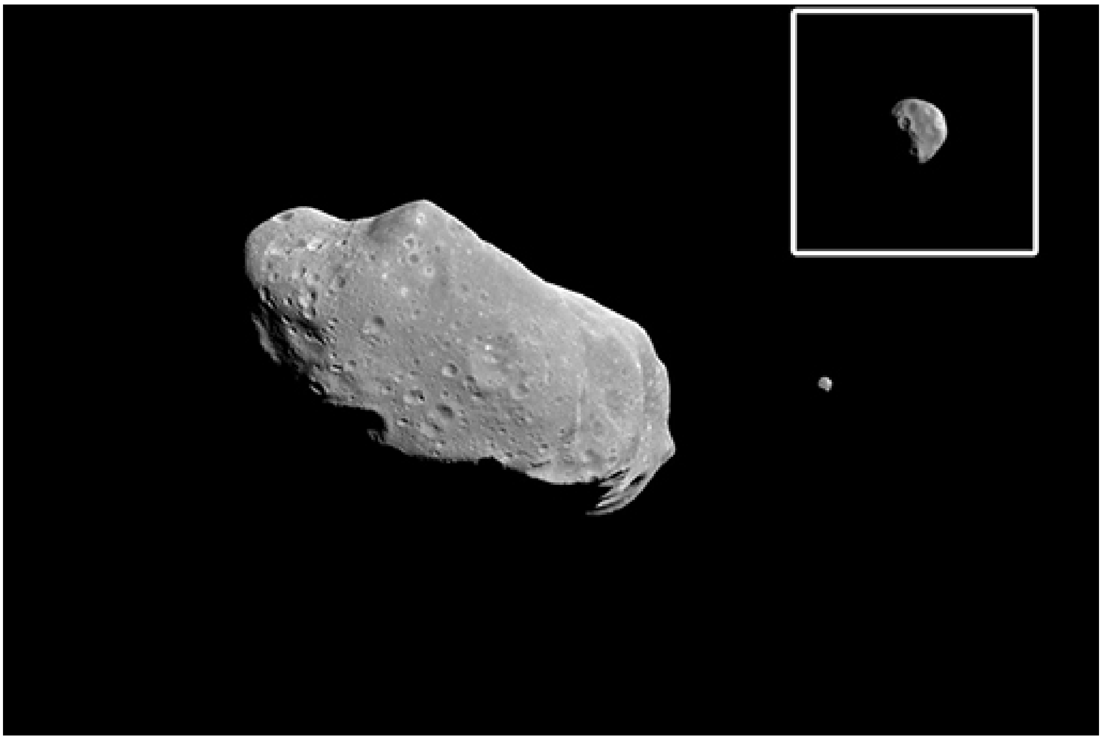

Figure 22 Ida and Dactyl

The most distant moon yet to be seen in close-up. Figure 23 is Triton, the largest moon of Neptune. It has a thin, nitrogen atmosphere and seasonal polar caps of nitrogen-ice. Only the south polar cap is visible here, because the northern one was in seasonal darkness. Beyond the polar cap is a richly textured surface formed largely by icy volcanism.

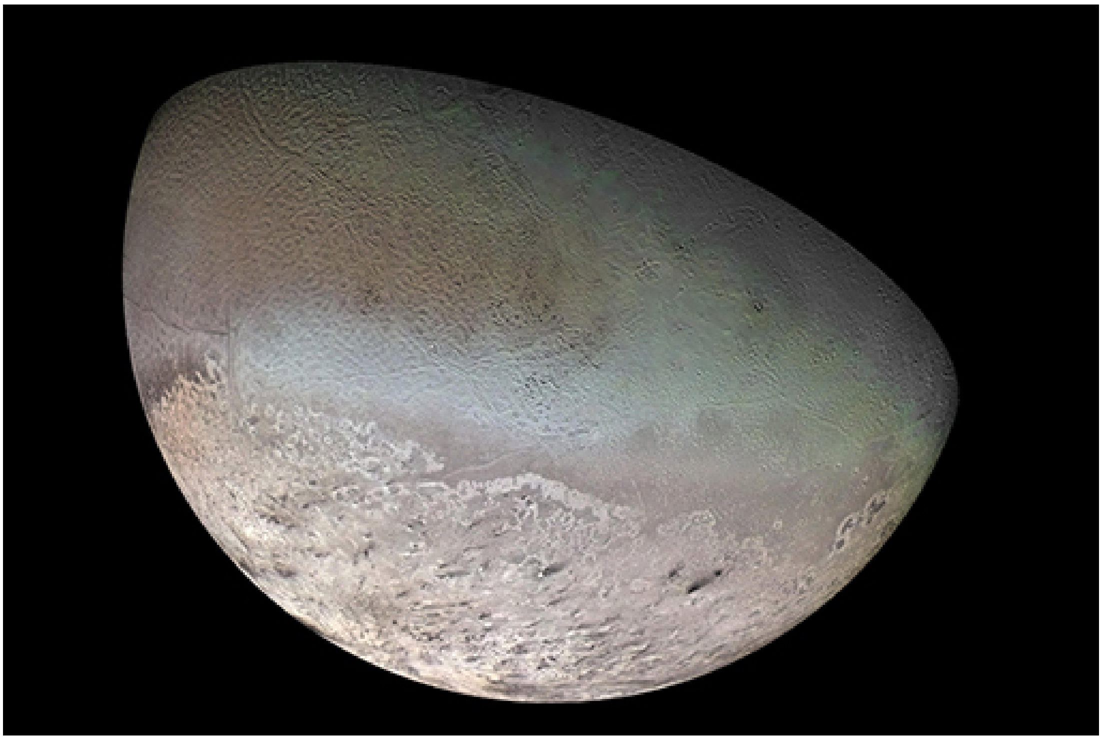

Figure 23 Global colour mosaic of Triton

Here are the five known moons of Pluto (Figure 24), imaged by the Hubble Space Telescope in 2012. Charon's diameter, about 1200 km, is over half that of Pluto. The other moons are much smaller and only appear large because of the long exposure used to reveal the smallest, Styx, which is less than 25 km across. Their orbits are almost circular but are foreshortened by the angle of viewing.

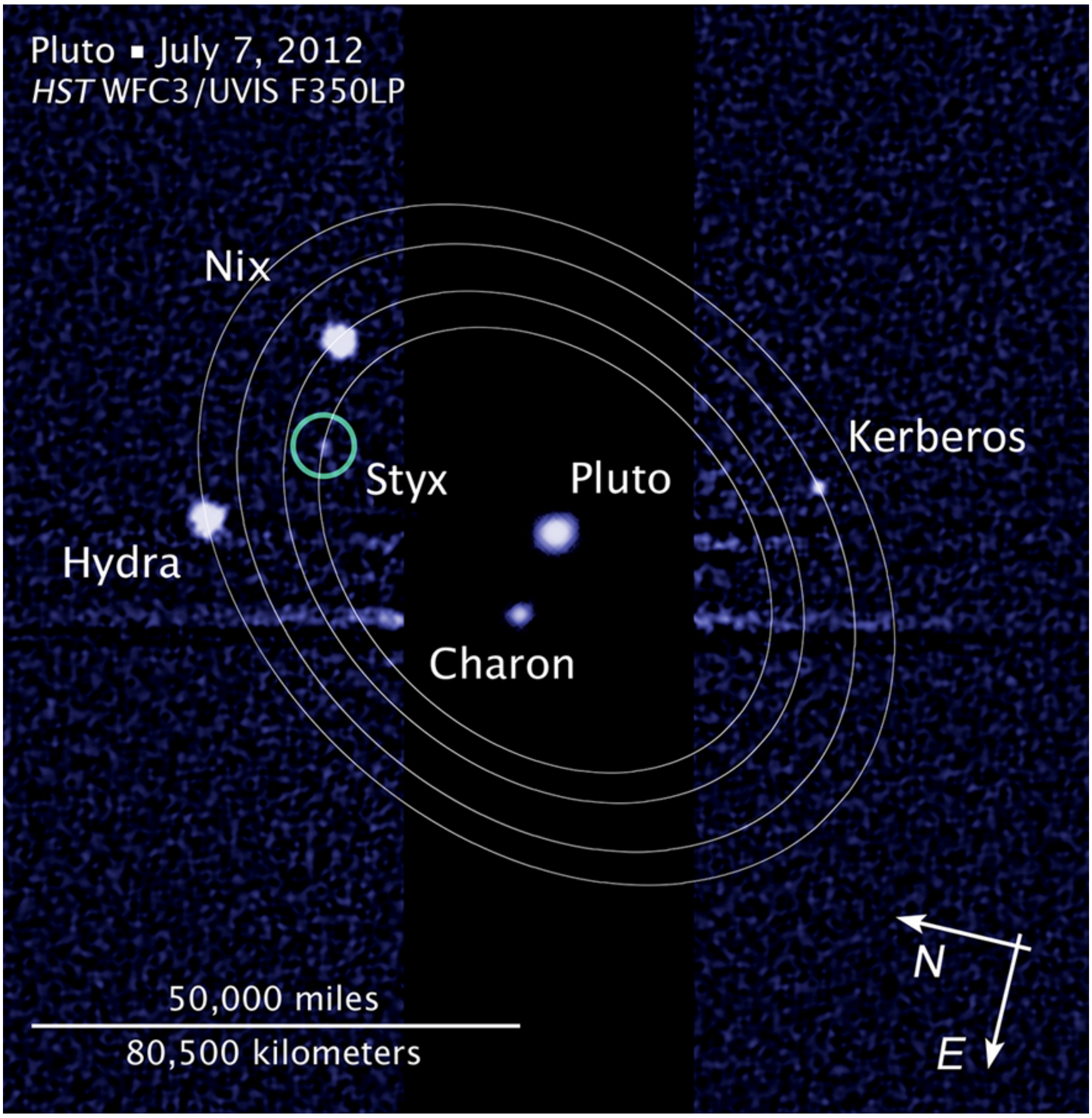

Figure 24 The five known moons of Pluto

Here is Charon as revealed close-up when NASA's New Horizons mission flew by in July 2015 (Figure 25). It is notable for the large-scale fractures that cross the disk.

Figure 25 Charon from close range

If you wanted to look into this further, you might find the following links of interest:

- Apollo 15 landing site flipbook. Visit this link for a ‘flip book’ series of images made at different times of day, allowing you to see the shadows changing.
- New Horizons. Find many amazing images from the New Horizons mission here.
- Oct-Dec 2015 final flybys of Enceladus. NASA’s Cassini probe’s final 3 flybys of Enceladus. On 14 Oct it saw the N polar region in detail for the first time. On 28 Oct it passed only 49 km above the S polar region to sample the eruption plumes.

Next it’s time for a Waltz Around Saturn (as seen in Figure 26), a video in the next section that was compiled from a sequence of images like this one, taken during Cassini’s orbital tour.

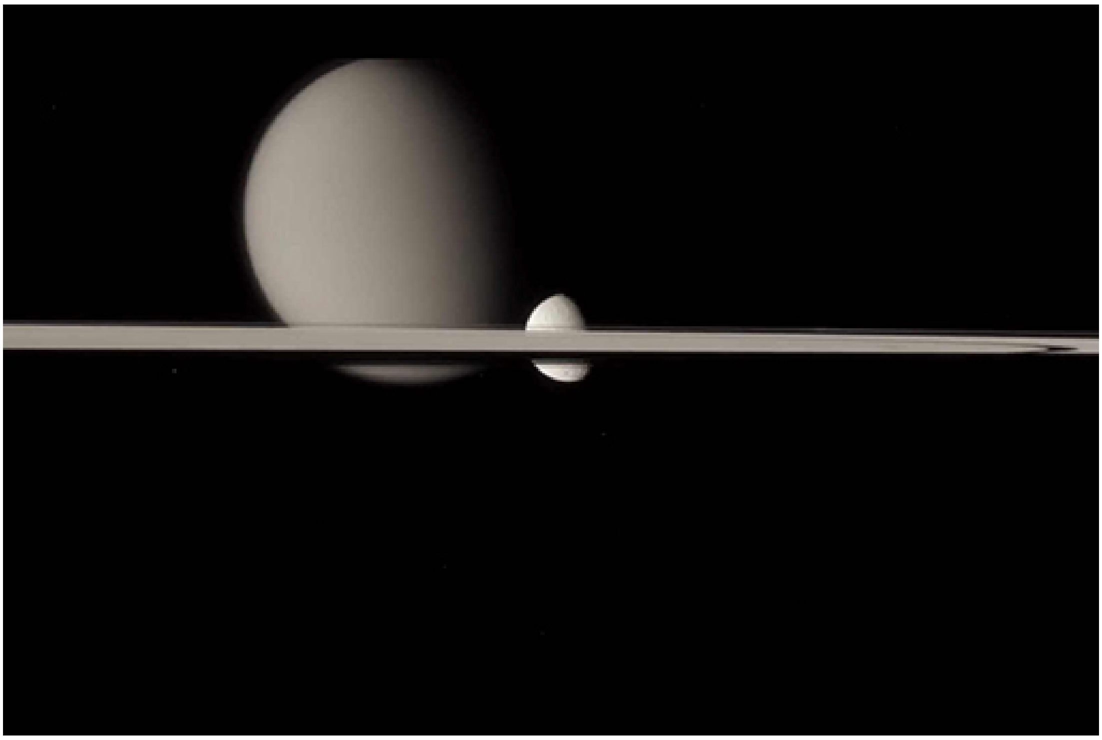

Figure 26 Waltz Around Saturn

1.5 Waltz Around Saturn

For a cultural and celestial *tour de force*, watch this *Waltz Around Saturn* video produced by Fabio Di Donato who edited together highlights from the Cassini mission during its orbital tour of Saturn. Turn your sound on, because we think that fitting the pictures to this music was a work of genius.

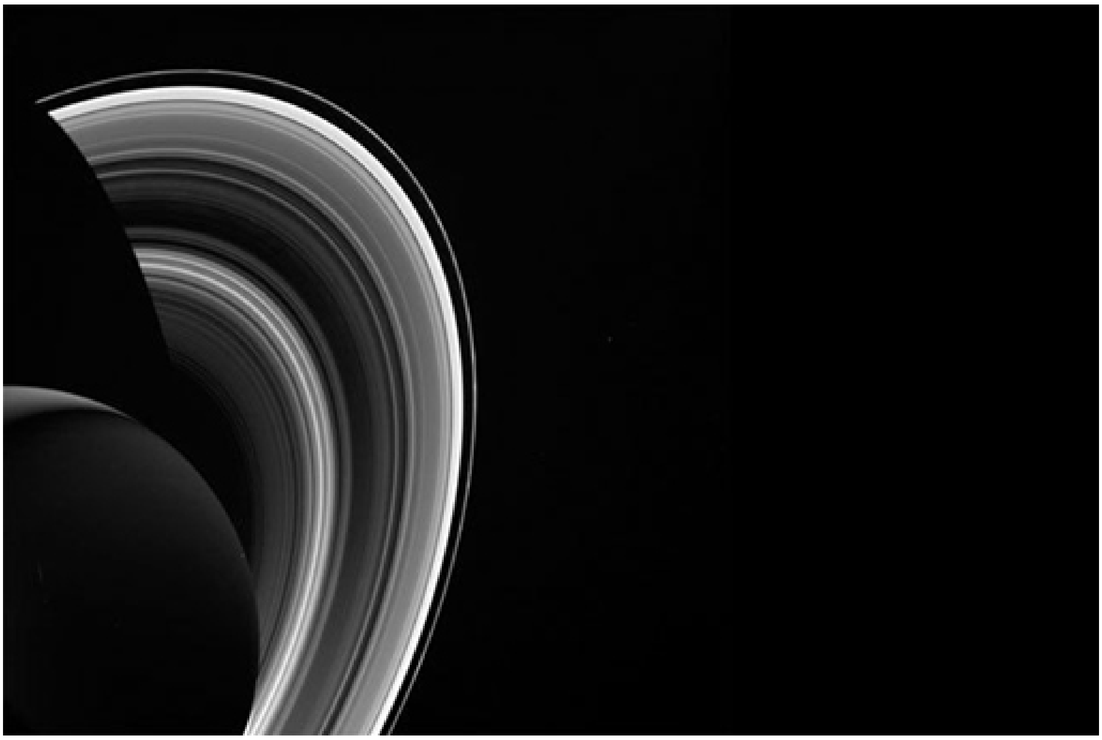

Figure 27 Highlights from the Cassini mission

Please pay attention to the warning for people with photosensitive epilepsy. Parts of the sequence may have the same effect as flash photography.

You can watch Waltz Around Saturn on Vimeo or YouTube.

1.6 What do you know?

This activity gives you the chance to find out what you already know about moons. It's a very basic non-scored quiz. Don't worry if you don't know some of the answers. Take an educated guess, and whether right or wrong you'll get some feedback that we hope will help you to understand things a little better.

Activity 1 What do you already know about moons?

Allow approximately 15 minutes.

The scale of the Solar System. How far is the Moon from the Earth?

○ 400 thousand km

Correct. The Moon is on average about 400 thousand km from the Earth. 150 million km is the distance from the Earth to the Sun, whereas 4.5 billion km is the distance from the Sun to Neptune, the most distant planet.

○ 150 million km

Too far. The Moon is on average about 400 thousand km from the Earth. 150 million km is the distance from the Earth to the Sun, whereas 4.5 billion km is the distance from the Sun to Neptune, the most distant planet.

○ 4.5 billion km

Too far. The Moon is on average about 400 thousand km from the Earth. 150 million km is the distance from the Earth to the Sun, whereas 4.5 billion km is the distance from the Sun to Neptune, the most distant planet.

Planets without moons. Which planets in our Solar System have no known moon?

○ Only Venus

No. Venus has no moon, but it is not the only planet without one. Try again.

○ Venus and Mercury

Correct. Neither Venus nor Mercury has a known moon and if one exists it can't be much more than a kilometre in size. Neptune has at least 13 moons.

○ Venus, Mercury and Neptune

No. Neptune has at least 13 moons. At least one of the others has a moon. Try again.

Orbits. What shape is a moon's orbit?

○ A circle

Not really. Some orbits are almost circular, but not quite. Try again.

○ Egg-shaped

No. Eggs have a fat end and a thin end. This is not true for orbits. Try again.

○ An ellipse

Correct. Orbits are ellipses. In many cases they are almost circular, but measured carefully the diameter across one direction is slightly longer than the diameter measured in a different direction. (We are describing a moon's orbit relative to its planet here. In fact, because a planet is travelling round the Sun, its moon's orbit traces a more complicated path.)

2 Moons and planets

Learn about orbits and rotation of moons. Find out what sorts of bodies can have moons. Learn about the Moon's phases, and apply what you have learned to a question about the crescent Moon seen from the Equator.

Can an orbiting object the size of a toaster qualify as a moon? How has the number of known moons in the Solar System changed in the past twenty years? Which planets have no moons? What is a 'captured' moon?

In this video Christine Shupla introduces some fundamental features of orbits of the Solar System and what it is about an object that qualifies it as a moon.

Video content is not available in this format.

2.1 The Moon's orbit

As you have just heard, a moon is a natural satellite that orbits another, always larger, Solar System body (sometimes called its 'primary'), which in turn orbits the Sun.

In the early 1600s, the Italian astronomer Galileo Galilei made improvements to his telescope design, which enabled him to observe the skies in greater detail than ever before. Using this telescope, in 1610, he documented the presence of four bodies that were orbiting the giant gas planet Jupiter.

This was a major breakthrough in human understanding of the Solar System and Earth's place in it; until these observations of four moons of Jupiter, the prevailing view was that the Earth was at the centre of the Universe and all motion was centred on it. However, if Jupiter had moons of its own in orbit around it, then clearly this was not the case.

Most orbits in the Solar System are slightly elliptical, meaning that at different times during a moon's orbit, it moves closer to, or further away from, its planet. The point at which an orbiting body is closest to its planet is called 'perigee' for anything orbiting the Earth, whereas the term 'periapsis' is the general term for orbits around any object. The furthest point of an orbit is called the 'apogee' in the case of an orbit round the Earth, whereas the general term is 'apoapsis'.

In the video the elliptical shape of the orbit has been exaggerated for clarity.

Video content is not available in this format.

(Please note this video has no spoken audio.)

2.2 Prograde orbits

In a prograde orbit the moon revolves in its orbit in the same direction as the planet rotates about its axis. Most of the large moons in the Solar System have prograde orbits. This means that they orbit their planet in the same direction as the planet is rotating. Earth's own Moon is a good example of this type of orbit.

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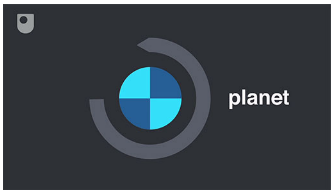

(Please note this video has no spoken audio.)

2.3 Orbital inclination

Prograde moons typically orbit their primary planet close to the planet's equatorial plane. That's true of the Moon's orbit too, but it is more useful to relate the Moon's orbit to the plane of the Earth's orbit round the Sun, which is called the ecliptic plane. The Moon's orbital plane is inclined about 5° away from the ecliptic plane.

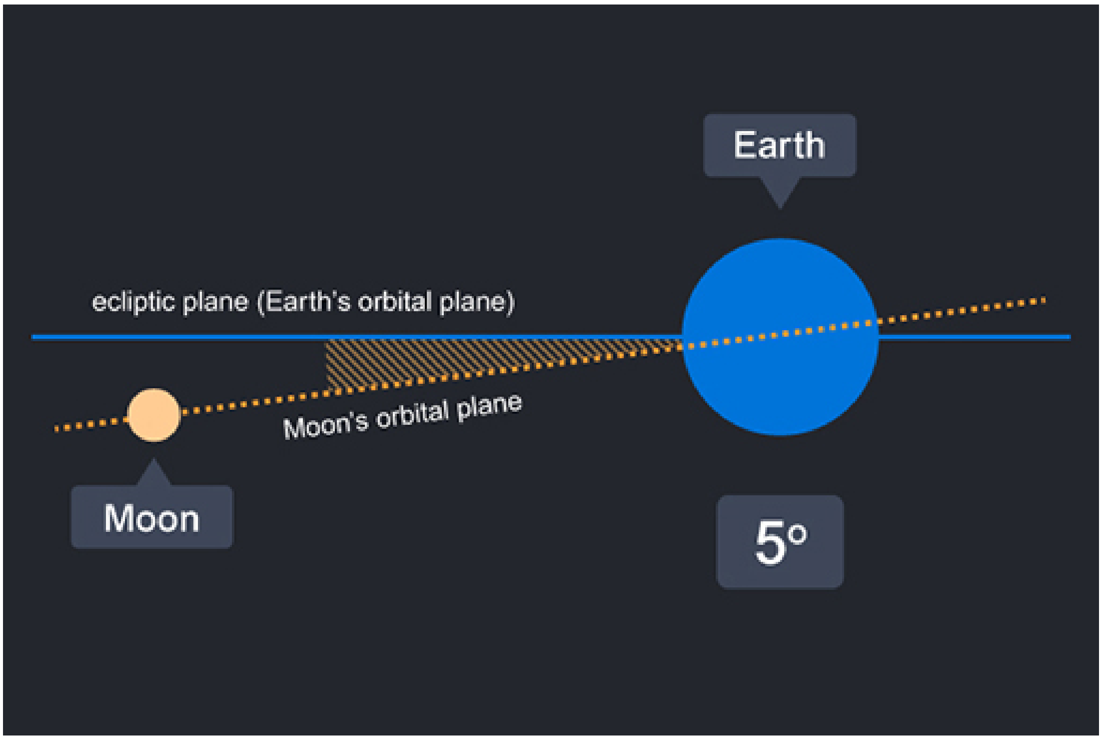

Figure 28 The orbital planes of the Earth and Moon are at an angle of 5 degrees (written 5°) to one another. The angle as drawn is exaggerated for clarity

2.4 Retrograde orbits

Although many moons in the Solar System follow prograde orbits, there are some notable exceptions. The gas giant planets Jupiter, Saturn, Uranus and Neptune have several small outer moons that follow retrograde orbits; this means that they orbit their planet in the opposite direction to the planet's rotation. In a retrograde orbit, a moon revolves in its orbit in the opposite direction from that in which the planet rotates about its axis.

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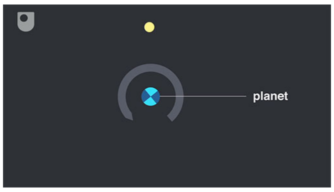


(Please note this video has no spoken audio.)

2.5 Triton's orbit around Neptune

Triton, Neptune's largest moon, stands out among retrograde moons. Although most retrograde moons are small and distant from their planets, Triton is large and its orbit is relatively close to Neptune.

Moons with retrograde orbits tend to have much more inclined orbital planes relative to their planet's equatorial plane than those with prograde orbits. In the case of Triton, this inclination is currently around 157°. Such moons are thought to have been captured and then held in their unusual orbits by their planets, rather than forming in situ.

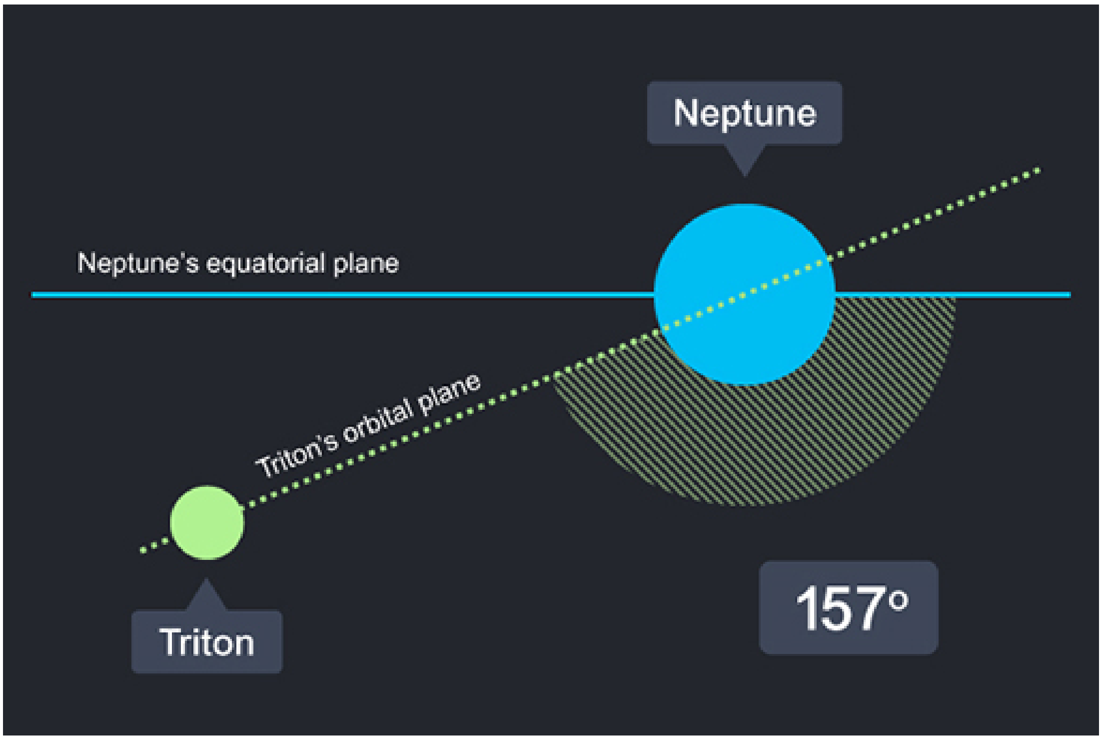


Figure 29 The orbital plane of Neptune's largest moon Triton

You may wonder why the inclination of Triton's orbit is shown as 157° rather than 23° (i.e. 180°−157°). This is just a way of showing that Triton's orbital motion is retrograde. If it was travelling in the other direction round the same orbit it would be described as a prograde orbit inclined at 23°.

2.6 Synchronous rotation

Because most moons in the Solar System are in close orbit around much larger planetary bodies, over time the speed of a moon's rotation is decreased as the tidal, or gravitational, pull between the two bodies drags on the moon's spin. Eventually, this slows down a moon's rotation so much that it completes only one rotation about its axis per orbit, resulting in the same side of the moon facing its planet at all times (known as captured rotation, or synchronous rotation). With the Earth and the Moon, these competing tidal forces have also exerted drag on the Earth's rotation, slowing its rate of spin about its axis and thus lengthening a day by almost two milliseconds per century.

Tidal forces affect you too. While standing on the Earth's surface, your head is nearly two metres further away from the centre of the Earth than your feet are. The Earth's gravitational field can be treated as if all the mass were concentrated at the planet's centre. Since the force of gravity decreases as the distance increases, your feet are pulled down slightly more strongly than your head. The anatomical consequences of this stretching are negligible for you, but for a much more extended body such as a moon, the physical consequences can be quite noticeable and in one case, as you will see later, very severe.

Video content is not available in this format.

Ever wondered where the Universe came from? Or more importantly, where it's headed? Voiced by David Mitchell, this series of 60 second animations examines different scientific concepts from the big bang to relativity, from black holes to dark matter. The series also explores the possibility of life beyond Earth and considers why David Bowie is still none the wiser about life on Mars.

2.7 Rings around planets

Tidal forces acting on moons can also be destructive, ripping apart any moon that migrates inwards too close to its planet. As the moon strays closer, the gravitational pull of the planet attracts the near-side material much more than material on the far side of the moon, deforming the moon and creating tidal bulges on both the near side and the far side. Closer still and eventually the difference between the planet's gravitational pull on the near- and far-sides of the moon overcomes the moon's internal strength. The moon begins to be torn apart. The end result is the disintegration of the moon, leaving behind only small particles of debris floating around the planet where the moon once orbited, forming rings like those seen today around Jupiter, Saturn, Uranus (Figure 30) and Neptune.

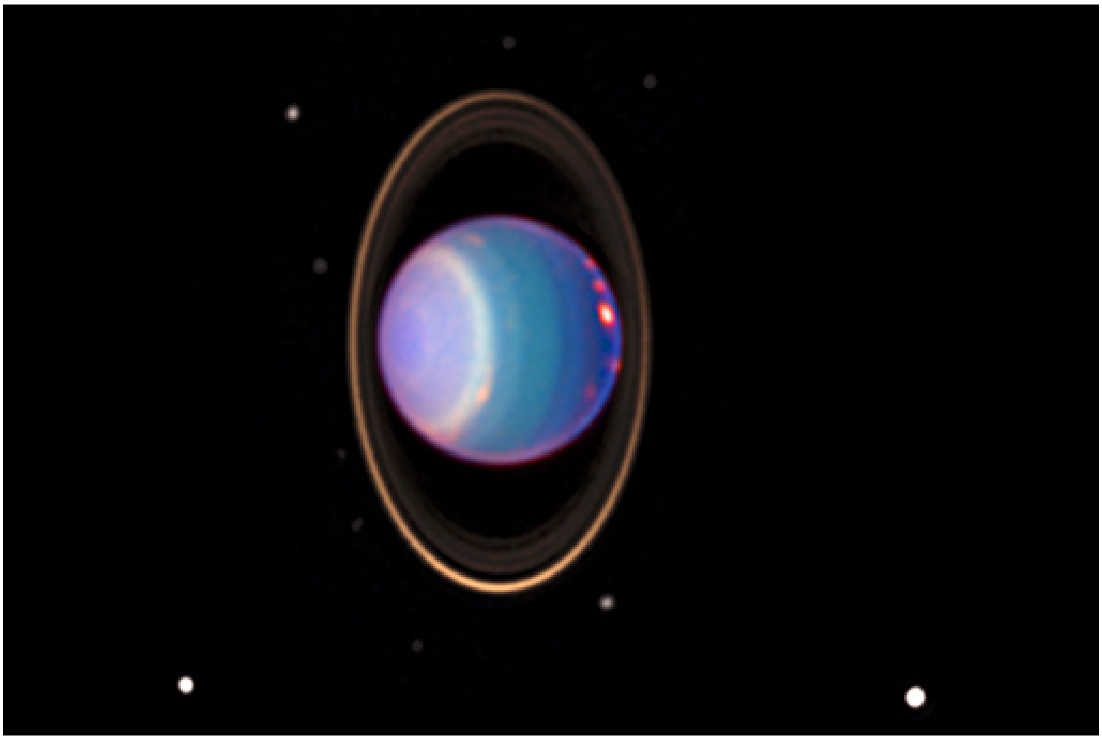


Figure 30 Rings around Uranus. Hubble Space Telescope image from August 2000, showing Uranus and several of its rings, with moons further away from the planet

The distance at which such moon destruction by strong tidal forces occurs is known as the Roche limit and varies from planet to planet, depending upon the planet's size and mass. Various small moons do exist among the debris in a planet's rings.

2.8 Are ring-particles moons?

Here's a question for you to think about. Is it acceptable to refer to small ring-particles as moons, given that there is no official lower size limit to define a moon?

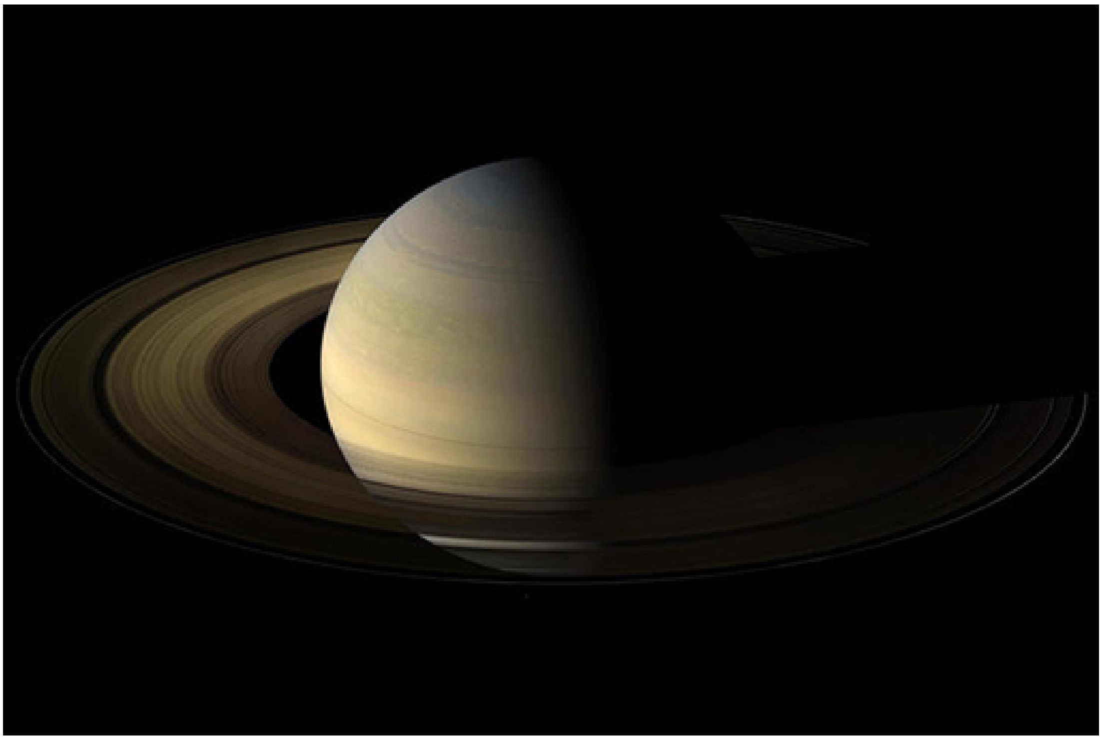


Figure 31 An oblique view across part of Saturn's rings, as seen by NASA's Cassini orbiter. The view is about 1000 km across

2.9 Small bodies can have moons

Many other objects in the Solar System, not just planets, have moons orbiting them. Sometimes, with smaller primary bodies, the moon in orbit around it may be almost the same size.

An example of this phenomenon is the dwarf planet Pluto; its moon, Charon, is so large in relation to Pluto that the centre of mass about which it orbits is not within the body of its primary, but outside, between the two bodies. Pluto and Charon each orbit their common centre of mass every six days in a synchronous rotation, in a form of binary or dual-body system.

Many objects even smaller than Pluto are known to have their own moons. The first moon of an asteroid to be discovered was Dactyl (Figure 32), found to be orbiting the asteroid known as 243 Ida by the Galileo spacecraft that flew by on its way to Jupiter in 1993.

Figure 32 Asteroid 243 Ida and its moon Dactyl, imaged in 1993 by the Galileo spacecraft. Ida is 54 km in length, but Dactyl is much smaller at less than 2 km across

2.10 Moon phases and libration

As viewed from the Earth, the disc of the Moon undergoes a complete waxing (growing) and waning (shrinking) cycle of phases once every 29 days, as varying amounts of the lunar near-side surface are illuminated by the Sun. The extent of illumination of the Moon's surface depends on where the Moon is at the time, in relation to the Earth and Sun.

The video here shows the Moon's phases throughout the year 2013. Concentrate on the main picture rather than the information around the edges. As well as the phase changes, you will notice it changing a little in apparent diameter as its distance from the Earth varies. You will also see it swinging slightly from side to side. This is called 'libration' and is because the Moon's varying orbital speed alternately gets slightly ahead of and then lags slightly behind its constant rate of rotation.

If the Moon's orbit takes it exactly between the Earth and the Sun, then the Sun is hidden by the Moon, causing a solar eclipse, but because the Moon's orbit is inclined this rarely happens.

Video content is not available in this format.

(Please note this video has no spoken audio.)

If you wanted to look into this further, you might find the following link of interest: Moon phases and libration. If you want to explore the Moon's orbital relationship with the Earth more fully than in this video, you can find explanations and other videos at this link, as well as a video of Moons phases during the current year.

2.11 How the Moon's phases look from the Earth

You see the Moon at its best after dark, when the Sun is below the horizon. Because the Moon orbits in almost the same plane as the Earth's Equator, the phases of the Moon look different depending on which side of the Equator you are standing on.

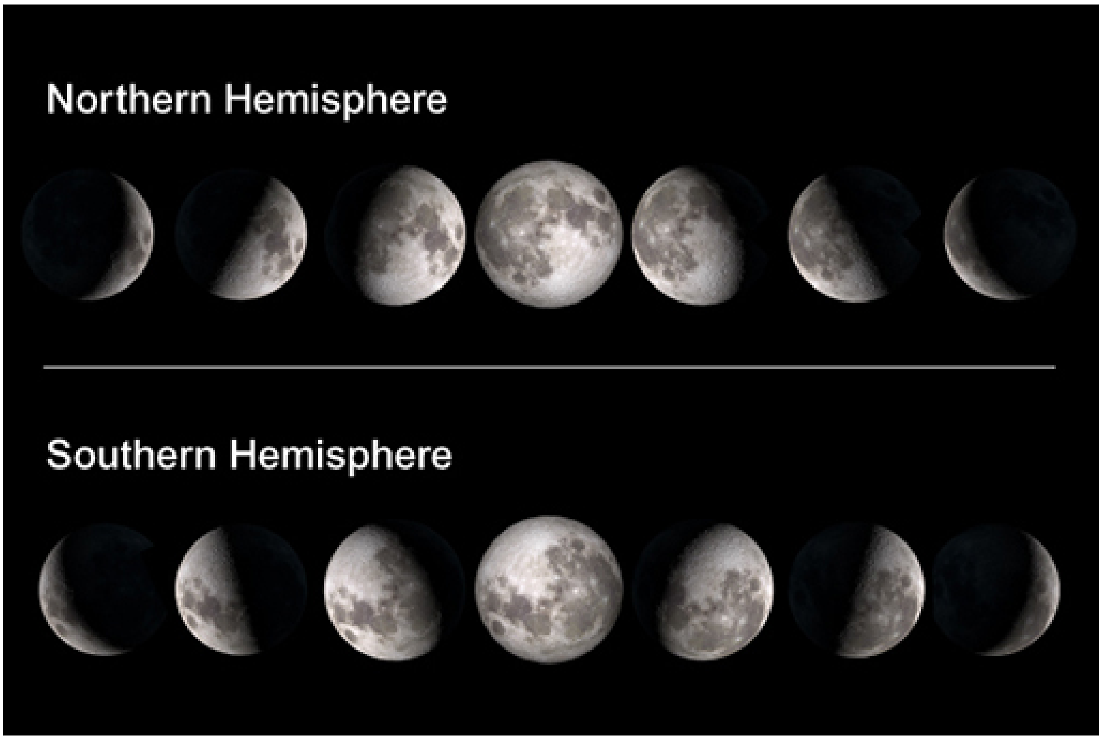


Figure 33 View of the Moon's phases from the Northern Hemisphere (top) and from a point at the same latitude in the Southern Hemisphere (bottom)

As seen from the Northern Hemisphere in Figure 33, the Moon rises in the east and moves left to right, passing to your south across the sky until it sets in the west.

However, in the Southern Hemisphere, the Moon is seen in the north at night. It rises in the east and moves right to left across the sky, passing to your north before sinking below the horizon in the west.

When the Moon's phase is a crescent, the direction to the Sun is away from the sunlit part of the crescent, at a right angle to the horns of the crescent. If the Sun is below the horizon, as it needs to be for the crescent Moon to be visible, this means that the sunlit part of the crescent must be tilted downwards. Therefore, for observers in the Northern Hemisphere, a waxing crescent forms a growing 'D' shape (by which we mean the mirror-image of a 'C') with the curve tilted slightly down, and a waning crescent forms a 'C' shape (also with the curve tilted slightly down). South of the Equator, the Moon waxes in a growing 'C', and wanes as a narrowing 'D', with the curve tilted slightly down in each case.

However, look for cartoon drawings of the Moon on the internet, or ask a friend to sketch a crescent Moon for you, and the chances are you will end up with a 'C' shape - despite the fact that most people live in the northern hemisphere and see the evening 'D' shape crescent far more often than the morning 'C' shape crescent. Is this your experience? Can you account for it?

If you wanted to look into this further, you might find the following link of interest: Even The Simpsons gets it wrong. A C-shaped crescent Moon was wrongly shown in the evening sky in Springfield, where the Simpsons live (supposedly in the USA) during a guest appearance by a space entrepreneur, sparking amusing comment in the Bad Astronomy blog.

2.12 The crescent Moon seen from the Equator

If phases are inverted in the Southern Hemisphere, compared to the Northern Hemisphere, how do you think waxing and waning crescents will look at the Equator?

Figure 34 Left: waxing Moon seen after sunset at the Equator. Right: waning Moon seen before sunrise at the Equator

At the Equator, a waxing crescent will form an 'n' shape as it rises, and a 'u' shape as it sets. A waning crescent will be the opposite, rising as a 'u', and setting as an 'n'. However, 'n' shaped crescents are not visible at the Equator, because the Sun would always be above the horizon in this situation so the sunlight drowns them out. Another way to describe it is that after dark, the crescent Moon never looks unhappy seen from the Equator; it always looks like a smile.

3 What makes a moon?

Figure 35 Planets, moons and asteroids to scale

With moons so widely distributed in the Solar System, it's natural to ask what they are. There are a large number, with the majority in the outer Solar System, orbiting the giant planets Jupiter, Saturn, Uranus and Neptune. It is not believed that a moon can have a smaller moon in a stable orbit around it, and this has never been observed. What makes a moon? There are many sizes and compositions and there doesn't seem to be a single explanation that holds for all.

Even our own Moon's origin remains a topic of research.

3.1 The Moon's origin

What's the most likely origin of the Moon? There are three classic explanations but all are flawed in some way.

Video content is not available in this format.

See here for another bonus video recorded by Professor David Rothery at the 2014 Lunar and Planetary Science Conference, this time with Bill Bottke about the Moon's origin.

View at: youtube:zNNy7KAablA

If you wanted to look into this further, you might find the following links of interest:

- David Rothery talks to Bill Bottke. David Rothery recorded this bonus video message at the 2014 Lunar and Planetary Science Conference, this time with Bill Bottke about the Moon's origin.
- When did the Moon form? In this short article, David Rothery discusses two pieces of research published in 2017, which suggest pushing the date slightly earlier and modifying the mechanism to a series of slightly smaller 'giant impacts' in place of a single Moon-forming giant impact.
- Multiple impacts to make the Moon? A blog by an Open University PhD student examining alternative hypotheses.

3.2 Forming other moons

But what about other moons?

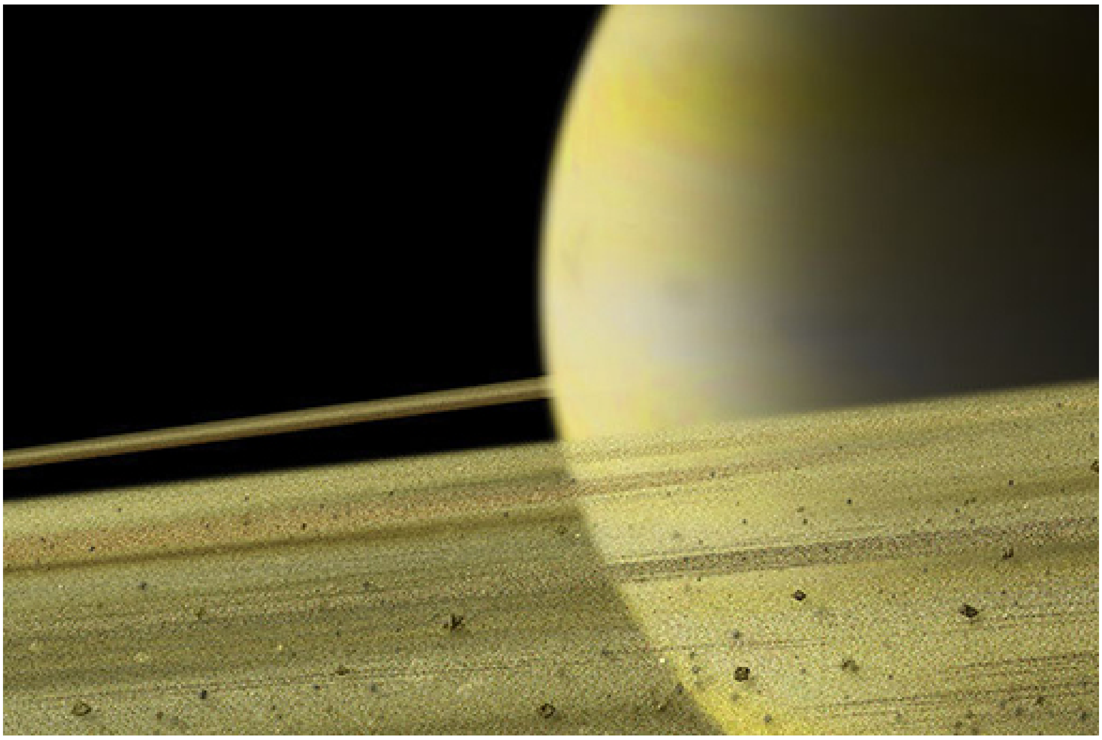


Figure 36 Forming other moons

Giant impacts can't be used to explain the numerous moons of the giant planets, or the two tiny moons of Mars. The moons of Mars, namely Phobos and Deimos, are believed to be asteroids that were captured into orbit around Mars. They have an irregular non-spherical shape and a composition similar to that of other asteroids. The same explanation applies for the small, irregular outer moons of the giant planets, many of which have orbits that are very inclined or in some cases, retrograde. But what about the large moons of the giant planets Jupiter, Saturn, Uranus and Neptune?

Most larger moons orbit very close to the planet's orbital plane and in the same direction as the planet spins (remember prograde orbits). This demonstrates that the moons share spin with their planet and this is a clue that they have a common origin.

These larger moons were probably formed in orbit around their planet from material in the proto-planetary disc that wasn't formed into the planet itself. The temperature in the centre of the disc around the Sun would have been very high near the Sun but decreasing as you move out towards the edge of the disc. There would have been a similar but less extreme temperature gradient working outward in the smaller disc surrounding each giant planet, and this could be responsible for the decrease in density with distance from the planet observed in the Galilean moons of Jupiter (the four of Jupiter's moons discovered by Galileo).

The small 'inner moonlets' of the giant planets, and their rings, are probably remains of bigger satellites that were broken up by collisions or ripped apart by tidal forces.

If you wanted to look into this further, you might find the following link of interest:
A moonlet lurking in Saturn's A Ring? An update on plans to get a spatially-resolved image of what may be a moonlet (nicknamed "Peggy") embedded in the outer edge of the densest part of Saturn's rings.

3.3 Triton – a moon with a difference

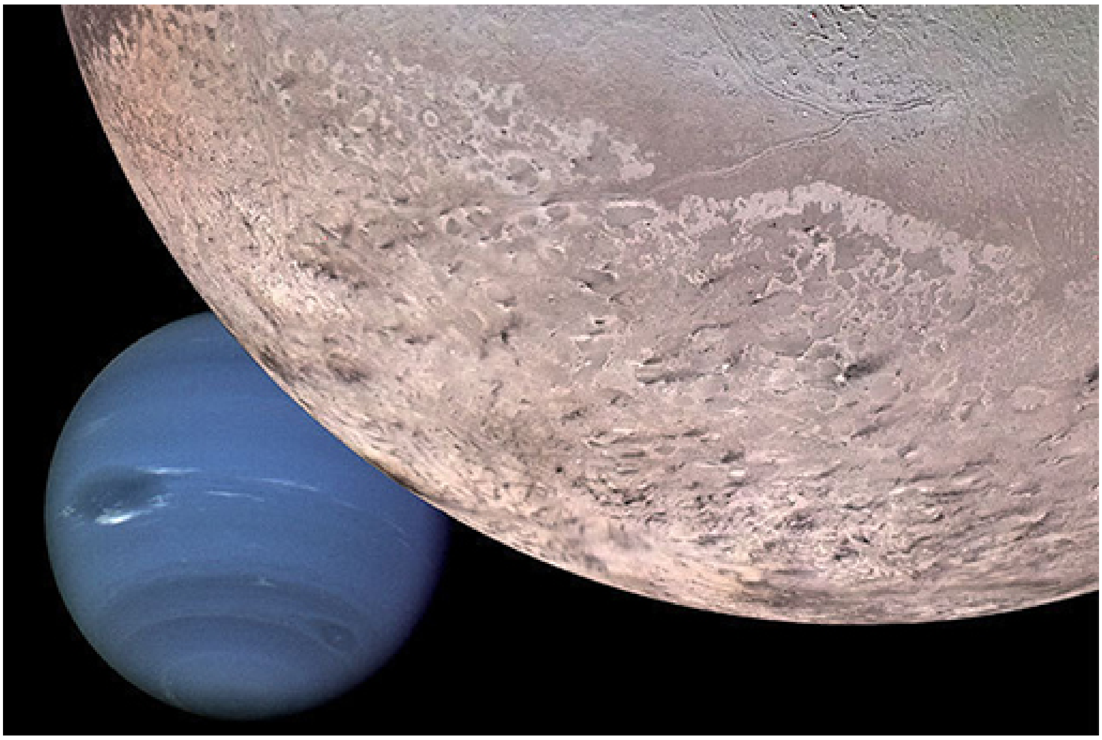


Figure 37 Triton (foreground) and Neptune (background), in a composite view assembled from two separate images obtained by NASA's flyby probe Voyager 2 in 1989

Neptune's largest moon Triton is unique in that it is the only large moon in the Solar System to have a retrograde orbit (orbiting in the opposite direction to the rotation of the planet). A retrograde orbit is regarded as sufficient proof that an object has been captured rather than formed from the same material as the primary. Other moons have been observed with retrograde orbits, but these are much smaller and further away from their primary. Discovered in 1846 by English astronomer William Lassell, Triton is thought to have been captured by Neptune from elsewhere in the Solar System. Where could this be? Well, look no further than Pluto. Triton has a very similar composition to Pluto, suggesting that they shared a common origin in the Kuiper belt. Triton is also one of the few moons in the Solar System known to be geologically active.

3.4 Pluto's eccentric orbit

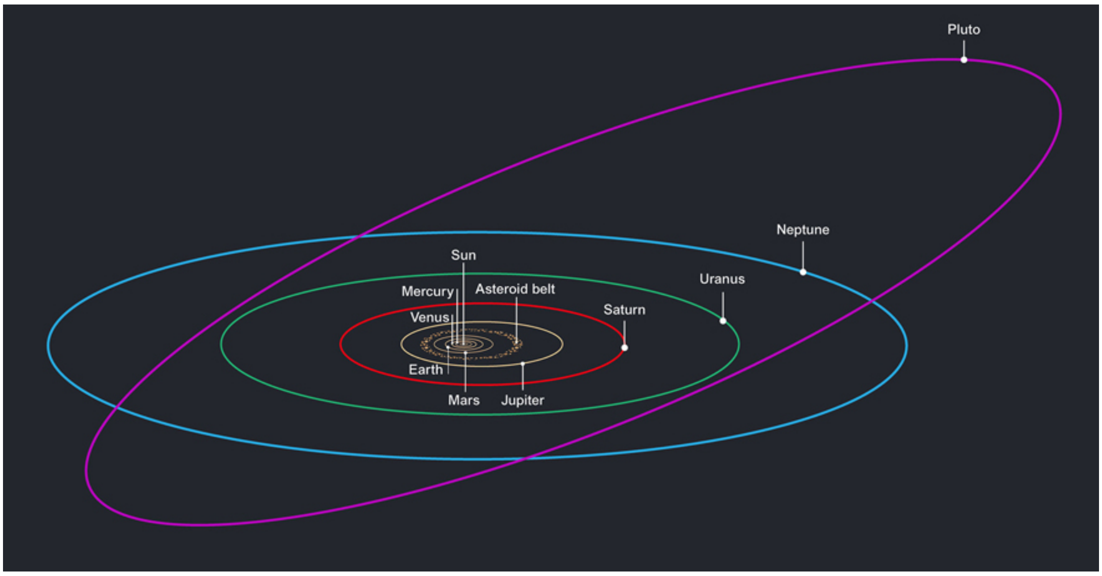


Figure 38 A perspective view of the Solar System

Pluto's orbit is so elliptical that it strays inside Neptune's orbit for 20 years out of its 248-year circuit round the Sun. It last crossed inside Neptune's orbit in 1979. Pluto orbits the Sun in an inclined orbital plane, and goes around the Sun twice for every three orbits that Neptune makes. The planets never actually pass through the same point in space at the same time, so they will never collide.

Suppose that a former Pluto-like object came close to Neptune, could Neptune have captured it? It sounds plausible, doesn't it? But in fact it is very hard to do. In order to be gravitationally captured by a planet, a passing body must lose sufficient momentum to be slowed down to a speed less than that required to escape. However, if the visitor had a large moon of its own, so three bodies were involved rather than just two, one could have been captured while the other was spun away travelling a bit faster than when it arrived. This could work if Triton is in fact a body from a Pluto–Charon type binary system that strayed too close to Neptune.

3.5 Pluto and Charon

Charon is the largest of Pluto's five known moons. It is unusual in that it is similar in size to Pluto (compared with other moons and their primaries, which differ substantially in size). Charon has a mass of around one-eighth that of Pluto whereas the Moon has a mass of around one-eightieth that of the Earth. This means that each have a strong gravitational effect on the other. Each tidally locks the other around the centre of mass of the system, which is a little way outside Pluto on a line between the two bodies.

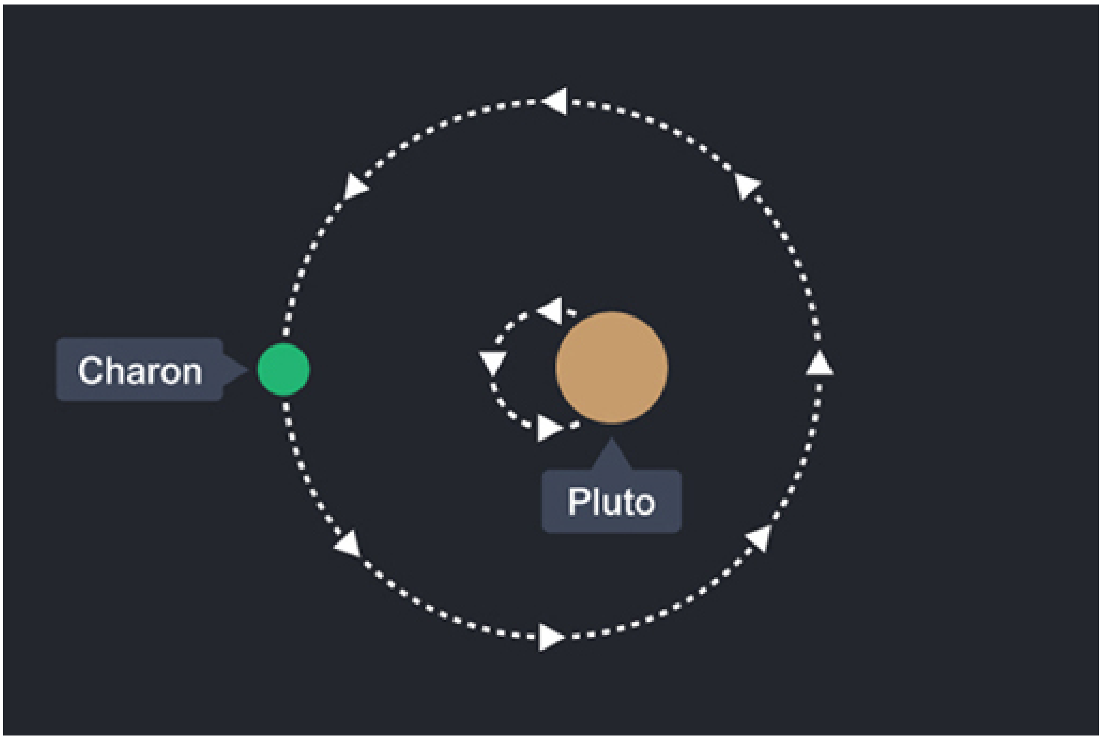


Figure 39 The orbits of Charon and Pluto around their common centre of mass

The Pluto–Charon binary system, the numerous moons of asteroids and the moons of Kuiper Belt objects beyond the planets are still a mystery. Such moons are more frequent than the probability of a three-body capture suggests. Perhaps giant impacts, like that suggested for the Moon-forming impact on Earth, took a role in creating these moons?

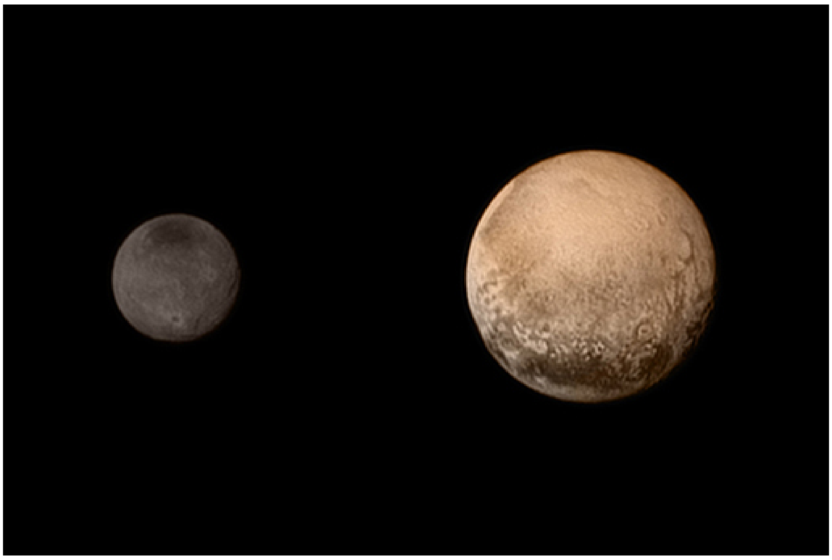


Figure 40 Pluto and Charon seen by New Horizons as it approached on 11 July 2015 (they are further apart from each other than it seems in this image)

3.6 Bombardment history

In the first of two short videos, Bill Bottke (known as William in the video) describes how the bombardment history preserved on our Moon shows what he refers to as the 'end game' of planet formation.

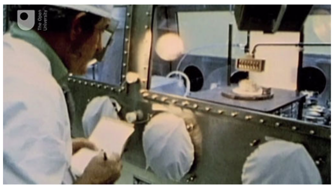
Video content is not available in this format.

3.7 A very Nice model

As Bill Bottke says in this video, samples brought back from the Apollo mission went a long way to develop our current understanding of the evolution of the Solar System. Our models are constantly being reviewed and refined with new scientific data. Notice in the Nice model how Jupiter migrated inwards, Saturn migrated outwards, and the orbits of Neptune and Uranus were swapped over from their original locations. This re-structuring after the formation of planets could have been a trigger for the formation of many of the moons in the Solar System, and could also explain the heavy bombardment suffered by the Moon about four billion years ago.

The video shows how gravity can influence the growth and the orbits of planets. Next you will look at how mutual gravitation acts to produce tides, and how this can affect the orbit, rotation and internal heating of a moon.

Video content is not available in this format.



3.8 What is a tide?

Tidal forces are the gravitational effect of a body on another body. A well-known example is the Moon's effect on Earth. The effect of this tidal force is that the Earth becomes slightly elongated, in the direction of the Moon. This is most easily seen in the behaviour of the Earth's water, where the gravity of the Moon pulls on the Earth's oceans causing them to swell. The Moon's gravitational attraction causes two tidal bulges in the Earth's ocean water, one on the side closer to the Moon and one on the side that is further away.

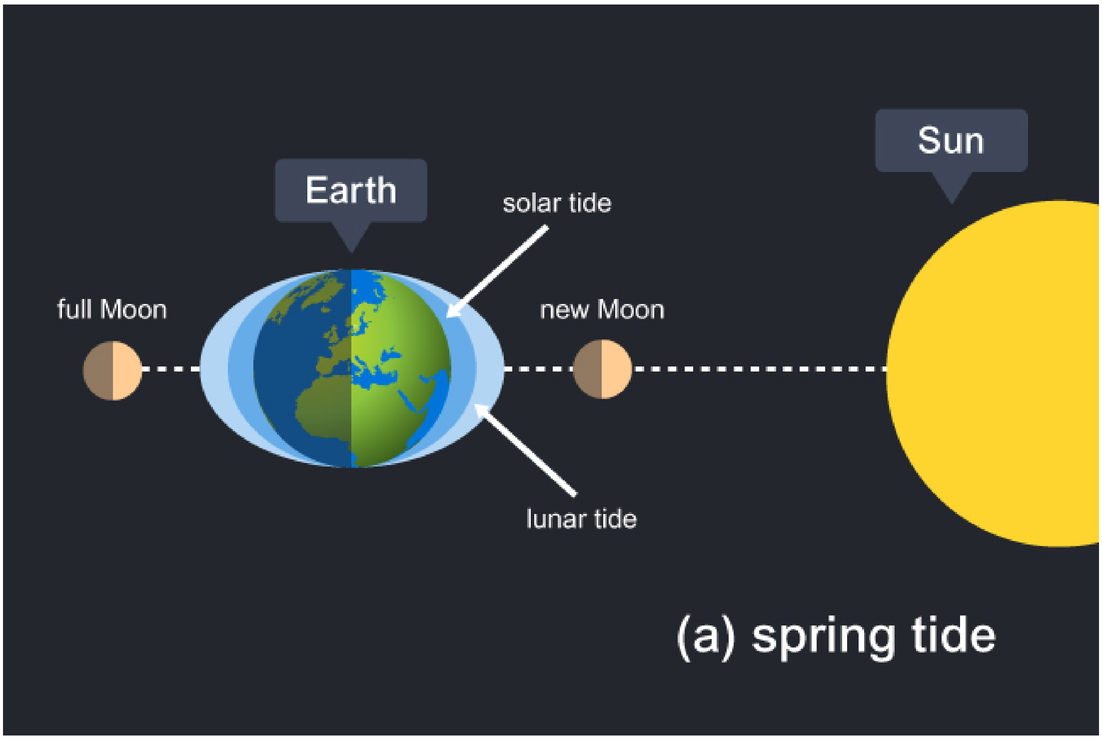


Figure 41 Spring tide

The Sun also has an effect on the Earth's oceans. When the Earth, Moon and Sun are all in a line as shown in (a), the lunar and solar tides will add together, creating a higher high tide and a lower low tide. This is known as a spring tide and occurs during the full Moon and new Moon.

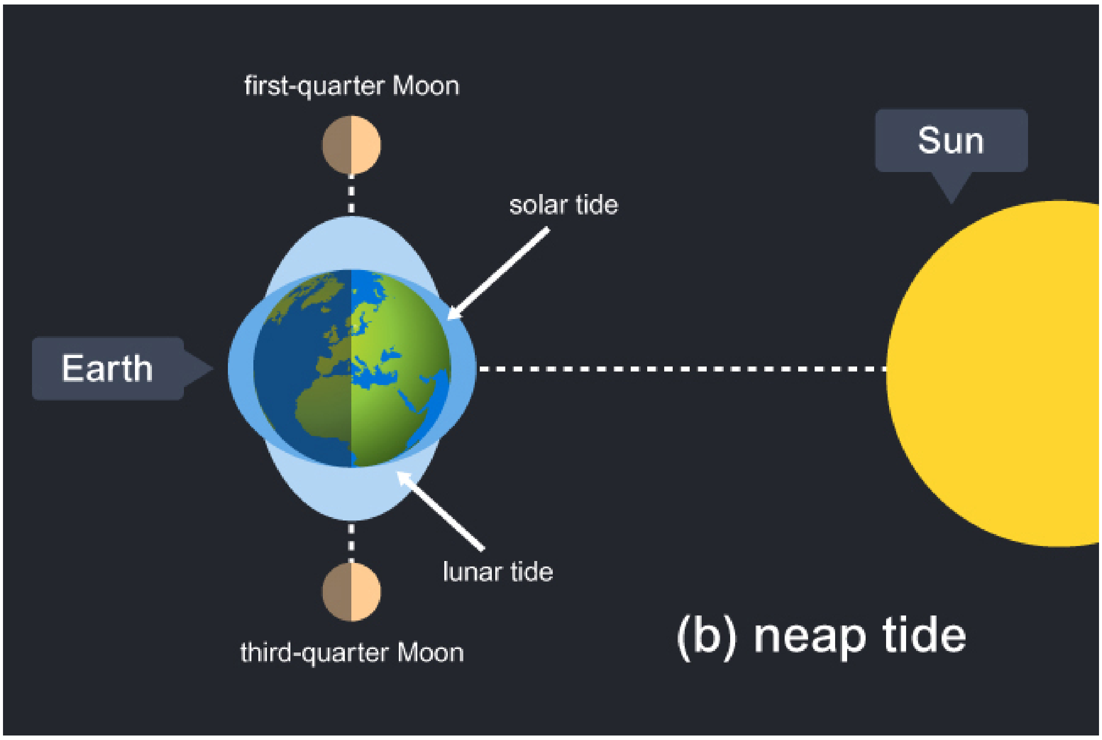


Figure 42 Neap tide

When the Earth, Moon and Sun are at right angles as shown in (b), the solar tide acting against the lunar tide will make the total tidal range smaller (you have to add the shapes of the lunar and solar tides to deduce the combined tide). This tide is called a neap tide and occurs during the first-quarter and third-quarter phases of the Moon. The Moon's gravitational pull also distorts the shape of the solid Earth.

3.9 Spring and neap tides

The Sun also has an effect on the Earth's oceans. When the Earth, Moon and Sun are all in a line the lunar and solar tides will add together creating a higher high tide and a lower low tide. This is known as a spring tide and occurs during the full Moon and new Moon. When the Earth, Moon and Sun are at right angles the solar tide will make the lunar tide smaller. This tide is called a neap tide and occurs during the first-quarter and third-quarter phases of the Moon.

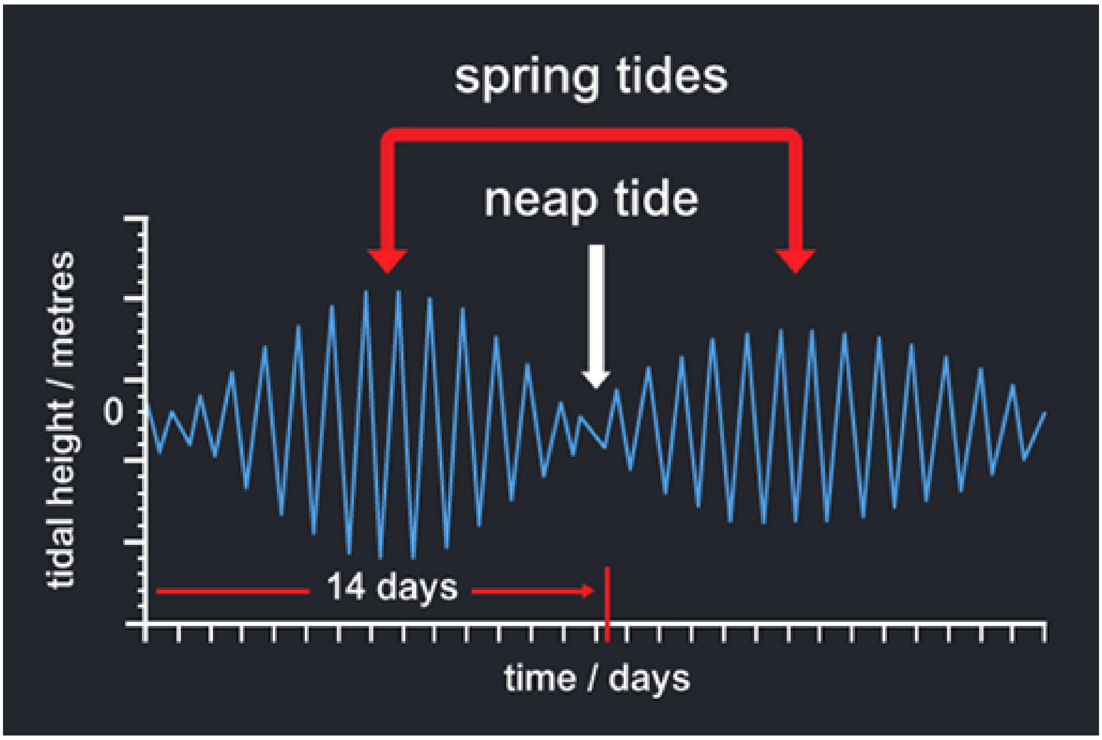


Figure 43 A graph showing how tidal range varies because of the competing tidal pulls of the Sun and the Moon as their positions in the sky change (the next month would be similar, but not an exact repeat)

3.10 Tidal heating explained

Here The Open University's Professor David Rothery explains tidal heating. (In the older part of the video, the term 'satellite' is used, where elsewhere in this course we say 'moon'.)

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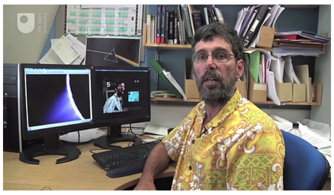


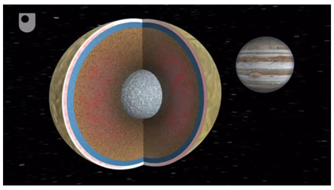
3.11 Tidal effects on Io and Europa

Tides play a great role in the geology of Jupiter's moons Io and Europa, which are geologically active at present, due to continual stretching of their interiors.

Europa, the second-closest Galilean moon to Jupiter, has a scarred icy surface as a result of tidal forces stressing the surface. The tidal heating effect warms the moon's interior, which keeps the interior water (blue layer above) in a liquid state.

Tidal forces don't just affect water; they can distort any elastic material. The strong tidal effect from Jupiter on its closest moon Io causes volcanic activity, continually re-surfacing it. Io, Europa and Ganymede line up periodically as they travel round their orbits: this is known as orbital resonance. So for every orbit of Ganymede, Europa would have orbited twice, and Io would have orbited four times. This orbital resonance prevents any orbit becoming circular, and allows tidal heating to continue. With over 400 active volcanoes, Io is the most geologically active body in the Solar System.

Video content is not available in this format.



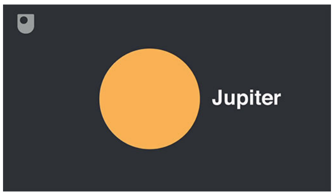
(Please note this video has no audio.)

3.12 Investigating orbital resonance

In the 'Tidal heating explained' video you saw that Io completes two orbits of Jupiter in the time that it takes Europa to make one orbit. This 'orbital resonance' is what prevents the moon's orbits from becoming circular, which means that tidal forces continually distort, and heat, their interiors.

In the Jupiter system, it is not just Io and Europa that share a resonance. The next moon out, Ganymede completes one orbit in the time that it takes Europa to complete two orbits, during which time of course Io will have completed four orbits. This is a '4:2:1 orbital resonance' relationship between Io, Europa and Ganymede. The animation here demonstrates this relationship.

Video content is not available in this format.



(Please note this video has no audio.)

3.13 Moons data

This downloadable PDF takes you to a table of data for the moons of all the planets plus Pluto. You may find this a useful source of reference as you progress through the course. However we would like you to consult it now to look a little further into orbital resonances. The only column of data that you need to look at for this purpose is the one listing orbital periods.

Activity 2 Orbital period

Allow approximately 15 minutes.

The table lists the orbital periods of Io, Europa and Ganymede as 1.769, 3.551 and 7.155 days. To verify that these are resonant orbits, you need to divide one period by another. For example the ratio between Europa's and Io's period is 3.551/1.769. If you use a calculator this works out at 2.00734878. The final digits are meaningless, and this number rounds down to 2.0. Similarly dividing Ganymede's period by Io's period 7.155/1.769 works out at 4.0.

But what about Callisto? Its orbital period is 16.689 days. Does this share an orbital resonance with the others?

Try dividing its orbital period by Ganymede's, and see what you get.

Answer

Dividing Callisto's 16.689 day orbital period by Ganymede's 7.155 day orbital period works out at 2.33249, or 2.3. This shows that Callisto's orbit is not resonant with Ganymede's.

To finish off, go back to the table and take a quick look at Saturn's satellites. Can you find any orbital resonances there? (Hint: you may have to look beyond a moon's immediate neighbour.)

3.14 Orbital resonances at Saturn?

In fact there are two examples of 2:1 orbital resonances among Saturn's principal moons. Mimas (0.942 days) and Tethys (1.888 days) are in 2:1 resonance with each other (2.0, rounded from 1.9832) and Enceladus (1.370 days) and Dione (2.737 days) are also in 2:1 resonance with each other (2.0, rounded from 1.9978).

The orbital resonance between Enceladus and Dione probably accounts for the present-day activity on Enceladus.

Resonant orbits do not remain constant. Their eccentricity (and hence the amount of heating) can increase or decrease over millions of years, and moreover moons can drift in and out of resonant relationships. Curiously, Mimas shows no signs on its surface that it was ever subject to significant tidal heating, but both Tethys and Dione show features that can be attributed to tidal heating in the distant past.

4 This week’s quiz

This quiz allows you to test and apply your knowledge of the material in Week 1.

Complete the Week 1 quiz now.

Open the quiz in a new window or tab then come back here when you’re done.

5 Summary

This week you learned about the nature of orbits and how the Earth's orbit is responsible for its phases. You also learned about the origins of the Moon, and how tidal heating occurs as a result of the Moon's rotation and orbit. Next week you'll find out more about moons, including what they are made of.

You should now be able to:

- understand the nature of orbits and how the Earth's orbit is responsible for its phases
- understand how tidal heating occurs as a result of the Moon's rotation and orbit
- describe various theories to explain the Moon's origin.

You can now go to Week 2: Looking at moons.

Week 2: Looking at moons

Introduction

Like planets, moons can have an internal layered structure: a core, mantle and crust. At Jupiter and beyond, the outer part of each moon is ice that behaves like rock. How do moons get their names?

Jess gives you a heads up on what to expect this week.

Video content is not available in this format.

By the end of this week, you should be able to:

- recognise the structure of a moon and what it's made of
- understand the significance of ice, and its different forms, in the moons of the outer solar system
- understand how a moon's surface is altered by comet or meteorite impact.

If you wanted to look into this further, you might find the following links of interest:

- 10 things you should know about moons In December 2015, Oxford University Press invited David Rothery to describe ten key points about moons on video. Here is the result. It sums up much of week 1, and introduces a few things that have not yet come up.
- Planets and moons chat recording. The recording our of live webcast made on Weds 9 March 2016, 19:30-20:15 GMT can be viewed at this link (you will see the video stream only, not the 'voting widgets')

1 Ice and rock – distance from the planet

The Solar System has at least 146 moons, not even counting the moons of asteroids, and they have a huge variety in size and composition (Figure 1). For many years, the composition of moons was a mystery and scientists are still unsure of many of the details.

Figure 1 Some moons to scale with the Earth

The variety of formation mechanisms (that you learned about in Week 1) is one reason for the variety of compositions. A moon that has been captured (Triton, for example) is likely to differ from a moon that formed within an accretionary disc (such as Io). Our own Moon is uncommon in being mostly rocky with only the merest traces of water. There are only two large rocky moons in the Solar System: the Earth's Moon and Io. The other moons have interiors with a varying ratio of ice : rock, and have surfaces that are made almost entirely of ice.

Ice is not necessarily pure frozen water. It can include specks of rocky or carbonaceous dust, various salts and the frozen forms of volatile substances, meaning substances that would tend to be gases if found on Earth. Example of such 'volatiles' include carbon monoxide, carbon dioxide, methane and ammonia. These too can occur in the form of ice, so be careful when you hear someone talking of 'ice' in the Solar System; they do not necessarily mean just frozen water. Generally, a moon's composition is related to where in the Solar System it formed and how far it is from the primary planet.

The moons that formed within accretionary discs around planets show a grading of density and ice : rock ratio. This can be seen easily in the Galilean moons (the four large moons of Jupiter discovered by Galileo Galilei): the inner two (Io and Europa) are significantly denser than the outer two (Ganymede and Callisto). Rock is denser than ice, so this is evidence that the ice : rock ratio increases with distance from Jupiter. The accretionary disc around Jupiter would have been hotter and denser towards the centre, hindering the accretion of icy volatiles onto the inner moons.

1.1 Inside a moon

Here's your chance to learn what scientists think the internal structures and compositions of the Moon and Jupiter's four Galilean moons are like.

Activity 1 Structures of the Moon and Jupiter's four Galilean moons

Allow approximately 15 minutes.

For each diagram, try to work out which parts of each moon's structure the empty labels are referring to.

When you're ready, click the 'Reveal answer' link below each diagram to see a fully labelled version.

The Moon

The Moon is a differentiated body: it has a geochemically distinct crust, mantle and core. It also has a largely or entirely solid iron-rich core with a radius of 300 km. The lowest part of the mantle may be partially molten.

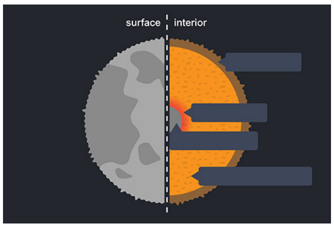


Figure 2a The Moon

Try to decide where each of these labels belongs:

- solid silicate mantle
- silicate crust
- small iron core
- partial melt.

Answer

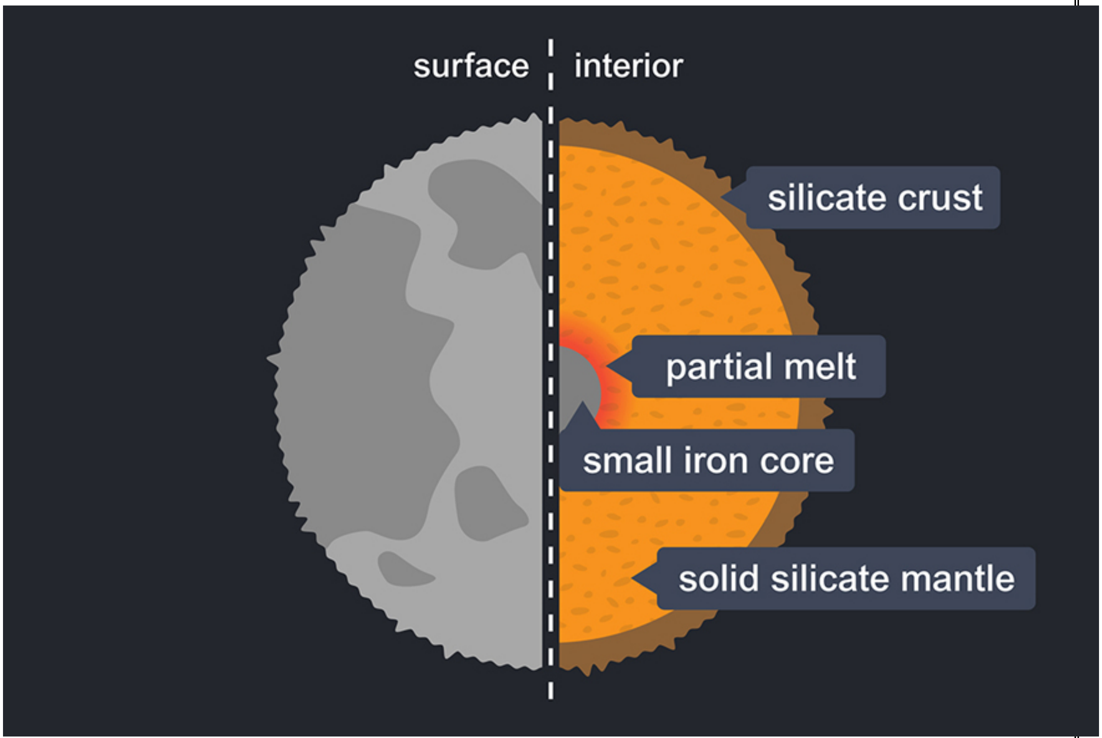


Figure 2b The Moon

Callisto

Callisto is the third-largest moon in the Solar System and it appears to lack a fully differentiated core. Callisto's battered surface lies on top of a cold, stiff and icy lithosphere that is between 80 and 150 km thick. A salty ocean may lie beneath the crust, indicated by studies of the magnetic fields around Jupiter and its moons.

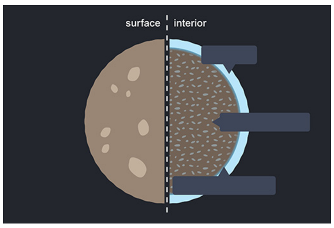


Figure 3a Callisto

Try to decide where each of these labels belongs:

- ice-rock interior
- icy crust
- subsurface ocean.

Answer

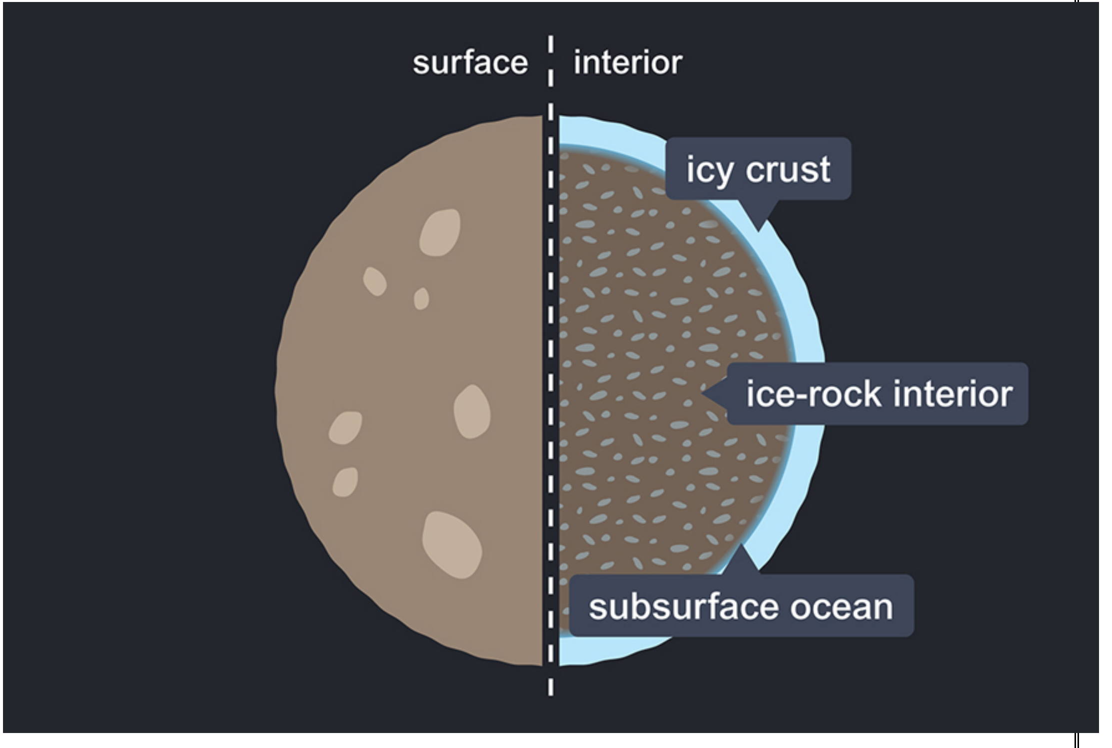


Figure 3b Callisto

Europa

It is believed that Europa has an outer layer of water around 100 km thick, some as frozen-ice upper crust and some as liquid ocean underneath the ice. Below the ocean, occupying most of Europa's volume, is a rocky interior. This probably contains metallic iron core at the centre.

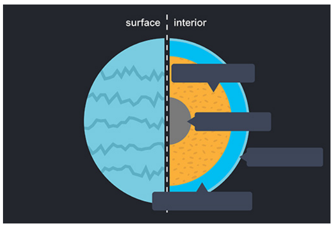


Figure 4a Europa

Try to decide where each of these labels belongs:

- silicate mantle
- iron core
- subsurface ocean
- thin ice crust.

Answer

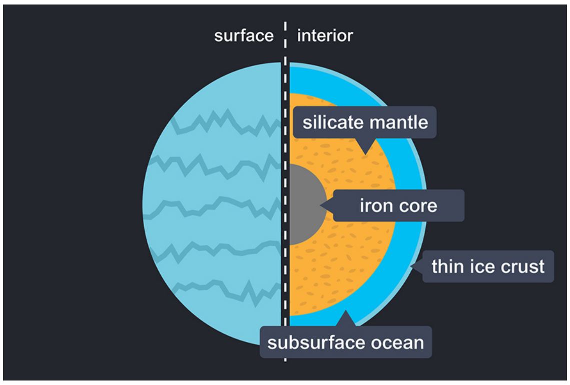


Figure 4b Europa

Ganymede

Ganymede is composed of approximately equal amounts of silicate rock and water-ice. It is believed to be a fully differentiated body with an iron-rich core. A saltwater ocean is believed to exist nearly 200 km below Ganymede's surface, sandwiched between layers of ice.

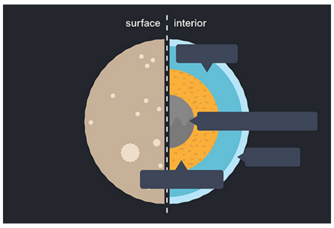


Figure 5a Ganymede

Try to decide where each of these labels belongs:

- silicate mantle
- mostly solid iron core
- ice crust
- icy water.

Answer

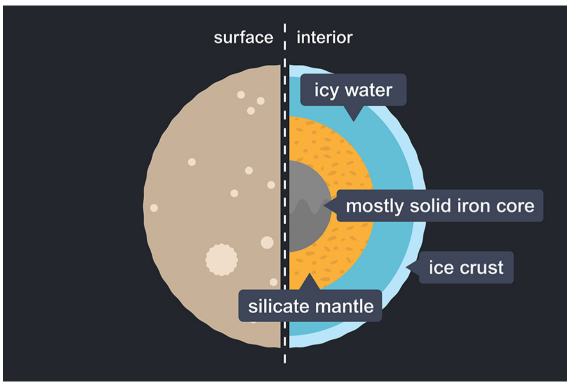


Figure 5b Ganymede

Io

Io is composed primarily of silicate rock and iron. Io is closer in bulk composition to the terrestrial planets than to other moons in the outer Solar System, which are mostly composed of a mix of water-ice and silicates. Models based on measurements of density and mass distribution suggest that its interior is differentiated between a silicate-rich crust and mantle, and an iron- or iron-sulfide-rich core. Io's metallic core makes up approximately 20% of its mass.

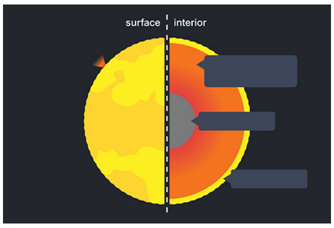


Figure 6a Io

Try to decide where each of these labels belongs:

- partially molten silicate mantle
- silicate crust
- iron core.

Answer

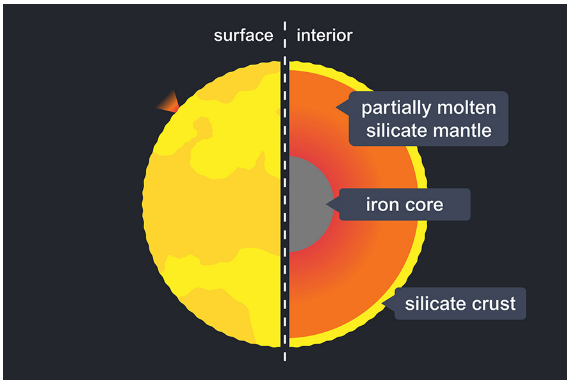


Figure 6b Io

1.2 Distance from the Sun is important too

The further out from the Sun a moon has formed, the more exotic the materials it is made of. Salts and volatiles all have the effect of lowering the melting temperature of the ice, making it easier for the moons to show signs of geological activity even if there is little internal heat. The richest-known cocktail of ices occurs on Neptune's large moon Triton, whose surface appears to be mostly water-ice and frozen carbon dioxide, with traces of methane, carbon monoxide and probably ammonia. In addition, it has seasonal polar caps of nitrogen-ice.

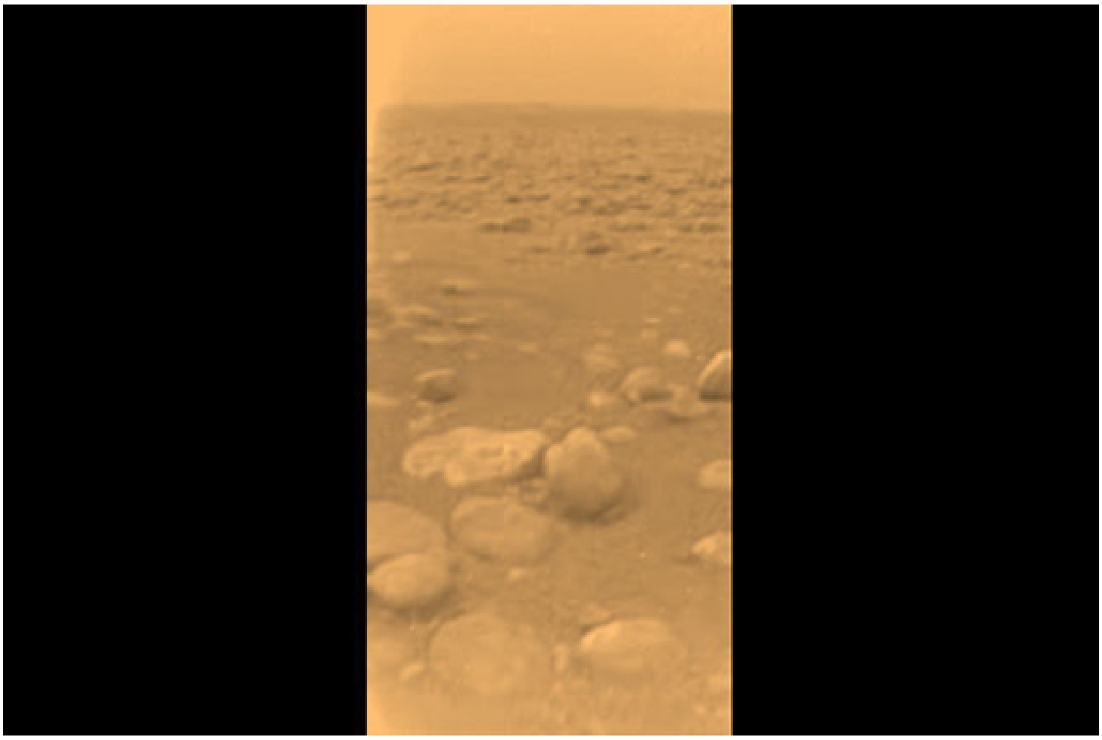


Figure 7 The surface of Titan as seen from ground-level by the Huygens lander. The largest pebble in the foreground is about 15 cm across.

Titan, the largest moon of Saturn, has a dense atmosphere composed mainly of nitrogen but with methane and other hydrocarbons forming clouds and haze. It sometimes rains methane and there are vast lakes of methane at the surface. The ground surface (which is made of water-ice that behaves as rock behaves on Earth) is eroded by rivers of methane creating visible channels and river beds. We know this because of the Cassini–Huygens mission. This mission was a joint venture of ESA and NASA and was a massive success. It reached Saturn in July 2004, with the Huygens lander touching down on Titan in January 2005. This gave us the most distant ground-level view yet achieved. Figure 7 is the surface of Titan taken by the Huygens lander. The thick orange haze is high in the nitrogen- and methane-based atmosphere. The pebbles are not in fact rock, but are water-ice.

See an artist's impression of a methane rainstorm on Titan in this Astronomy Picture of the Day

1.3 Ice and Ganymede

In this video, Louise Prockter describes why there is ice in the moons of Jupiter and beyond, and why she finds Jupiter's moon Ganymede – which is the largest moon in the Solar System – so fascinating.

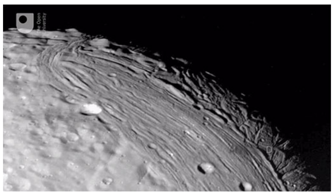
When Louise describes Ganymede as 'the third moon out from Jupiter' she means it is 'the third large moon out from Jupiter'. Jupiter has four known inner moonlets orbiting closer than Io, Jupiter's innermost large moon.

Video content is not available in this format.

1.4 Icy moons

In this video, Paul Schenk describes icy moons in general and tells you more about the exotic ices that can be found further from the Sun. He describes evidence for liquid-water oceans below the surface of some of the icy moons and argues that primitive life could exist there feeding off chemical energy rather than sunlight.

Video content is not available in this format.



1.5 Shapes of moons

The shape of a moon is largely determined by its size. Small moons such as Phobos and Deimos (both of which belong to Mars) are lumpy and potato-like, while moons like our own and Jupiter's Galilean moons are spherical. An icy body with a diameter less than about 400 km cannot pull itself into a sphere because its mass is not great enough to generate sufficiently strong gravity to overcome the ice's resistance to deformation. For a body made of rock (which has greater resistance to deformation than ice), the size of body required before its gravity can overcome the resistance to deformation is larger. Here are a few examples.

Callisto (Figure 8), the third-largest moon in the Solar System, is the outermost of the Galilean moons of Jupiter. It has the lowest density of the Galilean moons showing that it has a greater ice : rock ratio than the others. It has a diameter of 4820 km and is spherical.

Figure 8 Callisto

Phobos (Figure 9) is the larger of Mars' two moons, yet is only 22 km across. It is far too small to have enough gravity to pull itself into a sphere. Its orbit is not stable and Phobos is predicted to collide with Mars 40–50 million years from now. It is thought to be undifferentiated and so has a constant (homogenous) composition, which is thought to be the same as that of the asteroids in the belt between Jupiter and Mars.

Figure 9 Phobos

Dione (Figure 10) is a moon of Saturn and has a diameter of 1123 km. Its mass comfortably allows it to pull itself into a spherical shape. Roughly one-third of Dione is thought to be rock. The rest is ice.

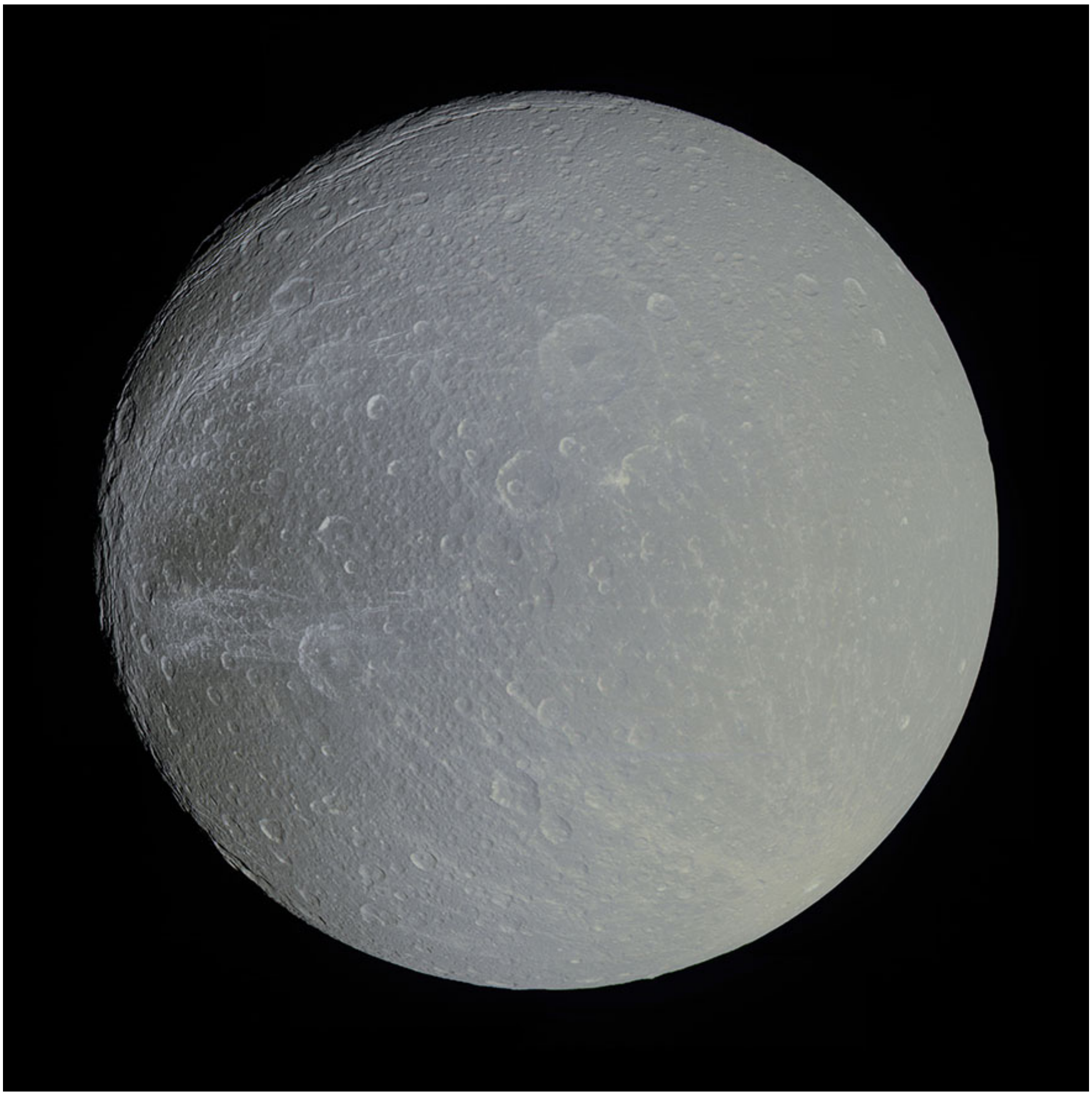


Figure 10 Dione

Hyperion (Figure 11) is a moon of Saturn and is one of the largest known irregular moons in the Solar System. It is thought to be the remnant of a larger moon that was destroyed by an impact. It measures 360 km along its longest axis. It has an exceedingly low density, which has led to the theory that it is made of very porous ice.

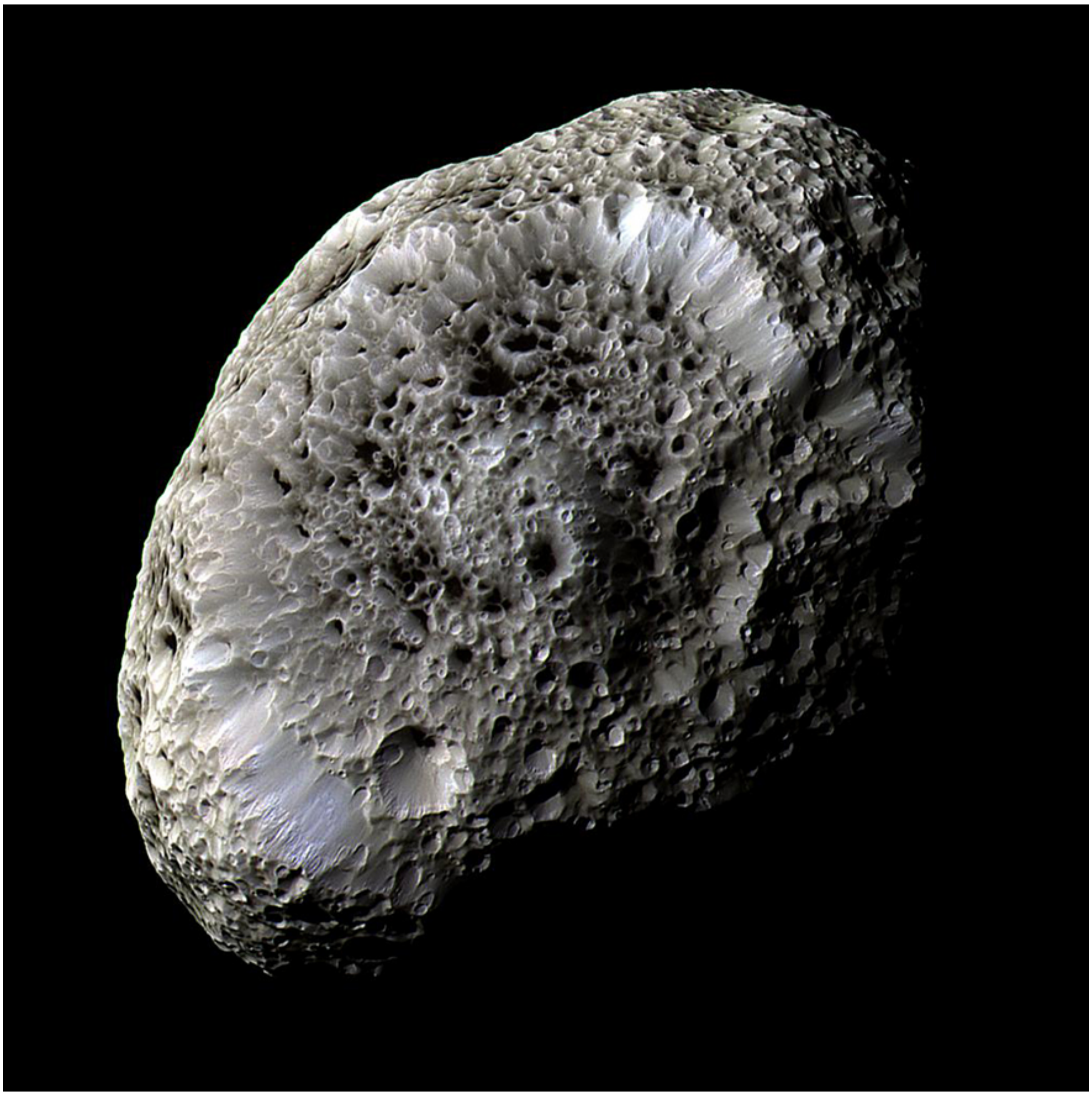


Figure 11 Hyperion

1.6 Naming moons

Agreeing on names for astronomical bodies has never been easy. Even the names of planets have been disputed. Uranus was originally called 'George's Star', in honour of King George III, by its discoverer Sir William Herschel. Apart from the Earth, the other planets of the Solar System are all named after gods in Greek and Roman mythology. The International Astronomical Union (IAU) now arbitrates on the names of moons (and their surface features), but the process is not without its twists and turns as this sequence describes.

Video content is not available in this format.

1.7 Sizing moons

Figure 12 The Moon and Tethys, shown to correct relative scale

To give you a feel for the sizes of some moons, have a go at Activity 2 below. There you will see we have provided images of eight moons, but not shown them to scale. All you have to do is guess the correct diameter for each moon (for markedly non-spherical moons we require the length of their long axis). If you get stuck, try consulting the moons data table from Week 1.

These are the moons we have chosen.

- Enceladus: the sixth-largest moon of Saturn and named after a mythological giant of ancient Greece.
- Deimos: the outer moon of Mars and named for the Greek personification of terror.
- Phoebe: thought to have been captured by Saturn's gravity. It is named after a Titan of Greek mythology who was grandmother to Apollo.
- Iapetus: the third-largest satellite of Saturn, named after the Titan who fathered Atlas and Prometheus.
- Tethys: a medium-sized satellite of Saturn, named after a Titan and aquatic sea goddess.

- Pandora: a satellite of Saturn named after the Greek mythological figure who inadvertently unleashed all the evils of humanity from a jar.
- Prometheus: a moon of Saturn, named after the Titan who stole fire from the gods. Zeus then condemned him to have his liver eaten daily by an eagle for all time.
- The Moon: which goes by many names in different cultures; our own name derives from a Proto-Germanic word, mǣnōn.

Activity 2 Sizing moons – what do you know?

Allow approximately 20 minutes.

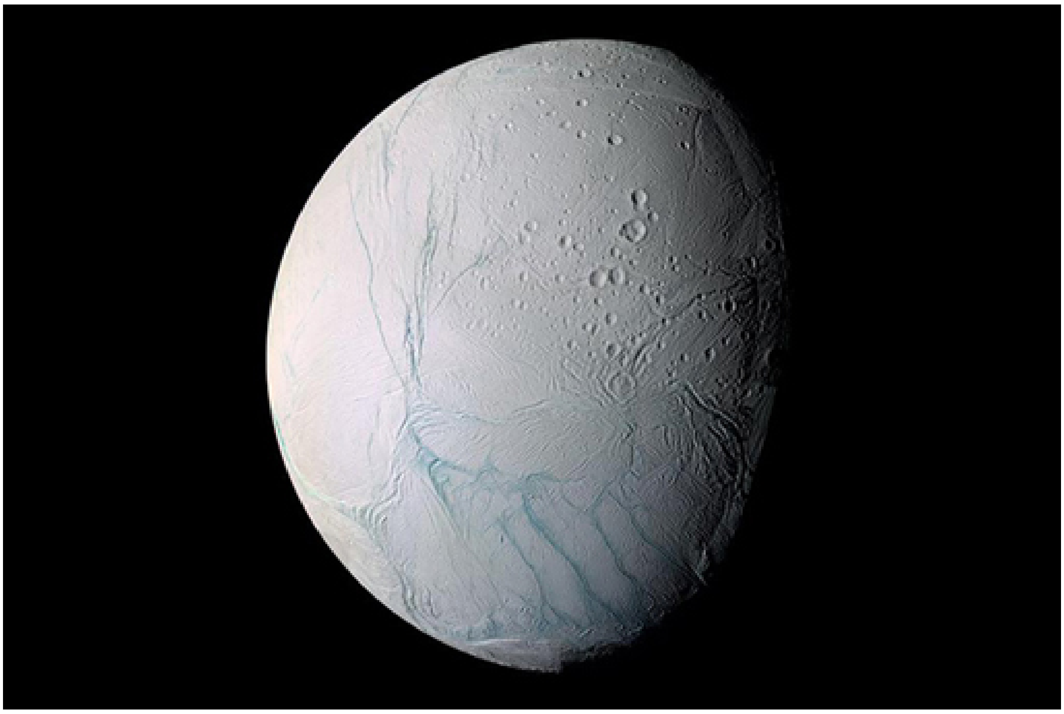


Figure 13 Enceladus

What is the diameter of this moon?

○ 504 km

Well done.

○ 1062 km

No. Enceladus is smaller than this.

○ 1470 km

No. Enceladus is smaller than this.

○ 12.4 km

No. Enceladus is larger than this.

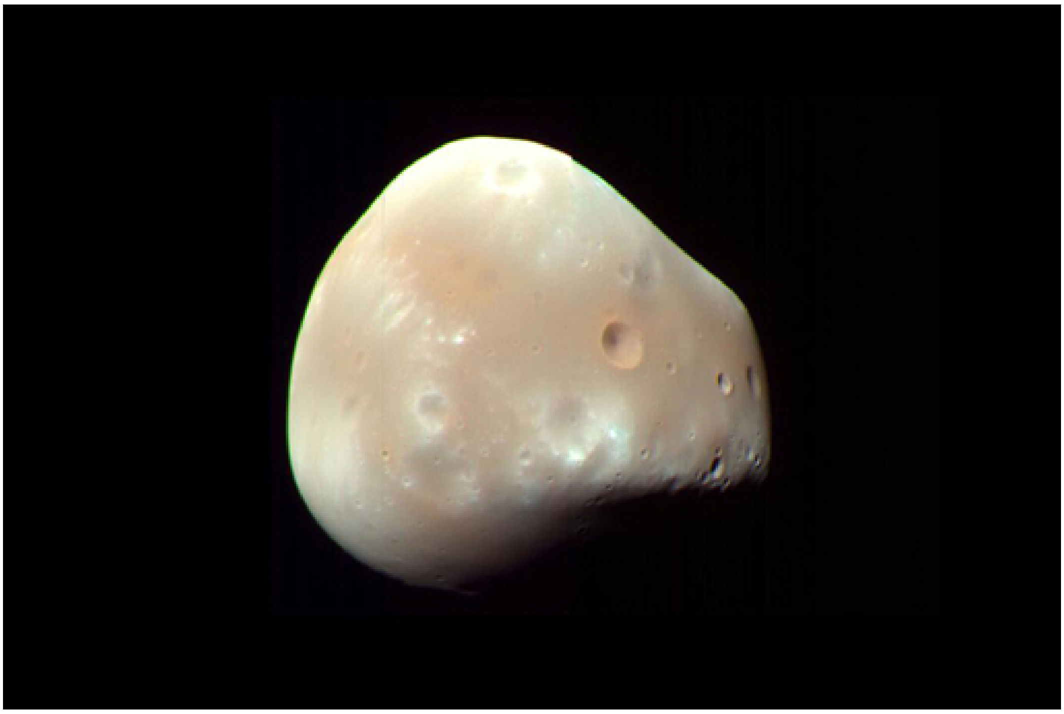


Figure 14 Deimos

What is the diameter of this moon?

○ 3474 km

No. Deimos is smaller than this.

○ 104 km

No. Deimos is smaller than this.

○ 12.4 km

Well done.

○ 213 km

No. Deimos is smaller than this.

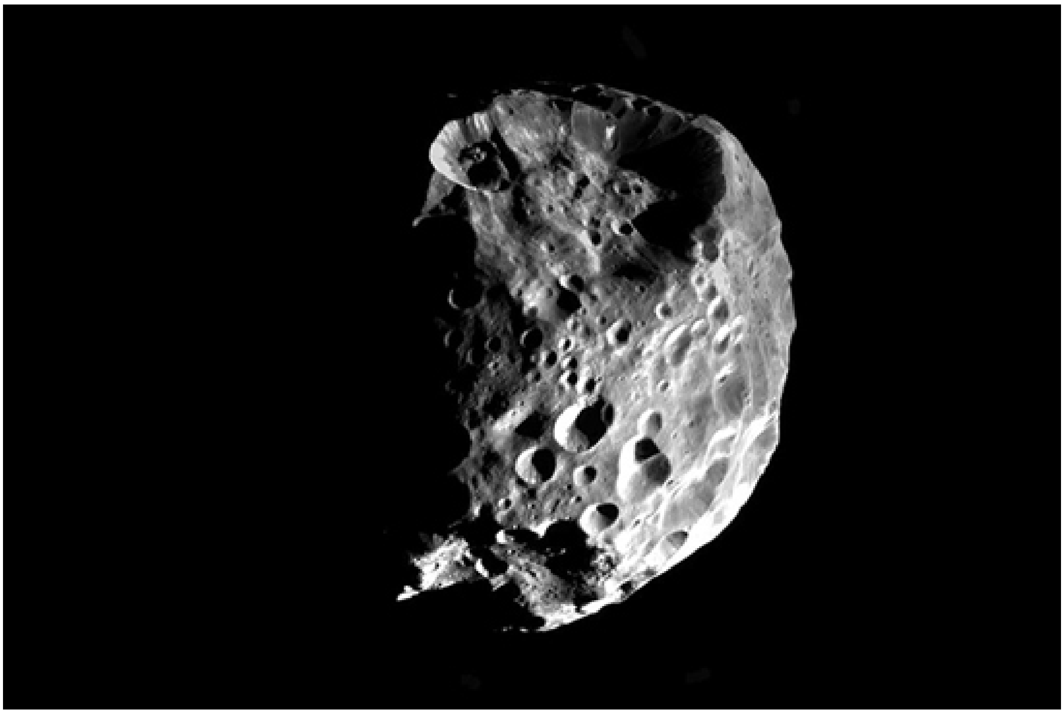


Figure 15 Phoebe

What is the diameter of this moon?

○ 213 km

Well done.

○ 1470 km

No. Phoebe is smaller than this.

○ 271 km

No. Phoebe is smaller than this.

○ 208 km

No. Phoebe is larger than this.

Figure 16 Iapetus

What is the diameter of this moon?

○ 1062 km

No. Iapetus is larger than this.

○ 3474 km

No. Iapetus is smaller than this.

○ 104 km

No. Iapetus is larger than this.

○ 1470 km

Well done.

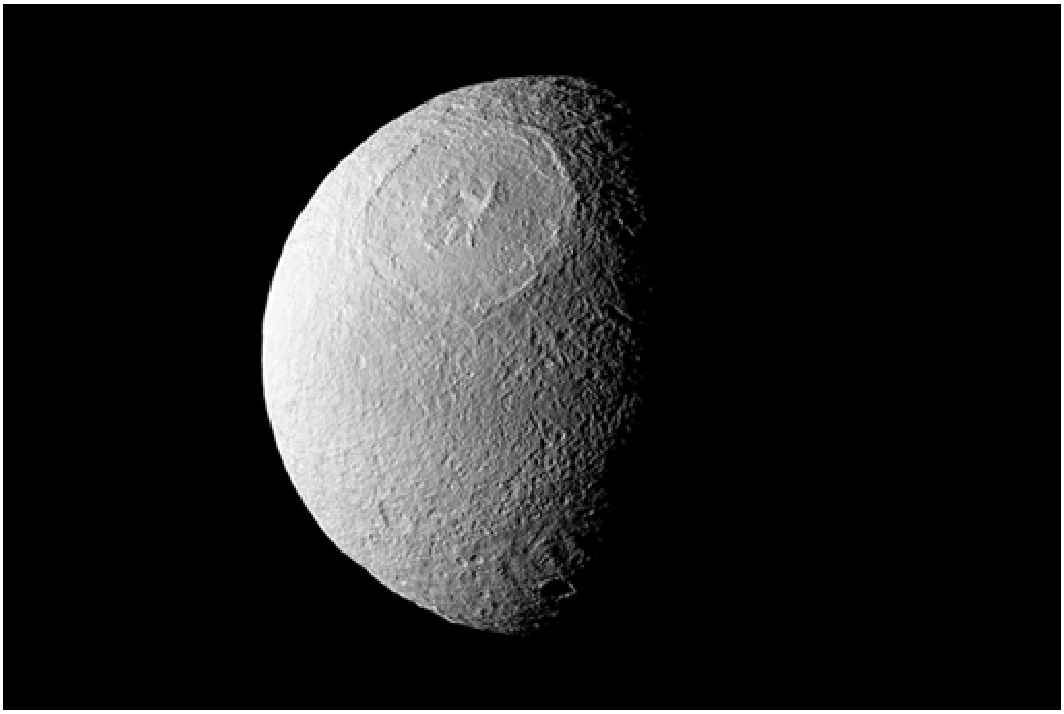


Figure 17 Tethys

What is the diameter of this moon?

○ 136 km

No. Tethys is larger than this.

○ 3474 km

No. Tethys is smaller than this.

○ 1062 km

Well done.

○ 504 km

No. Tethys is larger than this. As you’ve just seen, this is the diameter of Enceladus.

Figure 18 Pandora

What is the diameter of this moon?

○ 12.4 km

No. Pandora is larger than this. As you've just seen, this is the diameter of Deimos.

○ 104 km

Well done.

○ 271 km

No. Pandora is smaller than this.

○ 3474 km

No. Pandora is smaller than this.

Figure 19 Prometheus

What is the diameter of this moon?

○ 136 km

Well done.

○ 1062 km

No. Prometheus is smaller than this. As you've just seen, this is the diameter of Tethys.

○ 3474 km

No. Prometheus is smaller than this.

○ 213 km

No. Prometheus is smaller than this. As you've just seen, this is the diameter of Phoebe.

Figure 20 The Moon

What is the diameter of the Moon?

○ 1470 km

No. The Moon is larger than this. As you've just seen, this is the diameter of Iapetus.

○ 1062 km

No. The Moon is larger than this. As you've just seen, this is the diameter of Tethys

○ 3474 km

Well done.

○ 504 km

No. The Moon is larger than this. As you've just seen, this is the diameter of Enceladus.

2 Our Moon and its craters

Galileo discovered lunar craters in the 1600s but the debate about how they were formed was resolved only in the 20th century. Learn how different crater shapes and sizes come about, and have a go at classifying real Moon craters.

In this video Christine Shupla and Paul Schenk introduce you to the Moon, the craters upon it and the evidence for ancient volcanism. Christine concludes by speculating that pieces of rock that 'blew off early Earth' might one day be found on the Moon. By this, she means chunks of ejecta thrown out by large impacts onto the Earth (of the same size as those that formed the Moon's oldest craters), and which ended up on the Moon. No rock older than 3.8 billion years has survived on Earth, so finding older Earth rocks on the Moon opens a very important window into our own planet's past.

Video content is not available in this format.

2.1 Craters on the Moon's surface

For thousands of years, humans have been relying on nothing more powerful than the naked eye to observe features on the Moon's surface. What they have observed are large dark patches on an otherwise bright surface.

With the advent of the telescope, the nature of these dark patches began to be better understood. Using a simple telescope (up to 30× magnification), the Italian astronomer, physicist and mathematician Galileo Galilei (1564–1642) was able to observe that the patterns of dark shadows on the Moon's surface changed with the Moon's phases (Figure 21). He became the first person to realise that this is due to variations in topography. The prevailing view of the time was that the Moon's surface was perfectly flat, when in fact it is covered in mountains and craters.

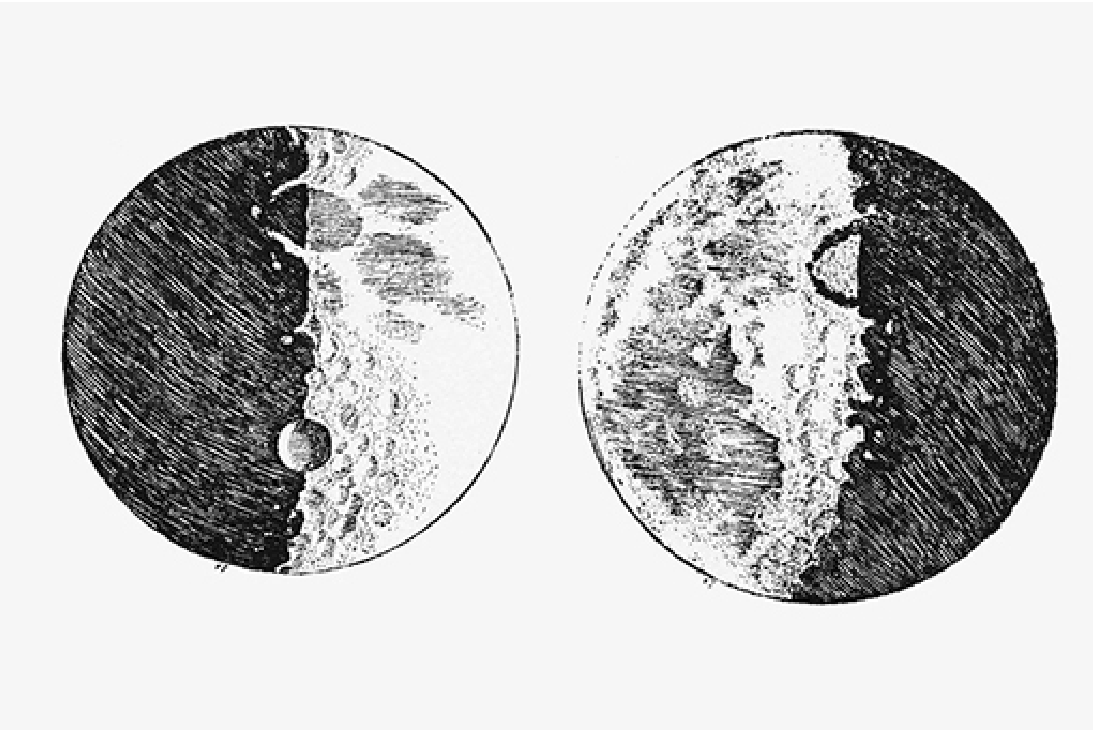
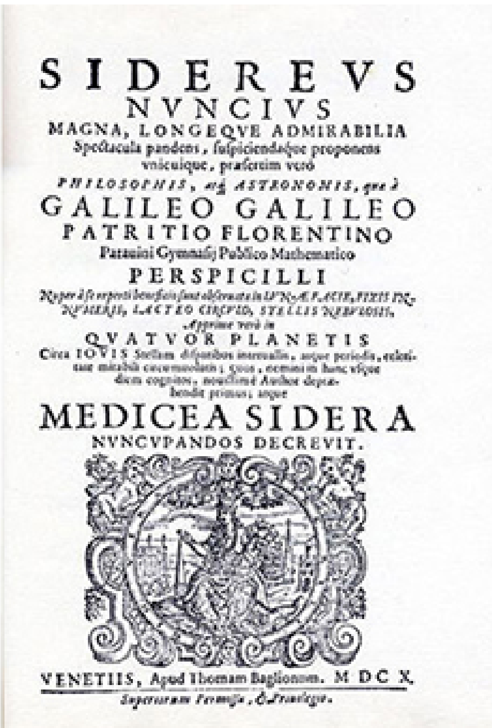


Figure 21 Sketches of the Moon's surface by Galileo, published in his short book Sidereus nuncius (1610), showing several craters

2.2 Galileo's thoughts



SIDEREVS
NVNCIVS
MAGNA, LONGEQVE ADMIRABILIA
Spectacula pandens, suspiciendaque proponens
vnicuique, praesertim verò
PHILOSOPHIS, atq; ASTRONOMIS, quæ à
GALILEO GALILEO
PATRITIO FLORENTINO
Patauini Gymnasij Publico Mathematico
PERSPICILLI
Apprime verò in
QVATVOR PLANETIS
MEDICEA SIDERA
NVNCVPANDOS DECREVIT.
VENETIIS, Apud Thomam Baglionum. M DC X.
Superiorum Permissu, & Priuilegio.

Figure 22 Galileo Galilei, Sidereus nuncius, 1610

Here, in Galileo's own words, are his thoughts about lunar craters. The 'great spots' are the dark lunar plains that can be seen by the naked eye. Galileo's smaller, 'thickly scattered' spots are what we now call craters:

> Now these spots, as they are somewhat dark and of considerable size, are plain to everyone, and every age has seen them, wherefore I shall call them great or ancient spots, to distinguish them from other spots, smaller in size, but so thickly scattered that they sprinkle the whole surface of the Moon, but especially the brighter portion of it.
>
> These spots have never been observed by anyone before me; and from my observations of them, often repeated, I have been led to that opinion which I have expressed, namely, that I feel sure that the surface of the Moon is not perfectly smooth, free from inequalities and exactly spherical, as a large school of philosophers considers with regard to the Moon and the other heavenly bodies, but that, on the contrary, it is full of inequalities, uneven, full of hollows and protuberances, just like the surface of the Earth itself, which is varied everywhere by lofty mountains and deep valleys.
>
> Galileo Galilei, Sidereus nuncius, 1610
> Translation by Peter Barker (2004)

2.3 Comparing craters

How do craters on the Moon form?

To many scientists over the last few centuries, the obvious answer was to look to the Earth for similar features. People already knew about the craters found on volcanoes. Such craters form when magma drains downwards after an eruption, leaving a circular depression (sometimes known as a 'caldera') at the surface, or when a volume of rock is ejected by an explosive eruption.

The apparent similarities between volcanic craters and images of lunar craters seemed to answer the question of how the Moon's craters were formed.

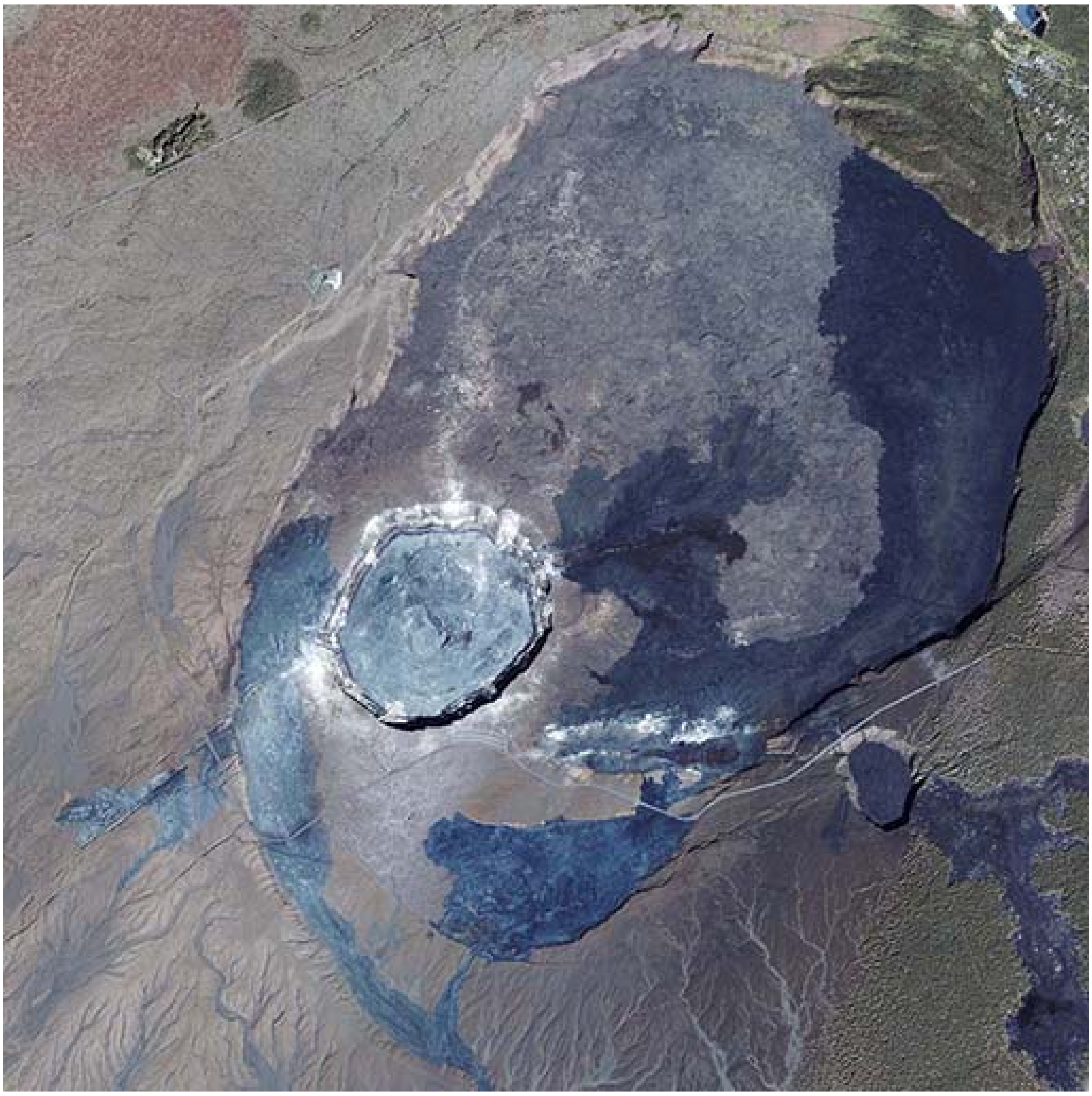


Figure 23 Aerial photograph of a volcanic caldera on Kilauea, Hawaii

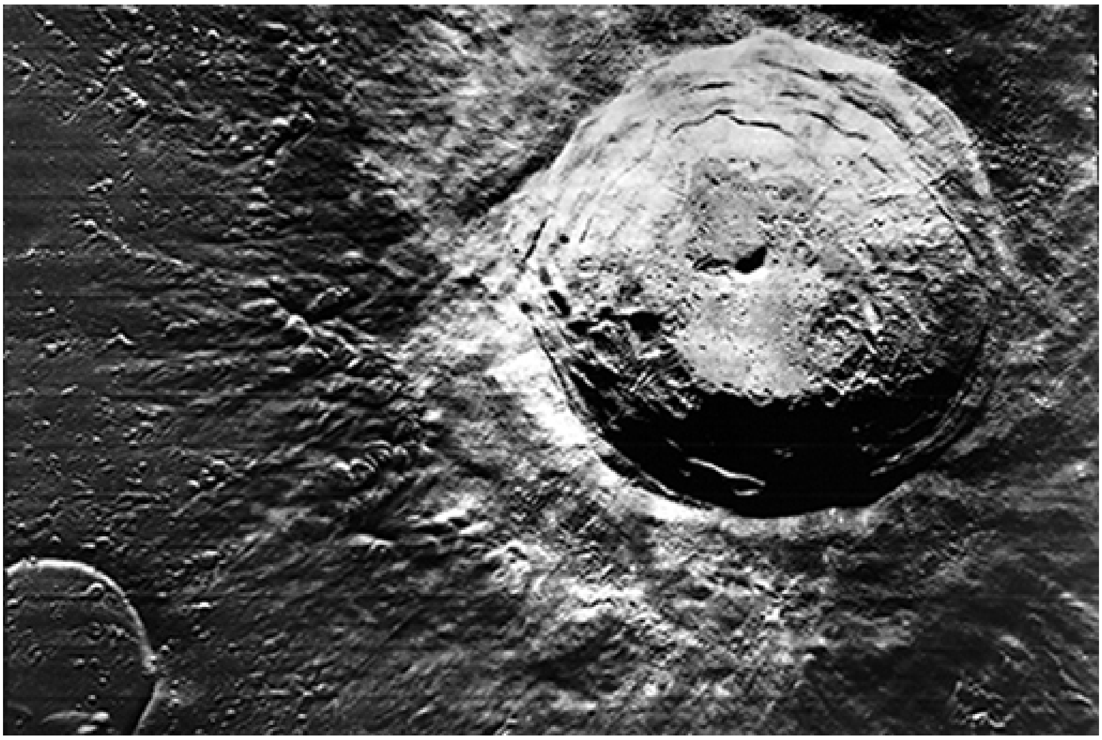


Figure 24 Aristarchus crater on the Moon, as photographed by Lunar Orbiter 5 in 1967

2.4 Meteor Crater, Arizona

However, a second theory for how craters on the Moon formed came to the fore in the light of further discoveries made on the Earth. According to the new theory, these lunar craters could have been created by impacts.

In the early 1900s, Daniel Barringer, an American mining engineer and businessman, first proposed the idea that the supposedly volcanic Canyon Diablo crater in Arizona was, in fact, created by a metallic meteorite impact. Barringer was so sure of his idea that he set about trying to find the impactor's iron metal, with a view to mining the crater. Perhaps fortunately, no significant iron deposits were ever found.

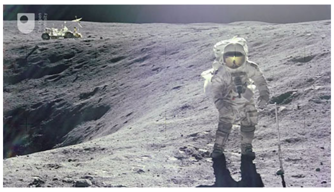
This suggestion was viewed with some scepticism, until in the 1960s, Eugene M. Shoemaker, a geologist and early planetary scientist, was able to confirm Barringer's claim. Shoemaker found rare silica minerals at the crater site, of a kind formed only when rocks are severely shocked by the instantaneous application of extreme pressure. The only known mechanism to generate such instant high pressures in nature is a high-speed (hypervelocity) meteorite impact. (The term 'hypervelocity' means speeds of several, perhaps tens of, kilometres per second.) This led to the realisation that other craters, such as those found on the Moon, could also be formed by impacts, not volcanism. Even though there has been extensive volcanic activity on the Moon, almost all the craters, including all of the large ones, are now known to have been made by hypervelocity impacts (as you will see shortly).

Figure 25 Aerial view of Meteor Crater (otherwise known as Barringer Crater), Arizona

2.5 How impact craters form

In this video Bevan French recalls crater studies in the 1960s and 1970s, and describes some of the processes that we now understand to occur when an impact crater is made.

Video content is not available in this format.



2.6 Gene Shoemaker at Meteor Crater

And here is the late Gene Shoemaker himself, speaking at Meteor Crater in 1997, and remarking on why impact craters are so much better preserved on the Moon than on the Earth.

Video content is not available in this format.

2.7 Making an impact

In the decades since Gene Shoemaker's discoveries in Arizona, the impact model of crater formation has gained wide acceptance.

Using data from computer-based modelling and real lab-based experiments, planetary scientists now know that when an impactor hits the ground at hypervelocity, most of the impactor material is vaporised, and the crater itself is excavated by intense shock waves, radiating out from the point of impact.

This video includes some classic experiments from the mid 1980s.

Video content is not available in this format.

2.8 Impact mechanics

The size of an impact crater is very variable and depends on the energy of the impact, on the properties of the material the impactor is hitting and on the surface gravity of the target body. The energy of the impact is also variable, depending on the velocity, size and density of the impactor material.

All of these variables give rise to a progression of different crater shapes or morphologies, changing from one to the next as crater size increases, from microscopic in scale to hundreds of kilometres in diameter.

This animation shows stages in the formation of an impact crater several tens of km across. The size of the impactor (the meteorite) has been exaggerated for clarity. Craters usually end up at least 30 times wider than the impactor that caused them. On the Moon, craters bigger than about 10–20 km develop central peaks as shown in the animation by a process called 'elastic rebound' (a similar rebound process occurs when water droplets hit the surface of a body of water). Central peaks are not seen in lunar craters bigger than about 200 km because they have subsided under their own weight, but peaks remain frozen in place in smaller craters where they are still visible unless the crater has become partly infilled.

Video content is not available in this format.

(Please note this video has no audio.)

2.9 Crater morphologies

Now explore these final cross-sectional shapes (morphologies) typical of craters of different sizes, and learn about some of the reasons why morphology depends on size.

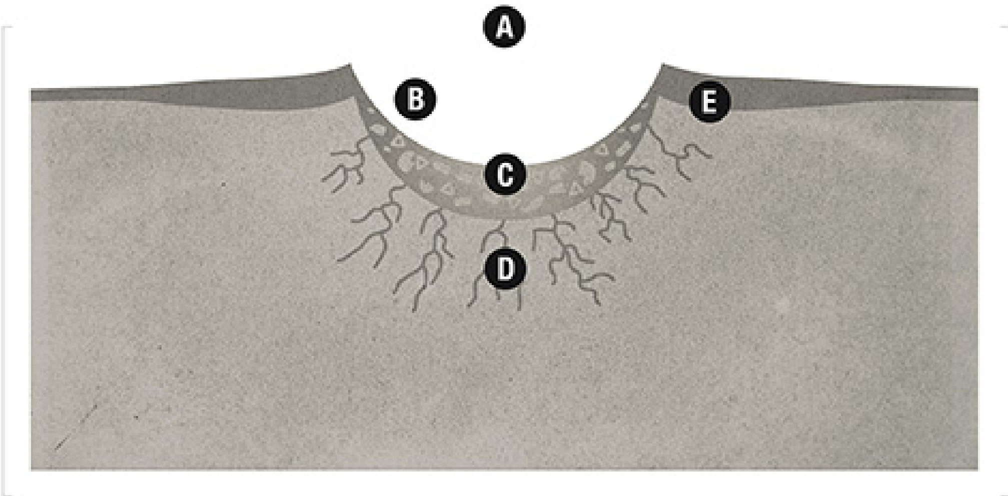


Figure 26 Bowl-shaped craters

- **A** – Smallest crater type.
- **B** – Depth typically 20% of crater diameter.
- **C** – Concave crater floors; made up of rocks melted during the impact and fractured pieces of solid rock.
- **D** – Ground beneath the crater floor is heavily fractured due to impact.
- **E** – Crater rim is built up by layers of material ejected as the crater formed.

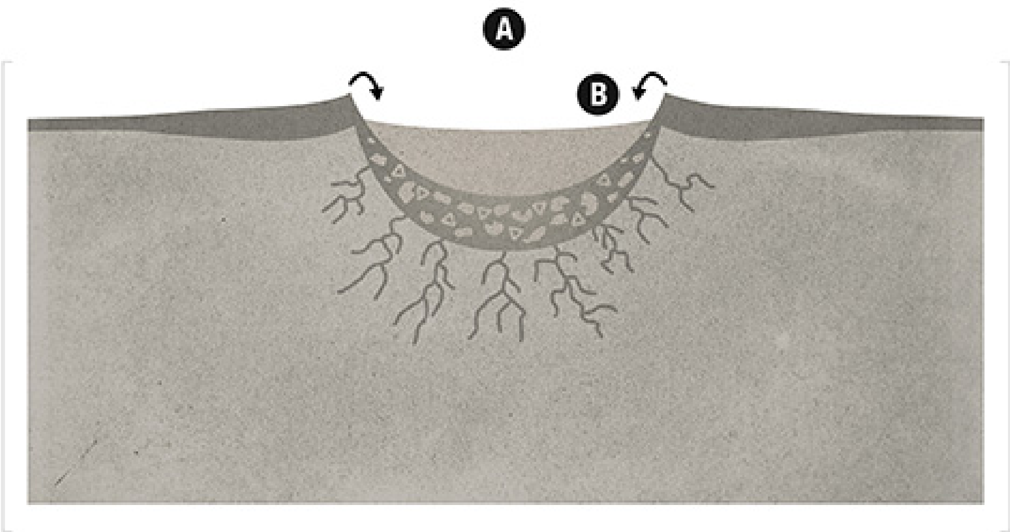


Figure 27 Flat-floor craters

- **A** – More mature simple craters.
- **B** – Like bowl-shaped craters, but material from crater walls slumps down into the crater, making the floor much flatter.

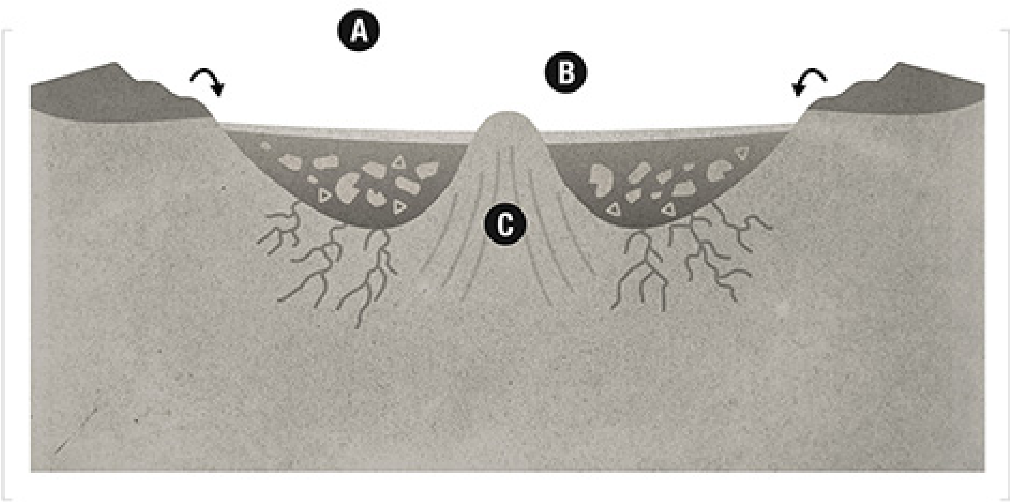


Figure 28 Central-peak craters

- **A** – Smallest of the complex crater morphologies.
- **B** – Generally flat crater floors, made up of significantly greater proportions of impact-melted rock compared to simple craters, with a peak or cluster of peaks in the centre.
- **C** – Peak forms when underlying material rebounds after crater formation, pushing upwards and rising above the crater floor.

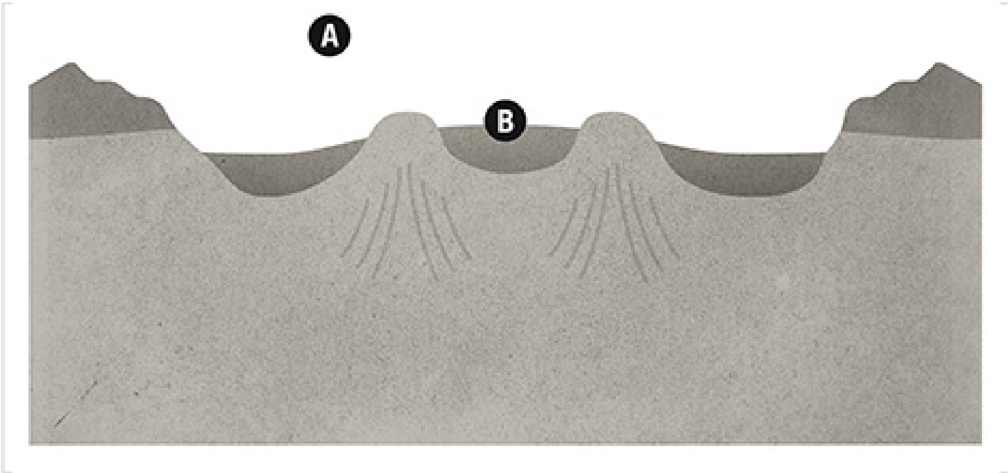


Figure 29 Peak-ring craters.

- **A** – Similar to central-peak craters, but the central peak here rebounds and rises so much that it becomes unstable.
- **B** – To regain stability, the oversized central peak collapses in on itself, leaving behind a ring of uplifted material surrounding a flat area in the centre.

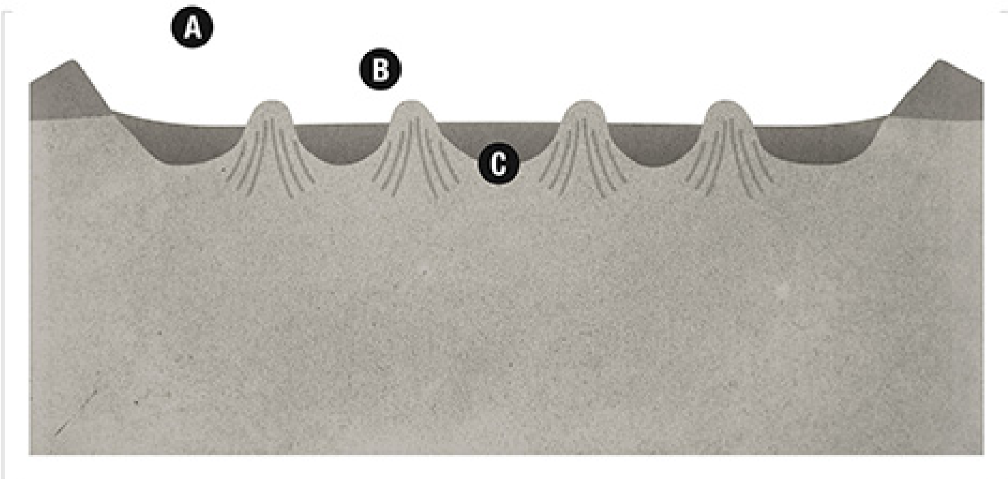


Figure 30 Multi-ring basin craters.

- **A** – The largest craters, associated with only the largest impactors and most energetic impacts.
- **B** – Crater diameters are so large that they contain several concentric rings of uplifted material, i.e. a larger version of peak-ring craters.
- **C** – In multi-ring basins, the largest proportion of material excavated by the impact event is melted, pooling in the centre of the basin floor.

2.10 Examples of crater shapes on the Moon

In this image gallery you see examples of lunar craters of different sizes. Examine the images to see how crater morphology changes according to the size of the crater. The actual size at which a crater changes from simple to complex varies across different Solar System bodies according to their surface gravity. For example, on the Moon, the transition from a simple crater to a complex one occurs at around 20 km in diameter. By contrast, on Earth, where gravity is six times greater than on the Moon, craters become complex at an average of 3 km in diameter or above.

Because the Moon has no atmosphere, impactors of all sizes are able to reach the surface, generating the full range of crater types shown here. Earth's thick atmosphere protects it from many of the smaller impacts that the Moon experiences. Smaller incoming impactors are burnt up as they enter the atmosphere and so do not reach the ground, or are slowed down as they fall, reducing their velocity and placing a lower limit on the size of any crater that can form.

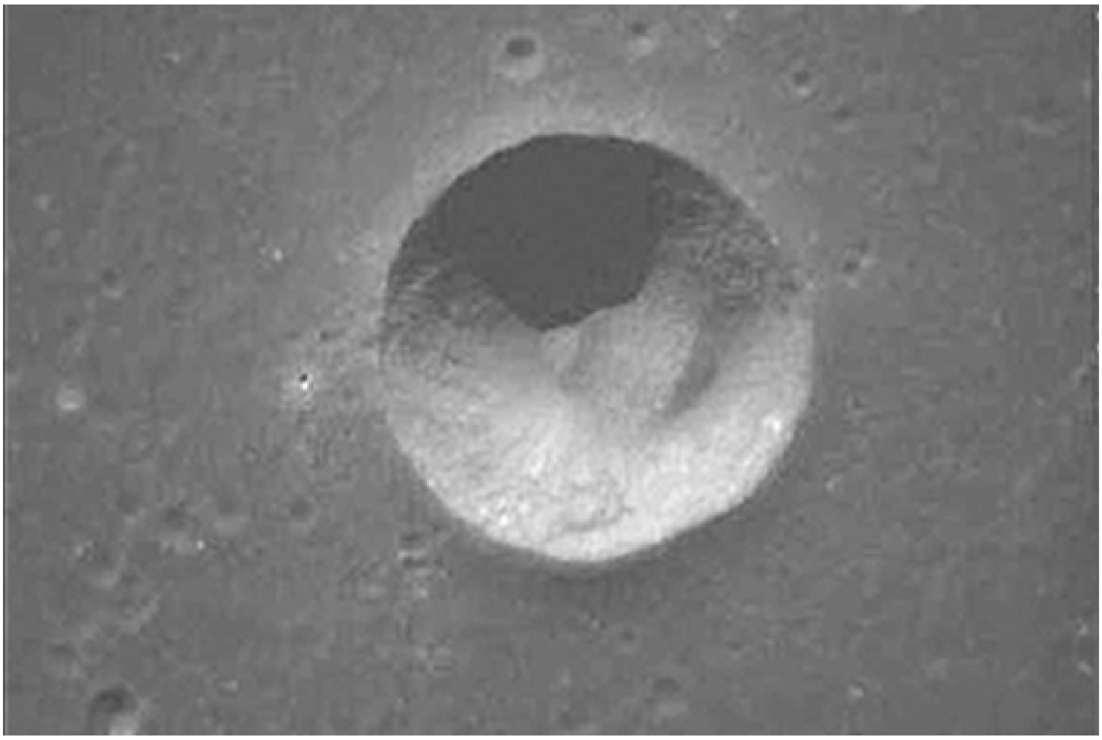


Figure 31 Anville (simple bowl-shaped). 11 km diameter.

Figure 32 Gruithuisen (simple flat-floor). 16 km diameter.

Figure 33 Agrippa (complex central-peak). 46 km diameter.

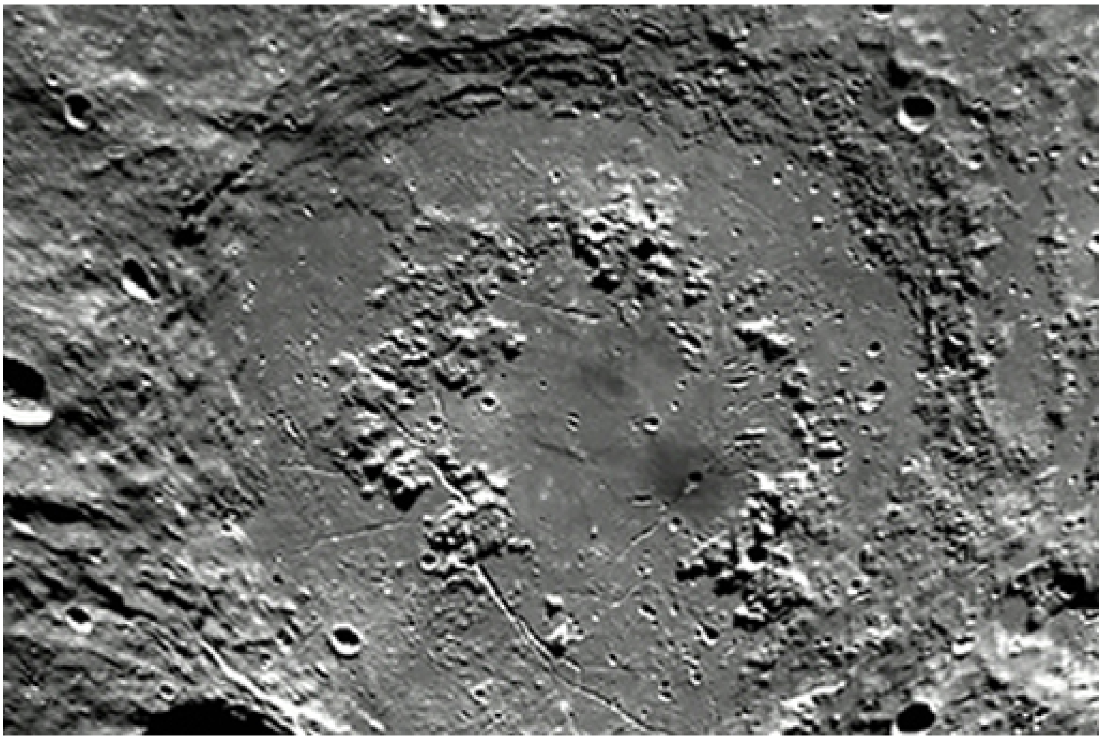


Figure 34 Schrödinger (complex peak-ring). 316 km diameter

Next you will see evidence of present-day impacts onto the Moon (all of them far too small to make a crater visible from Earth).

3 Lots of little impacts

You might think that craters on the Moon are all pretty old, but you'd be wrong. The craters that are big enough to see through a telescope are old, but the Moon is being hit by cosmic debris all the time. With no atmosphere to protect it, even small chunks of rock and ice strike the surface with undiminished speed. When that happens, there is a brief flash of light as the energy of the impact gets turned into heat.

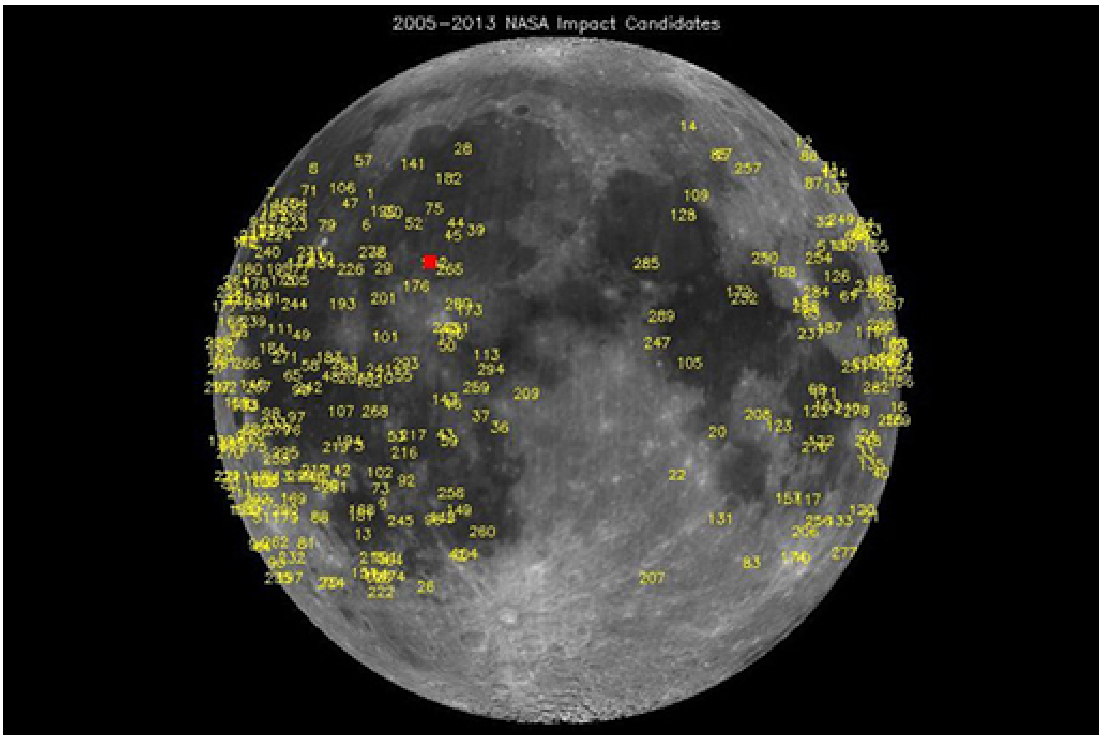


Figure 35 Impact candidates detected on the Moon 2005–2013.

This image shows the locations of hundreds of meteoroid impacts detected since 2005 by a NASA-led campaign using telescope cameras. One of the brightest flashes and therefore one of biggest impacts was on 17 March 2013 (the red square above), as you will see next.

If you wanted to look into this further, you might find the following link of interest: Detection of new craters on images. 222 new craters (10 m to 43 m in size) found by comparing high-resolution images from NASA's Lunar Reconnaissance Orbiter. Short article and animation.

3.1 One 'big' impact

Watch this NASA video reporting the event of 17 March 2013. The commentary for the video omits to point out that the video of the flash was made by imaging the part of the Moon that was in darkness and that the faintly visible Moon in the video is illuminated only by light reflected onto the Moon from the Earth. Faint flashes occurring on the sunlit part of the Moon would be almost impossible to see. The video refers to 'explosions', which is not strictly true – the crater is excavated by a shock wave generated at the point of impact.

The flash is the sudden glow caused by the incoming energy being turned into heat. Listen out for the estimated size of the crater in the video commentary.

The new crater has now been imaged, and you can swipe across a before and after comparison captured by the Lunar Reconnaissance Orbiter Camera. (This can be a little fiddly on small screens and will work best on desktops/tablets.)

Video content is not available in this format.

If you wanted to look into this further, you might find the following link of interest: 'Biggest observed meteorite impact' hits Moon. A report of an even bigger impact onto the Moon on 11 September 2013, seen by Spanish astronomers.

3.2 Scarce craters

As you have just seen, about a hundred meteoroid impacts onto the surface of the Moon are detected every year. Each one of these will produce a crater. Think about reasons why craters formed by meteoroid impact are so rare on the surface of the Earth. It may help you to know that an incoming object has to be bigger than about 100 m across to get through our atmosphere with undiminished speed. Smaller objects are slowed down and broken apart, and if any lumps survive they hit the ground too slowly to form a proper crater.

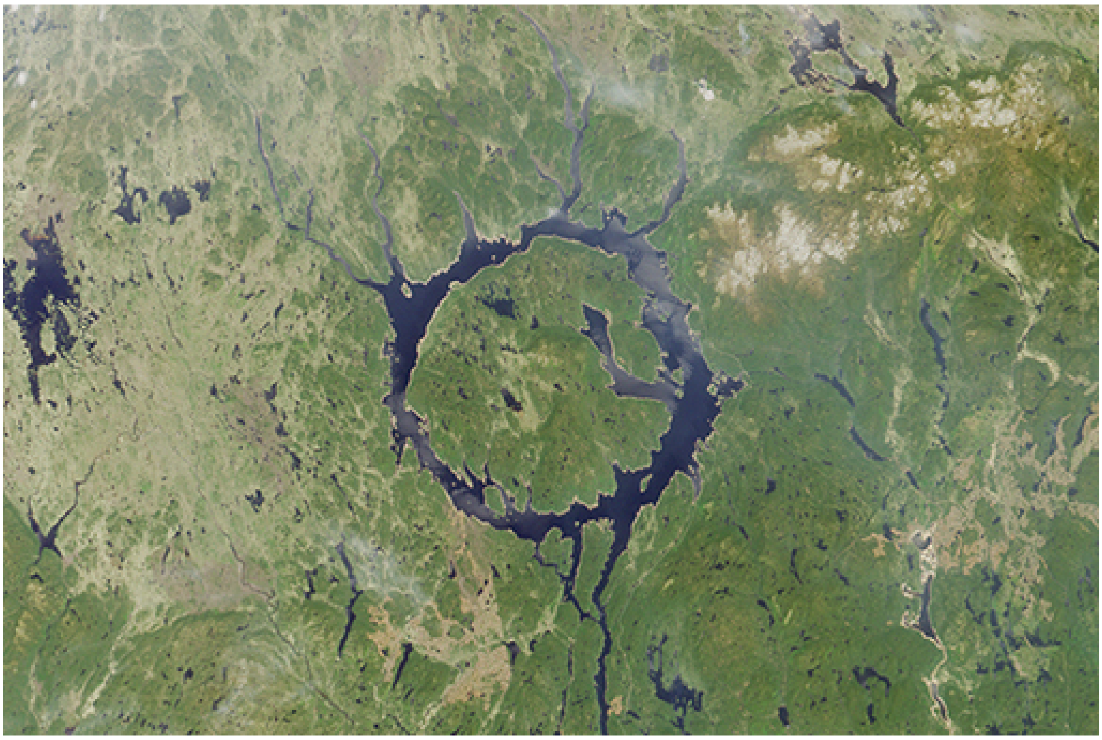


Figure 36 Lake Manicouagan seen from space: the partially lake-filled eroded remnants of a 100 km diameter, 214 million year old impact crater in Quebec, Canada.

3.3 Why some craters are big

So, how do scientists work out the size of the crater that a particular impact would form or, conversely, the properties of an impact that would have caused a crater of a particular size? Well, now that the process is understood, it is possible to calculate the relationships. The calculations can be tested against small-scale laboratory experiments and in rare cases if the actual crater is eventually imaged.

The size of a crater is controlled by various factors, some related to the impactor and others related to the target surface. The more energy delivered by the impactor, the bigger the crater. The easier it is to break apart and disperse the material from which the target surface is made, the bigger the crater. In the case of Valhalla, shown in Figuren 37, Callisto’s crust was too weak to support the crater that formed in the centre, which has sagged to flatness and is now marked by a pale blotch surrounded by concentric rings.

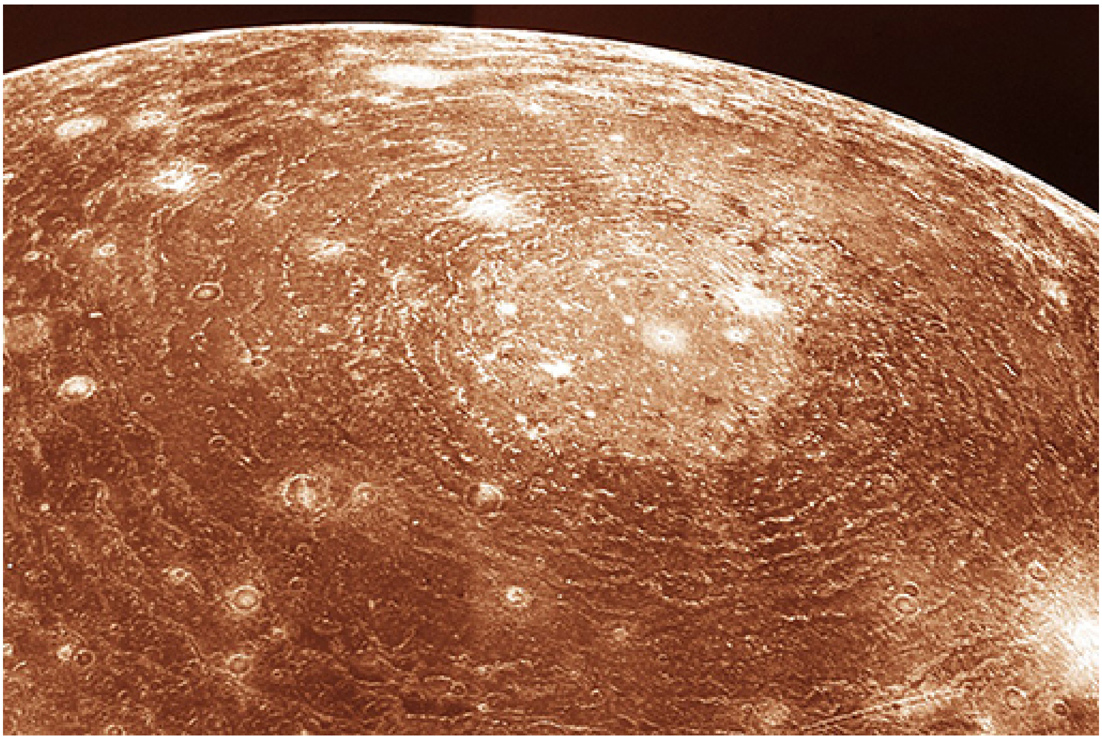


Figure 37 Valhalla, the Solar System's largest multi-ringed impact basin, on Callisto. The outer ring is 2000 km across.

The energy of the impactor depends on its mass (and therefore on both its size and its density) and on the speed at which it strikes the surface.

The ease with which the target surface breaks up depends on its density and on whether the surface is a solid layer or consists of fragmental material. The ease with which the target material is dispersed depends on the strength of the surface gravity of the target body.

3.4 Surface gravity

The strength of surface gravity on the Earth (measured as the rate at which a falling object accelerates) is 9.8 m s^{-2} (where m s^{-2} stands for metres per second per second, meaning the rate at which the speed of a falling object increases).

Read the following information and then try Activity 3, where you are asked to match the correct value of surface gravity to different moons. Feel your way by making intelligent guesses – we don't expect you to work out the value from first principles.

Figure 38 The Moon, Ganymede, Ariel and Enceladus, shown at correct relative scale.

- The Moon is a rocky body smaller than the Earth, whose surface gravity is about one-sixth of the Earth's and whose diameter is 3474 km.
- Ganymede is an icy moon of Jupiter whose diameter is 5262 km. Ice is less dense than rock.
- Enceladus is an icy moon of Saturn whose diameter is 504 km.
- Ariel is an icy moon of Uranus whose diameter is 1158 km.

Activity 3 Surface gravity – what do you know?

Allow approximately 15 minutes.

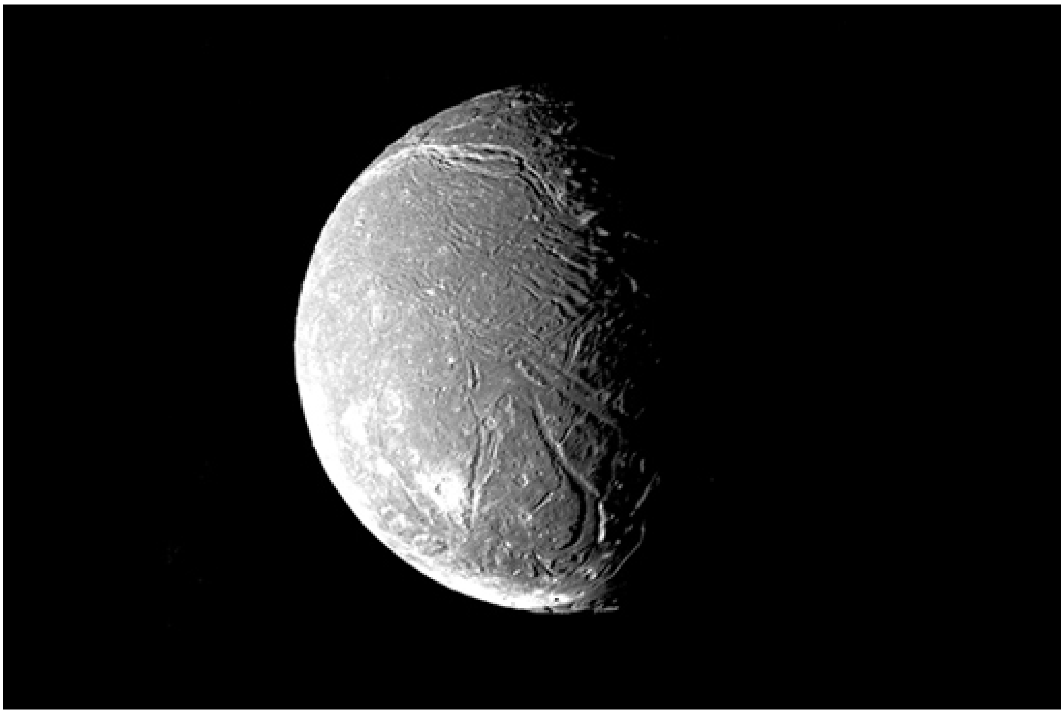


Figure 39 Ariel.

What is the surface gravity on this moon?

○ 0.114 m s^{-2}

No. The surface gravity on Ariel is greater than this.

○ 1.428 m s^{-2}

No. The surface gravity on Ariel is less than this.

○ 0.270 m s^{-2}

Well done.

○ 1.622 m s^{-2}

No. The surface gravity on Ariel is less than this.

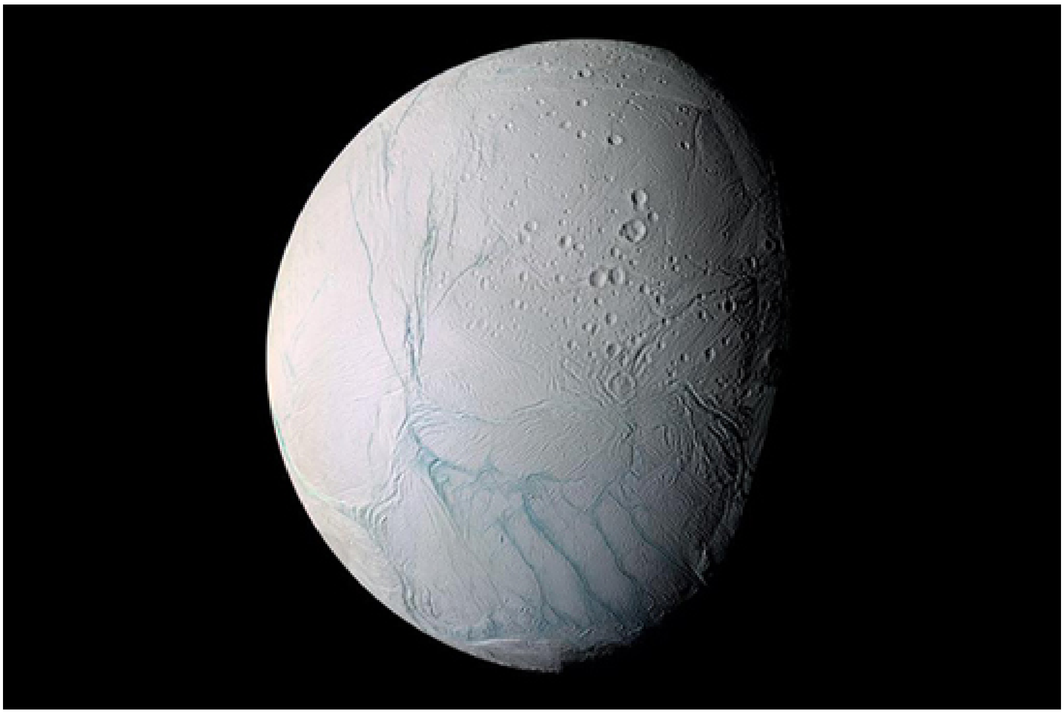


Figure 40 Enceladus.

What is the surface gravity on this moon?

○ 0.114 m s^{-2}

Well done. The surface gravity on Enceladus is not much more than one-hundredth of the Earth’s.

○ 1.428 m s^{-2}

No. The surface gravity on Enceladus is less than this.

○ 0.270 m s^{-2}

No. As you’ve just seen, this is the value of the surface gravity on Ariel. The surface gravity on Enceladus is less than this.

○ 1.622 m s^{-2}

No. The surface gravity on Enceladus is less than this.

Figure 41 Ganymede.

What is the surface gravity on this moon?

○ 0.114 m s^{-2}

No. As you've just seen, this is the value of the surface gravity on Enceladus. The surface gravity on Ganymede is greater than this.

○ 1.428 m s^{-2}

Well done.

○ 0.270 m s^{-2}

No. As you've just seen, this is the value of the surface gravity on Ariel. The surface gravity on Ganymede is greater than this.

○ 1.622 m s^{-2}

No. As you've just seen, this is the value of the surface gravity on Enceladus. The surface gravity on Ganymede is less than this, despite being the largest moon in the Solar System.

Figure 42 The Moon

What is the surface gravity on the Moon?

○ 0.114 m s^{-2}

No. As you've just seen, this is the value of the surface gravity on Enceladus. The surface gravity on the Moon is greater than this.

○ 1.428 m s^{-2}

No. As you've just seen, this is the value of the surface gravity on Ganymede. Although Ganymede is bigger (and has more mass) than the Moon, it is less dense. The net result is that its surface gravity is slightly less than the Moon's.

○ 0.270 m s^{-2}

No. As you've just seen, this is the value of the surface gravity on Ariel. The surface gravity on the moon is greater than this.

○ 1.622 m s^{-2}

Well done. Although Ganymede is bigger (and has more mass) than the Moon, it is less dense. The net result is that its surface gravity is slightly less than the Moon's.

If you wanted to look into this further, you might find the following link of interest: Detection of new craters on images. 222 new craters (10 m to 43 m in size) found by comparing high-resolution images from NASA's Lunar Reconnaissance Orbiter. Short article and animation.

4 Crater sizes

Use the three short crater calculation tables on this page to find out about the effects of a range of variables on the diameter of impact craters.

Use the data supplied to help you think about what you might expect in each case (how big will each crater be?), then select ‘Click to reveal answer’ below each diagram to see a fully labelled version and find out how good your intuition was. Don’t worry if you were way out. We do not expect you to perform calculations or work out the answers in some other way. This is a learning exercise.

Activity 4 How big will each crater be?

Allow approximately 20 minutes.

Porous rocky impactor (likely to be an asteroid) onto the Moon

First, find out the size of craters on the Moon formed by four porous rocky impactors that vary in diameter but are identical in composition, impact speed and impact angle.

Crater diameter is calculated according to impactor diameter, as you see in the table, and the following values:

- impact speed – 17 km s^{-1}
- impact angle – 90° (vertical)
- surface gravity – 1.622 m s^{-2}
- target density – 1500 kg m^{-3}.

Impactor diameter	0.4 m	4 m	40 m	400 m
Crater diameter	?	?	?	?

Figure 43 Porous rocky impactor (likely to be an asteroid) onto the Moon.

When you’re ready, select ‘Reveal answer’ to see the completed table.

Answer

Porous rocky impactor (likely to be an asteroid) onto the Moon

Impactor diameter	0.4 m	4 m	40 m	400 m
Crater diameter	19 m	350 m	2.1 km	12.7 km

Figure 44 Porous rocky impactor (likely to be an asteroid) onto the Moon.

What your results show

The 0.4-m diameter impactor represents something like the object that struck the Moon on 17 March 2013 as you saw in the ‘One “big” impact’ video. If it excavated a crater about 20 m in size, as your results suggest, then this would be easily visible by probes in lunar orbit.

Varying the impactor properties

Next you can consider different impacts onto the Moon. To make the comparison straightforward, we have fixed the impactor diameter at 40 m. You will compare impacts at identical speed but at different angles. You will also see what happens if the impactor is made of ice rather than rock. When a lump of ice hits the Moon, it is usually a comet. Since comets tend to travel faster than other impactors, you will also see the effect of greater impact speed. It should be fairly obvious that a lump of ice will make a smaller crater than a lump of rock of the same size and arriving at the same speed. But what if the ice arrives with a speed three times that of the rock?

The following values are also used to calculate the crater diameter:

- impactor diameter – 40 m
- surface gravity – 1.622 m s^{-2}.

Impactor characteristics	Porous rock 17 km s^{-1}, at 90°	Porous rock 17 km s^{-1}, at 30°	Ice 17 km s^{-1}, at 90°	Ice 50 km s^{-1}, at 90°
Crater diameter	?	?	?	?

Figure 45 Varying the impactor properties

When you're ready, select 'Reveal answer' to see the completed table.

Answer

Varying the impactor properties

Impactor characteristics	Porous rock 17 km s^{-1}, at 90°	Porous rock 17 km s^{-1}, at 30°	Ice 17 km s^{-1}, at 90°	Ice 50 km s^{-1}, at 90°
Crater diameter	2.1 km	1.7 km	1.8 km	3.0 km

Figure 46 Varying the impactor properties

What your results show

A 40-m diameter comet (mostly ice) hitting the Moon at the same speed as an asteroid (mostly porous rock) of the same size would make a smaller crater. However, comets tend to make bigger craters because their higher speed compensates for their lower mass. Your results also show that an oblique impact by an asteroid (30° in your example) will make a slightly smaller crater than a vertical impact of the same size and speed.

Varying the target bodies

Now investigate how the target's composition and surface gravity affect the crater size. Slower impact speeds will be used here because, as a result of slower orbital speeds further from the Sun, lumps of ice hitting icy moons probably arrive with slower speeds than is usually the case for objects hitting the Moon.

The following impactor values are also used to calculate the crater diameter:

- impactor diameter – 40 m
- impactor composition – ice
- impact speed – 5 km s^{-1}
- impact angle – 90° (vertical).

Target body	The Moon, rock, gravity: 1.622 m s^{-2}	Ganymede, ice, gravity: 1.428 m s^{-2}	Ariel, ice, gravity: 0.270 m s^{-2}	Enceladus, ice, gravity: 0.114 m s^{-2}
Crater diameter	?	?	?	?

Figure 47 Varying the target bodies

When you're ready, select 'Reveal answer' to see the completed table.

Answer

Varying the target body

Target body	The Moon, rock, gravity: 1.622 m s^{-2}	Ganymede, ice, gravity: 1.428 m s^{-2}	Ariel, ice, gravity: 0.270 m s^{-2}	Enceladus, ice, gravity: 0.114 m s^{-2}
Crater diameter	1.1 km	1.3 km	1.8 km	2.2 km

Figure 48 Varying the target bodies

What your results show

For fixed impact conditions, craters on the smaller (lower surface gravity) icy moons will be larger than those on the bigger icy moons, but the difference in crater size between the biggest icy moon (Ganymede) and a fairly small one (Enceladus) is less than a factor of two.

If you want to investigate further the effects of target and impactor properties on crater size, you can explore the LPL crater calculator. This will let you calculate crater size based on the impactor (like you did here) or calculate the impactor size based on the crater. You should always use final crater size, not transient crater size. (If you try to use this calculator to replicate the results in our tables above, and this is NOT something that we are asking you to do, you will find that we have adjusted the 'target type' to be loose and/or porous for small craters - likely to be confined to the surface regolith layer – or competent and/or solid for larger craters – likely to extend down into stronger material.) You can also play The Open University's 'Meteoric' game to see for yourself the craters that form in certain conditions.

4.1 A changing moonscape

Look at Figure 49, of the surface of the Moon. What do you notice about the number and size of craters across the image? Is there a difference between one part of the image and another? Why might this be?

Figure 49 An image of the Moon, roughly 200 km across the foreground, as seen from Japanese lunar orbiter SELENE.

This image shows the ancient lunar highland region to the right, with the younger, darker basaltic 'mare' (pronounced 'MAH-ray', Latin for 'sea') to the left. Because of the Latin origin of the word, the plural of mare is maria (pronounced 'MAH-ria'). Early observers saw these dark smooth surfaces and guessed wrongly that they might be seas, hence the name.

The reason why there are so few craters on the left is that this area was flooded by volcanic lava after most of the impact craters were formed.

If you wanted to look into this further, you might find the following link of interest: Kaguya fly-over of Tycho crater. To see more examples of lunar craters, watch this superb fly-over tour of the crater Tycho.

5 This week’s quiz

This quiz allows you to test and apply your knowledge of the material in Week 2.

Complete the Week 2 quiz now.

Open the quiz in a new window or tab then come back here when you’re done.

6 Summary

This week you were shown the structure of a moon and what it's made of. You also learned about the prevalence of ice in the moons of the Solar System. This week also looked at the creation of craters as a result of comet and meteorite impact. The week ahead looks at volcanic eruptions, the impact of Galileo's discoveries of the first moons of another planet, and the conditions that might make a moon's interior habitable for microbial life.

You should now be able to:

- recognise the structure of a moon and what it's made of
- understand the significance of ice, and its different forms, in the moons of the outer solar system
- understand how a moon's surface is altered by comet or meteorite impact.

You can now go to Week 3: Looking closer.

Week 3: Looking closer

Introduction

Find out about ancient volcanism on the Moon and elsewhere, as well as present-day hot volcanism on Io and icy volcanism on Enceladus. Discover the heat source that keeps such small bodies active.

First of all, Jess introduces the whole week.

Video content is not available in this format.

By the end of this week, you should be able to:

- understand the significance of volcanic activity on moons
- consider the importance of Galileo's discovery of four moons around Jupiter
- consider the place in our Solar System that is most likely to host extraterrestrial life.

1 Volcanism in the Solar System

Earth is not the only volcanically active body in the Solar System; it is not even the most volcanically active body. Smooth surfaces on moons and differing numbers of craters on different areas of the same moon suggest more recent geological activity, as can be seen in the examples here.

In Figure 1, smooth dark patches stand out, showing their younger ages from the relative lack of craters.

Figure 1 The Moon.

Figure 2 is of Io, Jupiter's closest large moon. It is slightly bigger than Earth's Moon but is volcanically active and no impact craters can be seen at all at this scale. They have all been buried by lava flows or by fall-out from explosive eruptions. The yellow colour is because of sulfur and sulfur dioxide frost supplied by the eruptions.

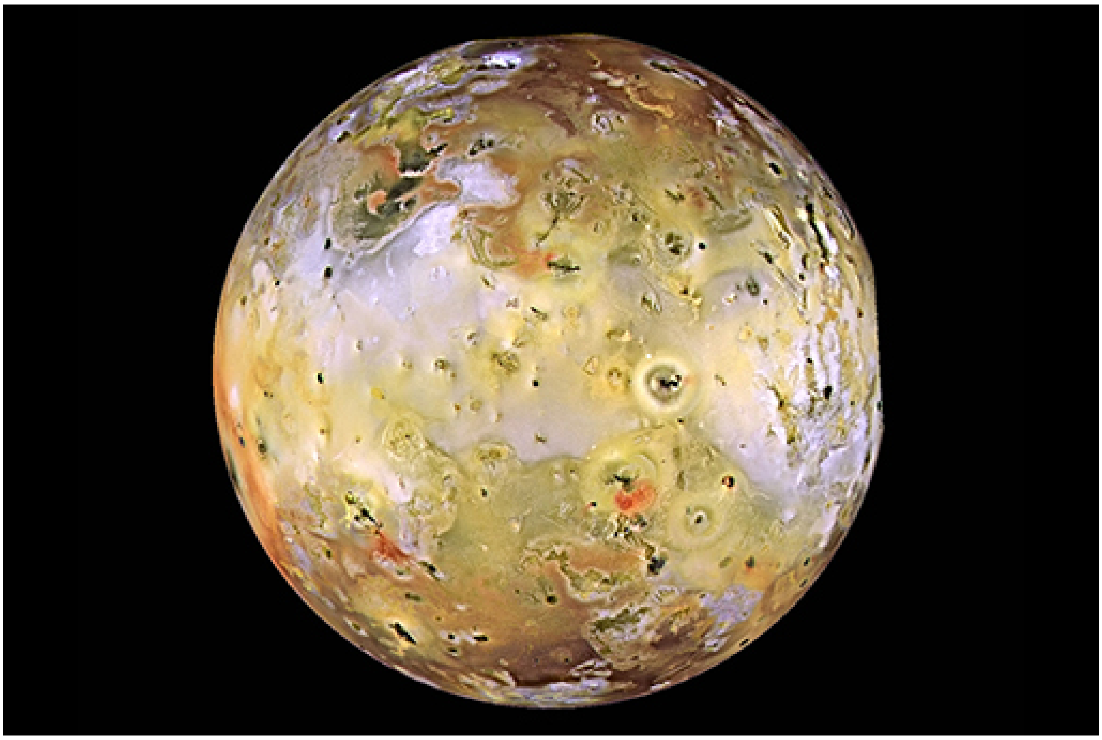


Figure 2 Io.

Figure 3 is a 504-km diameter moon of Saturn, which has a surface made largely of very cold (-200 °C) water-ice. Impact craters can be seen in much of the upper right portion, but elsewhere they have been destroyed by younger tectonic activity, in the form of many generations of fractures (cracks) that cross the surface. The blue tinge adjacent to the younger cracks in the south is probably because the ice crystals here are larger. These cracks, informally called the ‘tiger stripes’, are sites of explosive icy eruptions, where jets of ice crystals and volatile substances are spouted into space. The surface of Enceladus is extremely bright, reflecting 99% of the sunlight that falls on it; this is not apparent in this image because the exposure has been adjusted to show the surface clearly.

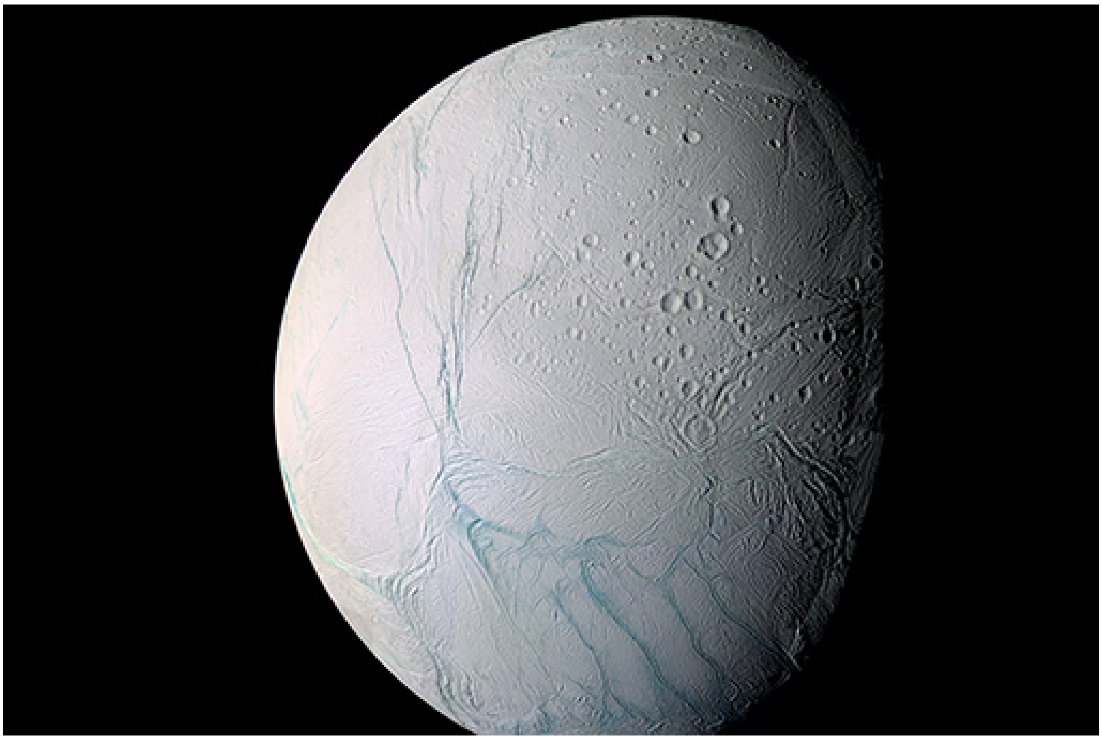


Figure 3 Enceladus.

Figure 4 Neptune's largest moon. It was discovered in 1846 by the British astronomer William Lassell just 17 days after Neptune was discovered. It is unusual in the Solar System, being a large moon that has an orbit opposite to the direction of the planet's rotation (retrograde). Smooth plains in the upper right are probably icy lava flows, and the curious ridges and dimples elsewhere may be volcanic features too.

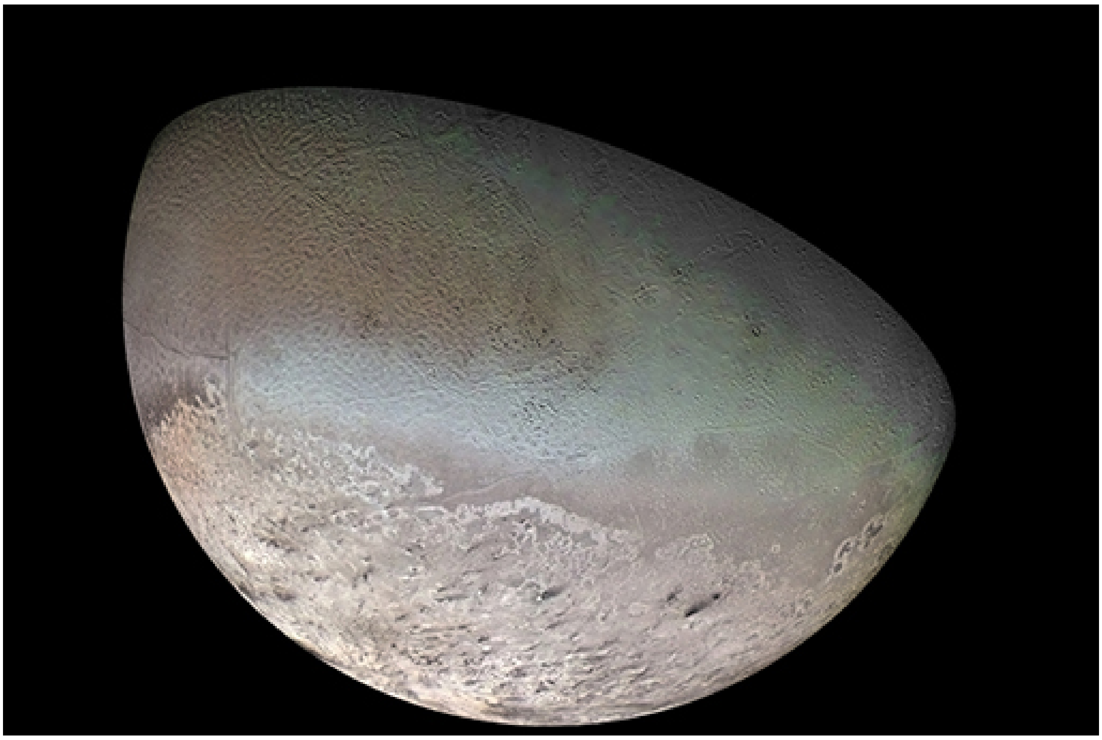


Figure 4 Triton.

Figure 5 is an icy moon of Uranus, 1158 km in diameter. It was discovered in 1851 by the same man who discovered Triton – William Lassell. The straight-sided troughs that cross its surface are probably defined by pairs of faults, and the smooth material on their floors may have been erupted as flows of an ammonia–water mixture.

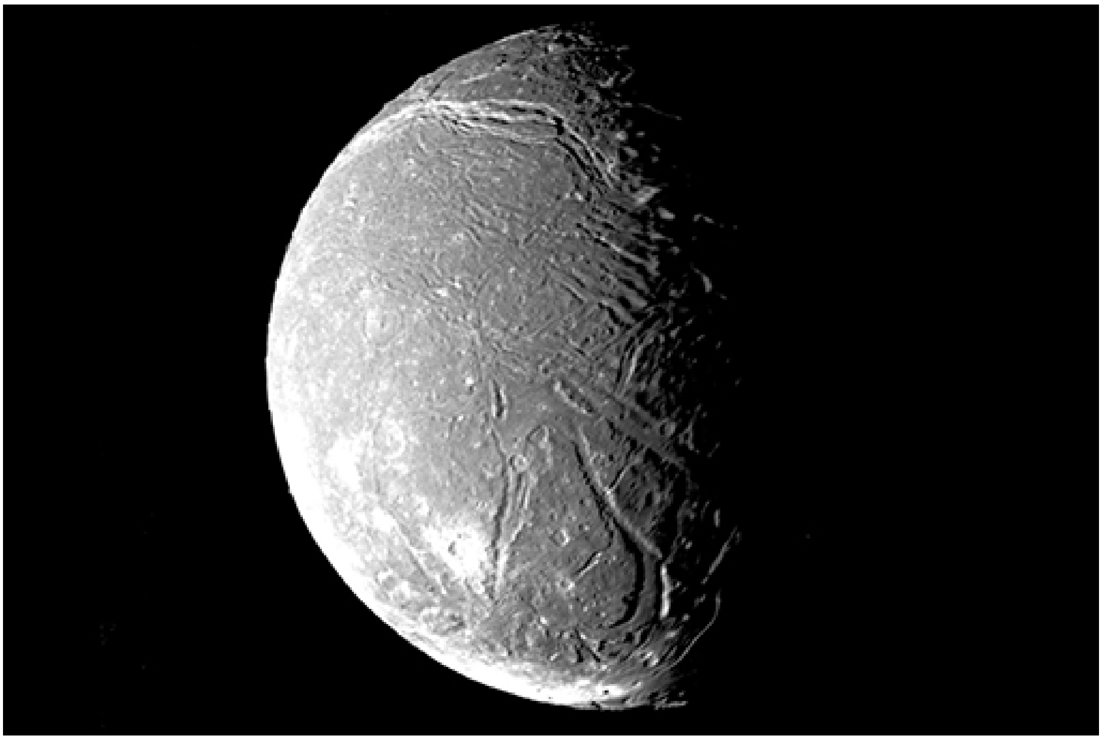


Figure 5 Ariel.

Figure 6 is a 472-km diameter moon of Uranus, with a very unusual surface. At top, middle and bottom are regions of grooved or stripy terrain, which may be partly volcanic in origin. They sit uncomfortably within more normal-looking areas of cratered terrain.

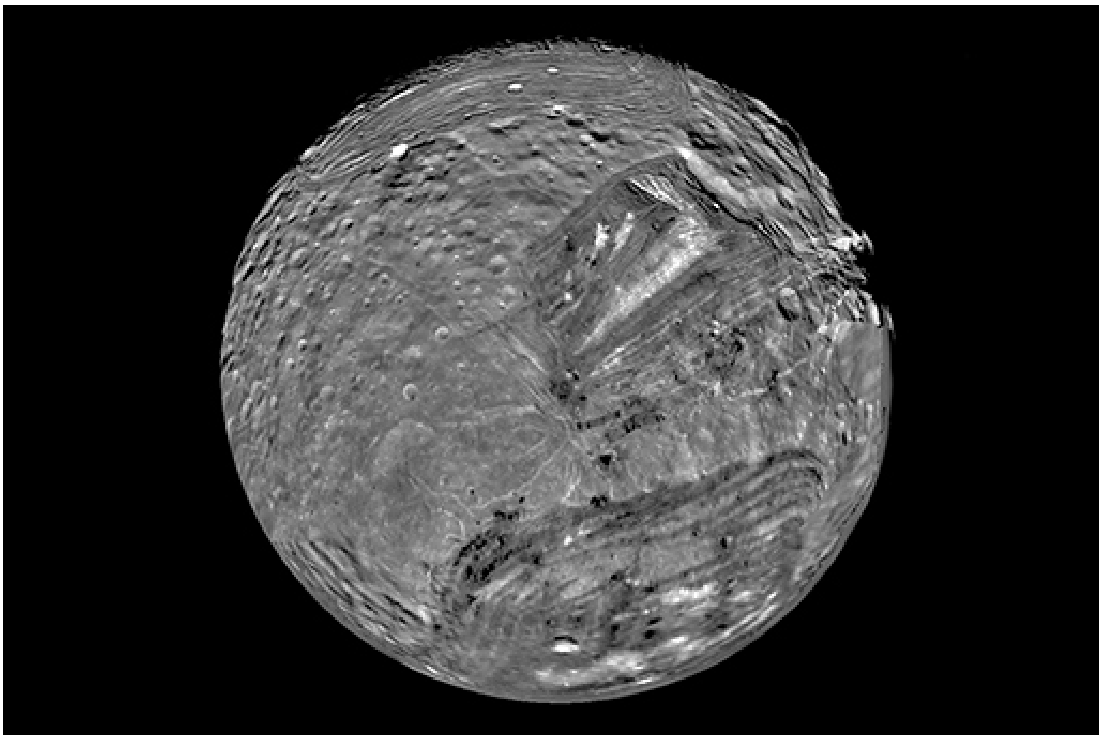


Figure 6 Miranda.

1.1 Past volcanism on the Moon

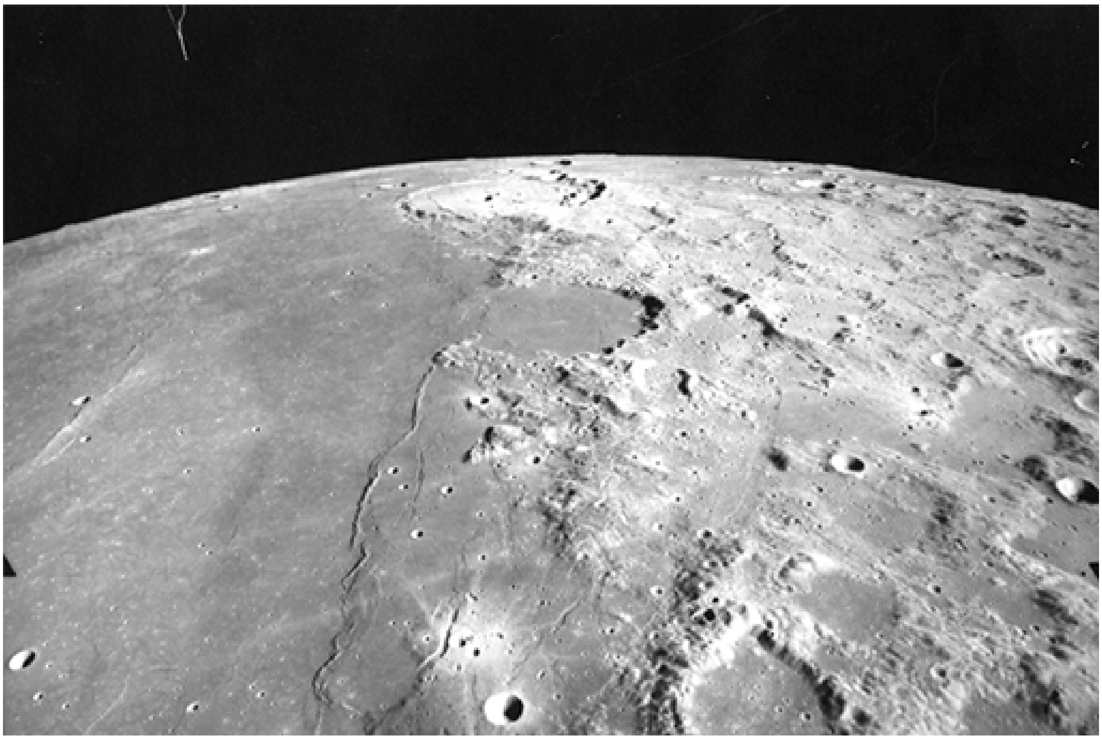


Figure 7 This image was taken from Apollo 17 in lunar orbit and shows a smooth lunar mare on the left and more rugged and cratered older lunar highlands on the right.

A geologically active surface can mean many things, but for many planetary geologists it means volcanoes. For volcanoes to form, an eruptible magma is required. This means an internal melting mechanism such as heating is necessary for the production of the magma below ground, which can then rise towards the surface. The addition of gas aids the rise of magma and helps to make eruptions explosive, explaining the difference between a jet of magma shooting skywards and a gentle flow of lava onto the surface.

Evidence of volcanic flows on the Moon can be seen as smooth plains overlying older, more cratered surfaces. However, our Moon has not been majorly active for a long time. Most lunar maria were flooded by lava about 3 billion years ago, and the most recent volcanic activity on the Moon seems to have been more than a billion years ago. Since then, the Moon has gradually frozen solid and is no longer capable of producing magma, as the radioactivity keeping the deep mantle and core hot has diminished. How then, is it possible that volcanism on other moons still occurs? Io is the most volcanically active body in the Solar System, yet it is only marginally larger than our own Moon.

1.2 Present volcanism on other moons

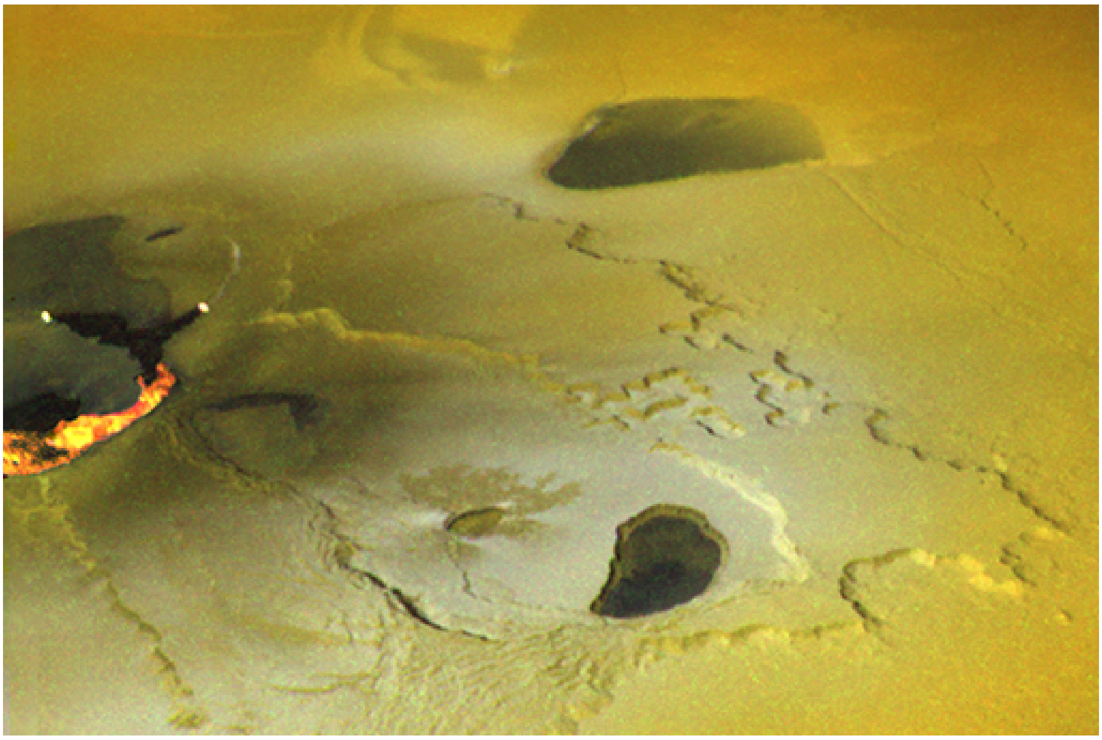


Figure 8 Io, caught in the act. 200-km-wide false-colour image taken by NASA's Galileo spacecraft shows an incandescent lava flow at the Tvashtar volcano.

We know several moons in the Solar System to be volcanically active and see evidence in the form of recognisable surface deposits and by imaging of eruptions in progress.

What is driving Io?

Allow approximately 10 minutes.

Earth's Moon froze long ago. What heat source could possibly be driving Io's continuing volcanism, such as the eruption producing the plume visible on the left of this image, which is rising more than 100 km above the surface? Think back to the 'Tidal heating explained' video near the end of the first week.

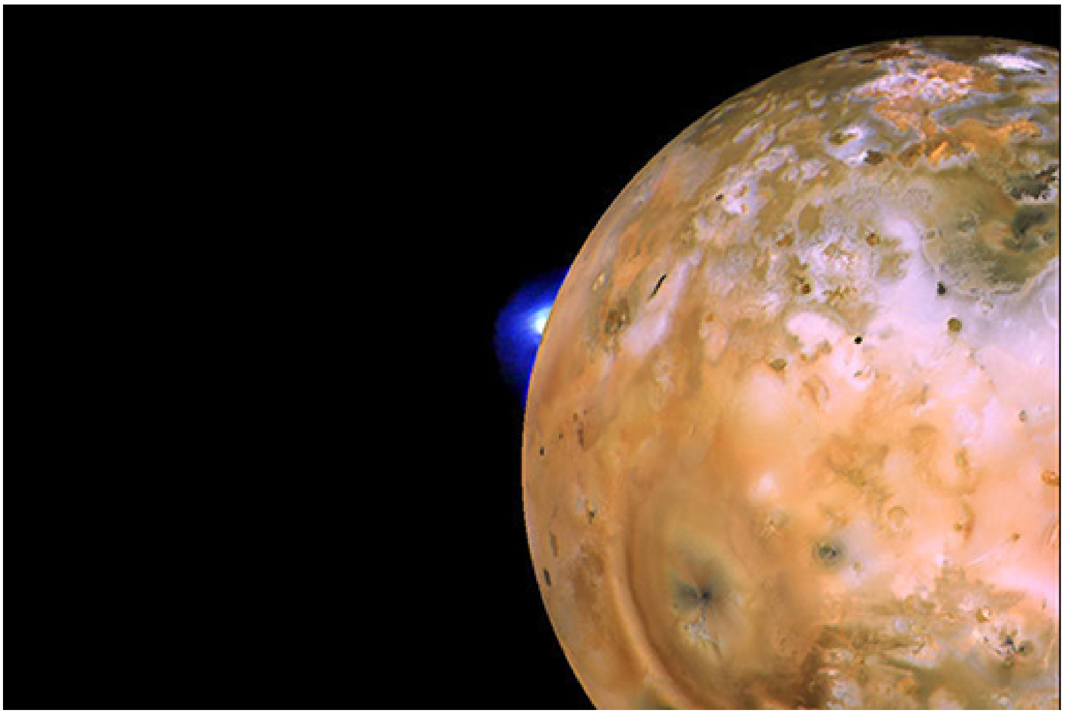


Figure 9 Voyager 1 image of Io showing an active plume from Loki volcano rising above the limb.

Answer

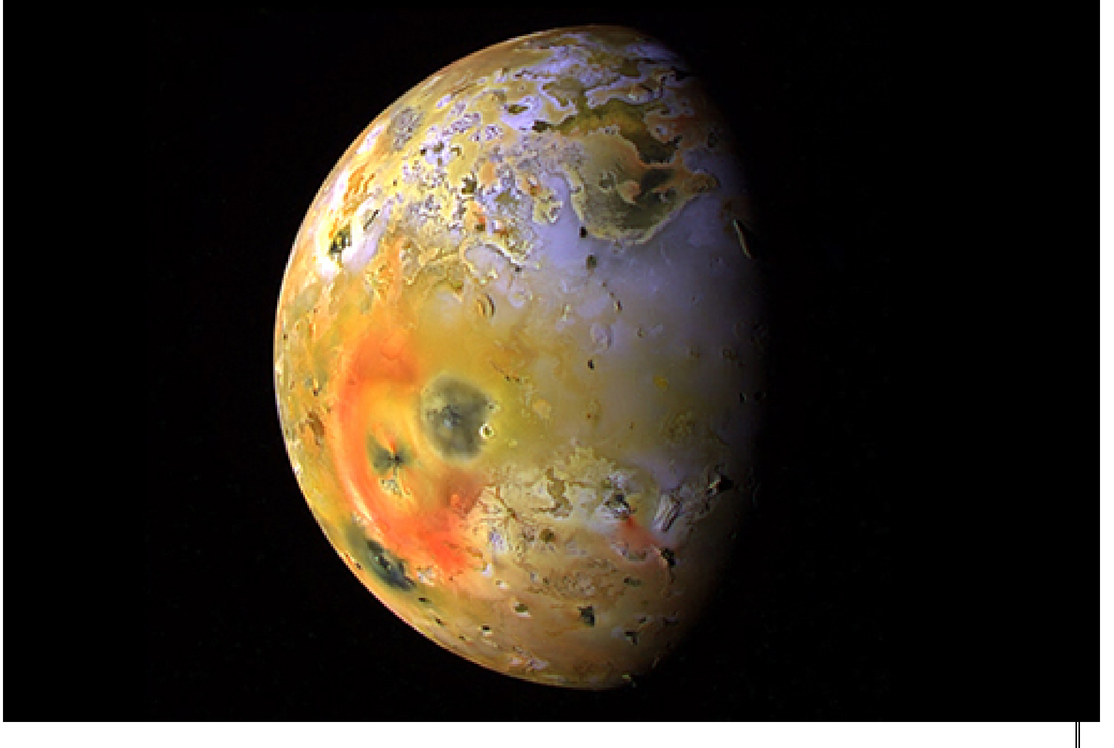


Figure 10 Io image captured by Galileo in 1997.

Thanks to orbital resonance with Europa, the varying tidal forces on Io caused by the eccentricity of its orbit around Jupiter are so strong that Io's tidal bulges rise and fall by up to 100 m during a single orbit, and also migrate to and fro a little. This distortion generates an immense amount of heat, fuelling the most volcanic body in the Solar System.

1.3 Volcanic eruptions on Io

In this video Paul Schenk of the Lunar and Planetary Institute and David Rothery of The Open University discuss the orbital resonance that leads to the tidal heating that powers Io's volcanoes and keeps several other moons warm inside too.

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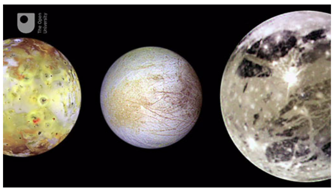

See also:

- David Rothery talks to Stan Peale. In May 2014 David Rothery recorded a bonus video with Stan Peale about his work that predicted Io's tidal heating just before it was discovered.
- Where does the energy to heat Io come from? This question was answered by David Rothery on The Naked Scientists BBC radio programme 6 March 2017 (2 minute audio).

1.4 A closer look at volcanism on Io

Io has hundreds of centres of volcanism on its surface, caused by the tidal heating from Jupiter creating a huge tidal bulge at the surface. Eruption temperatures have been measured up to 1400 °C. It's likely that the material erupted would be similar in composition to an Earth basalt. The huge Tvashtar plume that you saw in the previous video was most likely composed of pyroclastic material, sulfur and sulfur dioxide. With no atmosphere to hinder the plume, it created a huge umbrella as gravity pulled the material back to the surface. Many of the volatiles erupted escape into space, however, and are thought to land on other nearby moons such as Europa. The lack of impact craters on Io's surface demonstrates the young age of the surface as new craters are quickly flooded by lava or buried by fall-out from plumes.

In Figure 11 the 200 km circular feature near the upper right is because we are looking down through a persistent eruption plume at Prometheus volcano. The Galileo image shows more detail, but many genuine changes have occurred on the surface, notably the dark lava flow that was erupted from the volcano between these two dates.

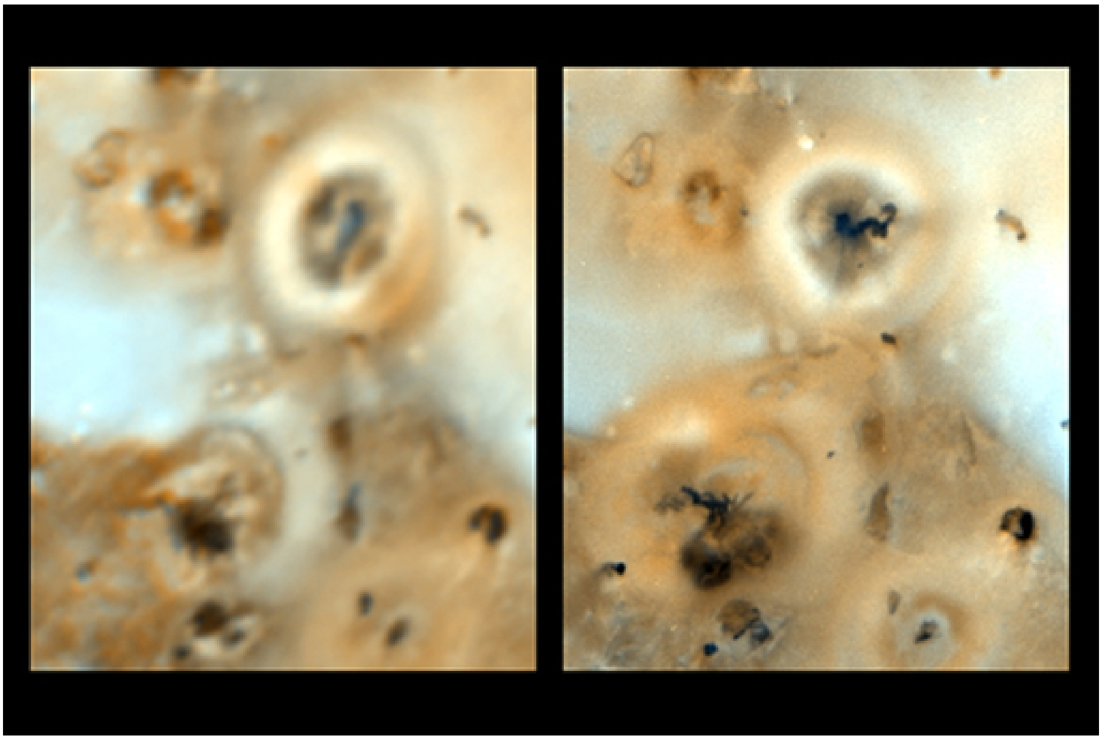

Figure 11 The same 600-km wide region of Io seen in 1979 by Voyager (left) and seen in 1997 by the Galileo spacecraft (right).

1.5 Cryovolcanism on Enceladus

Volcanism does not just occur on rocky bodies like Io; it has also been seen occurring on Saturn’s small icy moon Enceladus. In March 2006, the Cassini probe captured images of large icy jets erupting from cracks near Enceladus’ south pole. House-sized boulders of ice litter the neighbourhood of the cracks, which turns out to be a volcanic ‘hot’ spot. The volcanoes responsible for the jets seen were, however, not erupting molten rock. Cassini has flown through the plume and measured its composition as mostly salty water-ice, tainted by traces of carbon dioxide, ammonia, methane and other hydrocarbons, and microscopic particles of silica that show that the water has reacted with warm rock inside Enceladus.

The contaminants lower the melting temperature of the ice on Enceladus’ crust and allow the generation of cryomagma. This can be erupted in plumes reaching hundreds of kilometres from the surface.

In this video David Rothery of The Open University and Michele Dougherty of Imperial College London describe the amazing world of Enceladus.

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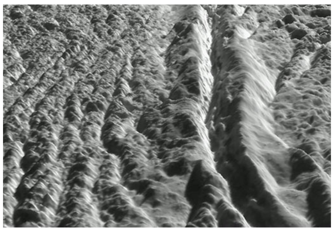

See also:

- The Plumes of Enceladus. A three-minute TED talk by Carolyn Porco, leader of the Cassini imaging team, reporting the latest (as of 2009) findings.
- Learn more about Enceladus. This NASA page is a good place to begin if you want to study Enceladus in more detail.
- Molecular hydrogen from hydrothermal activity inside Enceladus? David Rothery's October 2015 article discussing new experimental simulations relevant to Cassini's closest fly-by through Enceladus's plumes.
- David Rothery 2015 Enceladus radio interview. Interview about Cassini's closest flyby of Enceladus broadcast 31 October.

1.6 How Enceladus works

This video explains how the eruption plumes of Enceladus might be generated as 'cold geysers'. Remember that you saw a video that attempted to explain the general processes involved in tidal heating ('Tidal heating explained') near the end of Week 1.

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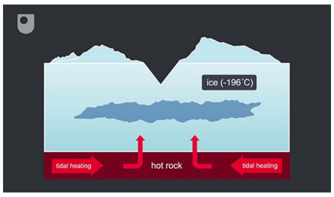

See also:

- Enceladus ocean 'must be global'. BBC news report on the global nature of Enceladus's internal ocean
- Cassini Finds Global Ocean in Saturn's Moon Enceladus. NASA press release that reports that Enceladus's internal ocean must be global.
- The previous concept: Enceladus's 'great lake'. Our understanding as it was 18 months before the global ocean was demonstrated.
- Enceladus tidal heating news. A story that broke in November 2017, with a mechanism to produce tidal heat in Enceladus's rocky core over tens of millions to billions of years.

1.7 Some other cryovolcanic moons

Cryovolcanism is not restricted to Enceladus. Other icy moons also show evidence of cryovolcanism.

The surface of Ariel (Figure 12) is thought to be the youngest of all of Uranus' moons, having had the most recent geological activity. While it is unknown if it is currently active, it has been completely resurfaced since the beginning of the Solar System. The deep canyons seen in the image have been filled in and are possibly linear vents. Some similar features occur on Pluto's largest moon, Charon.

Figure 12 Ariel

Figure 13 is Inverness Corona. This large corona is interpreted as an enormous cryovolcanic complex. It is one of three cryovolcanic complexes identified on Miranda.

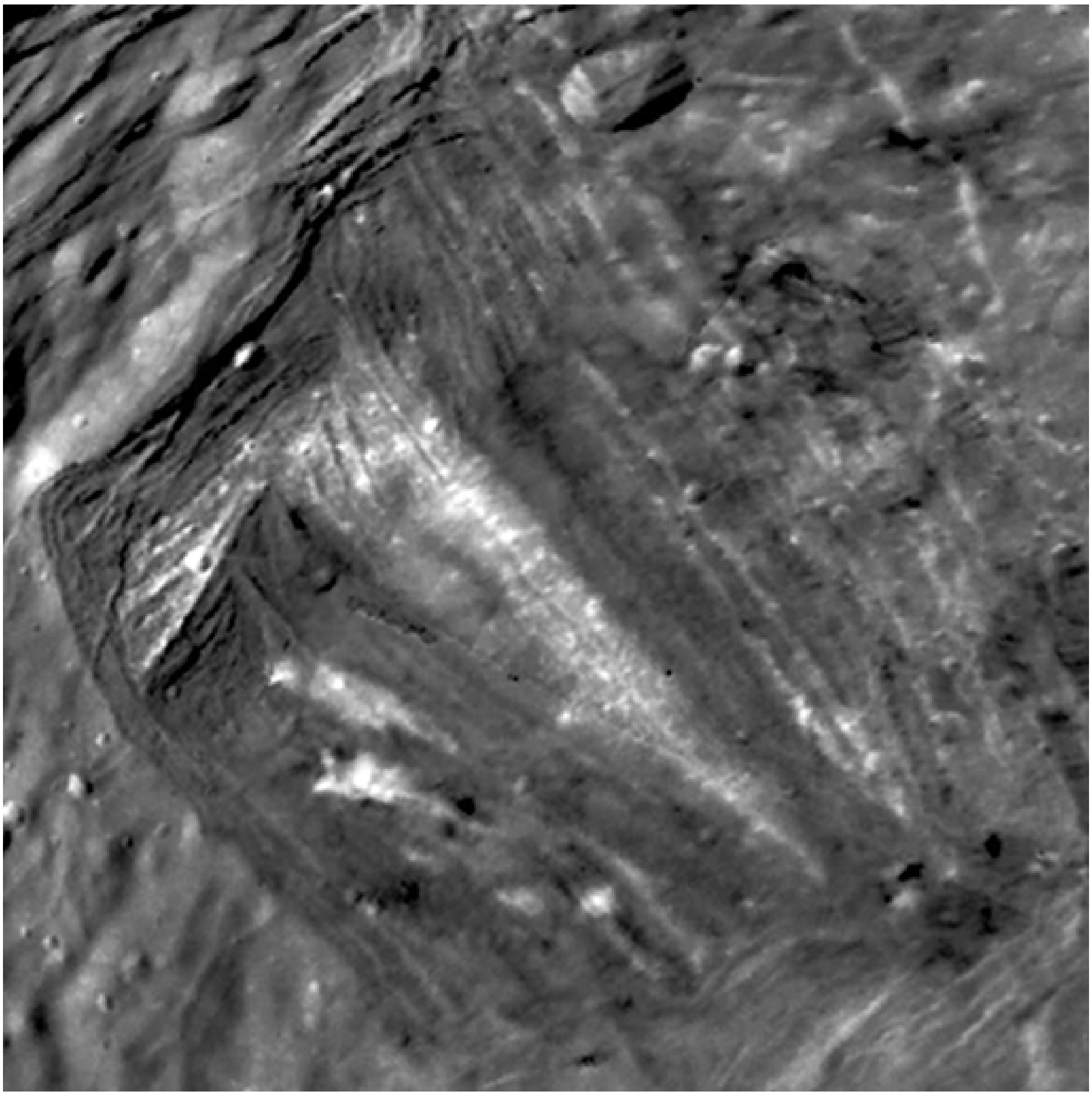

Figure 13 Miranda

The smooth surface (shown in Figure 14) is thought to be of cryovolcanic origin with mounds and pits formed by ice flows. It has a thin, nitrogen atmosphere that is thought to have been created by the volcanic activity.

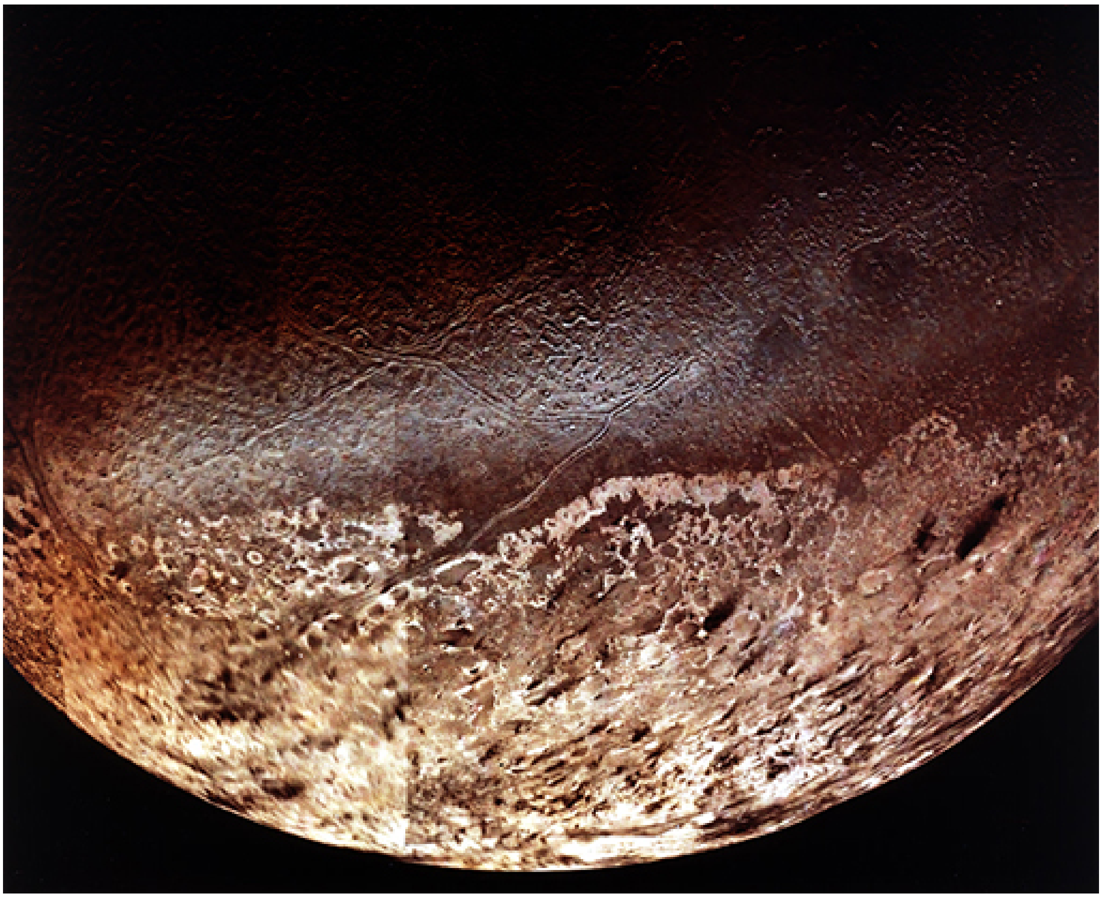

Figure 14 Triton

Next, try a short activity on some of what you've learned so far this week.

Activity 1 Moons volcanism

Allow approximately 15 minutes.

The heat source for cryovolcanism is likely to be:

○ Radioactive decay from the body's centre

No, these bodies are too small to generate enough radioactive heat.

○ Tidal heating

Correct!

○ Relic heat from the body's formation

No. The largest moons may have been hot when they formed, but any such heat has long since leaked away.

Inverness Corona is a massive volcanic complex on which moon?

○ Miranda

Correct. Inverness Corona is the chevron-patterned area apparent in most images of Miranda.

○ Ariel

No. Ariel is noted for flat-bottomed, faulted valleys, but it has no coronae.

○ Triton

No. Triton has an interesting cryovolcanic surface and a polar cap, but no coronae.

The volcanic activity on the Moon was mostly when?

○ 3 million years ago

No. There are no signs of such recent volcanic activity on the Moon.

○ 3 billion years ago

Well done.

○ 3 trillion years ago

No. This would actually be older than the Universe itself. The Moon's age is about 4.6 billion years.

Which of the following, when added to water-ice, lowers the melting temperature enough to allow the water-ice to melt in cryovolcanoes?

○ Sodium

No

○ Oxygen

No

○ Ammonia

Correct. Ammonia is one of several substances believed to occur within icy moons that could lower the melting temperature of the ice.

2 Discovery of Europa

Explore Europa, Jupiter's icy moon that probably has an ocean below the surface. Could there be life there?

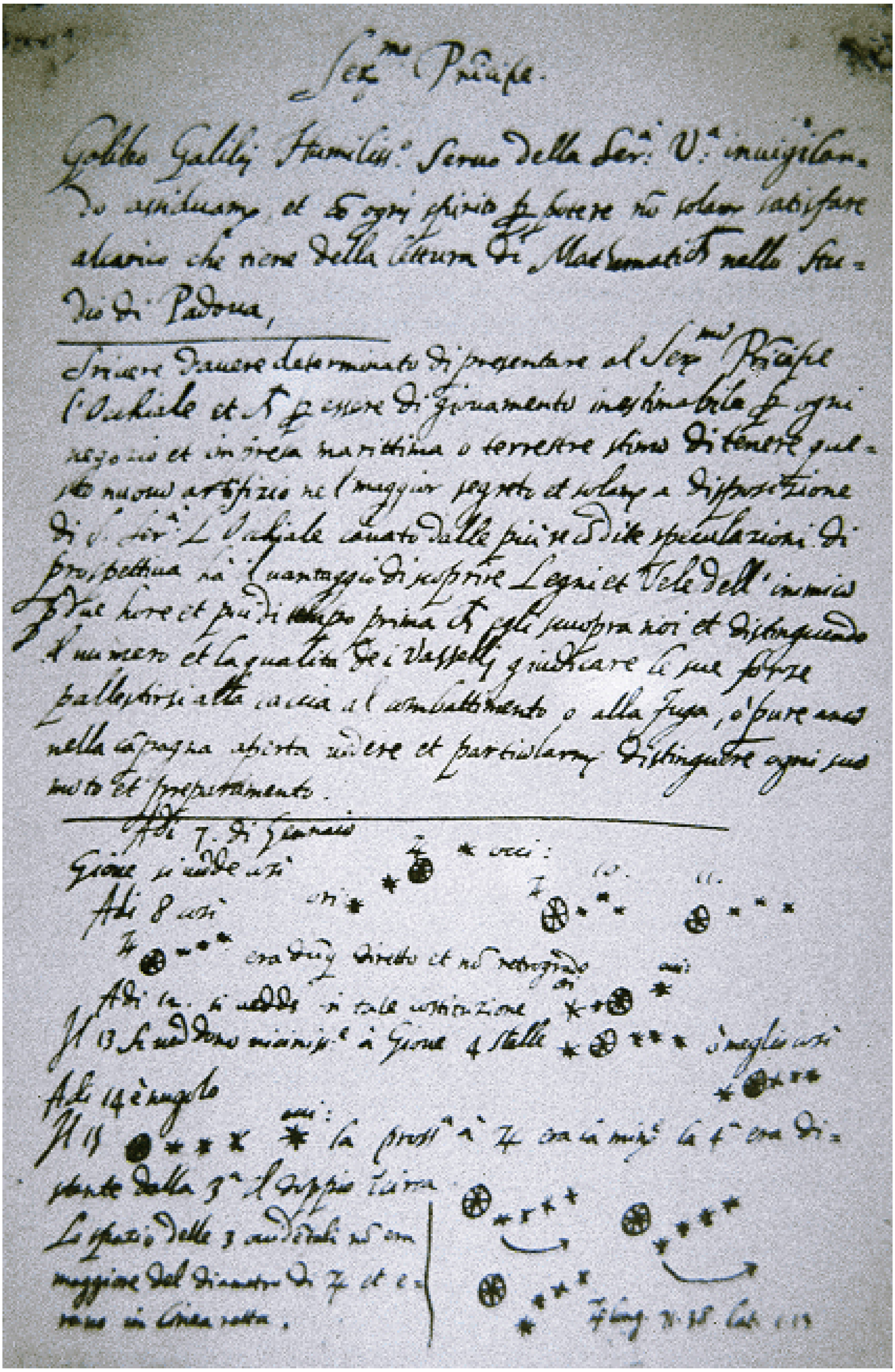

Figure 15 A page from Galileo's journal, showing sketches of Jupiter and four of its moons.

Europa was discovered by the astronomer Galileo Galilei in 1610, at the same time as he discovered Ganymede, Callisto and Io. Equipped with just a very basic telescope, Galileo noticed points of light around Jupiter that looked like stars, but that changed their positions relative to the planet on successive nights. Galileo recorded their changing positions and concluded that the objects must be moons orbiting the planet. This challenged the accepted idea at the time that the Earth was the centre of everything and that all the observable objects in the sky were orbiting the Earth.

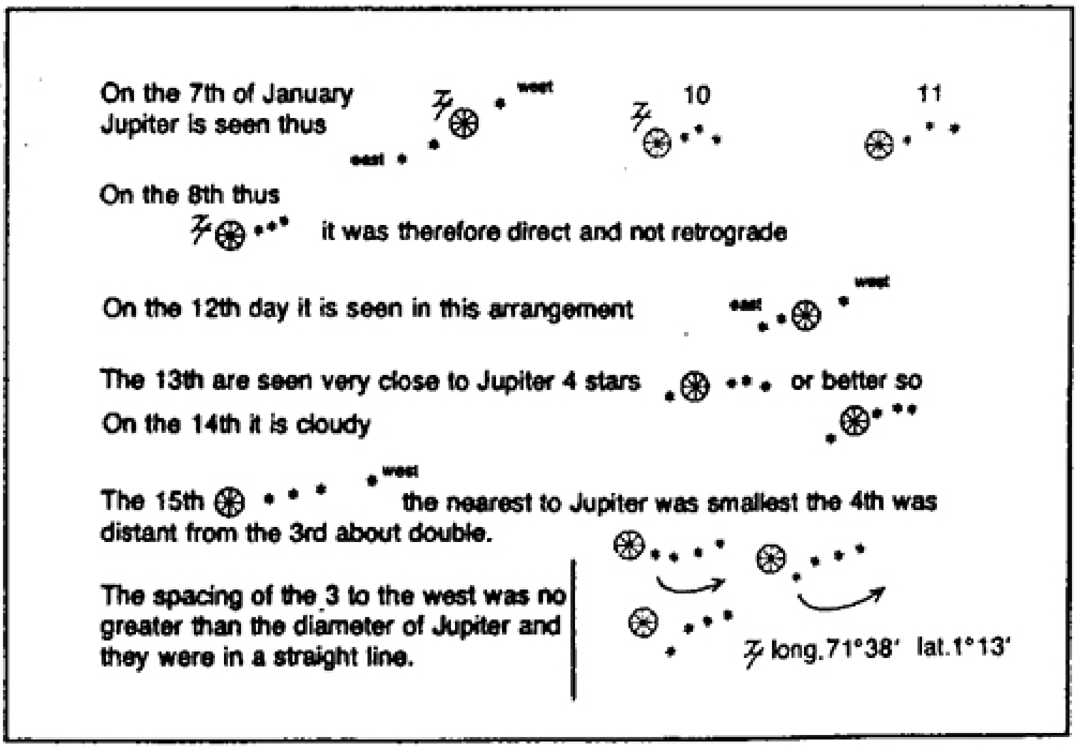

Figure 16 A translation of the bottom part of the page from Figure 15 shown above.

2.1 Nobody expects the Italian inquisition

Galileo got into deep trouble with the Vatican for publicising the proof, based on his observations of the movement of Jupiter's moons, that not all heavenly motion is centred on the Earth. The video presents a reconstruction of some of the arguments at the time.

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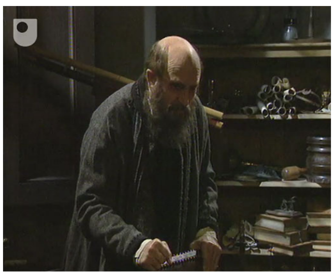


2.2 See for yourself!

Figure 17 Compare what Galileo sketched with what can be seen with binoculars or a small telescope. You might like to try to see this for yourself.

Jupiter can be seen with the naked eye as a bright yellowish dot. It will be prominent in the pre-dawn sky from October 2015 onwards, and for northern hemisphere observers it will be visible in the southeast by midnight in December. To see its moons yourself, you'll need some powerful binoculars or a small telescope.

You can find out when Jupiter will be visible in the sky by going to websites such as In The Sky or Naked Eye Planets. The other thing you'll need is a clear sky!

Next you will explore the surface features of Europa and discover how this icy moon is influenced by the awesome tidal effect of Jupiter.

2.3 Europa's surface

Before spacecraft were sent to Europa, spectroscopic measurements revealed that its surface is mainly water-ice. As it is so small and so far away from the Sun, it was expected that Europa would be like a frozen snowball orbiting Jupiter and so would be a completely inactive world densely peppered by impact craters. This idea was changed when unmanned spacecraft were sent to the Jupiter system.

Take a look at this gallery. It contains images taken by the Voyager and Galileo spacecraft and reveals how these observations transformed our view of the moons of the outer Solar System.

Earth's Moon is rocky (Figure 18), with a low albedo (it reflects only 14% of the sunlight falling on it).

Figure 18 The Moon.

The planet Mercury (Figure 19) is not much larger than our Moon and has a similar highly cratered surface, though most of it was originally volcanic. Craters are most easily seen near the terminator (the day–night boundary, on the left), where they are emphasised by shadows.

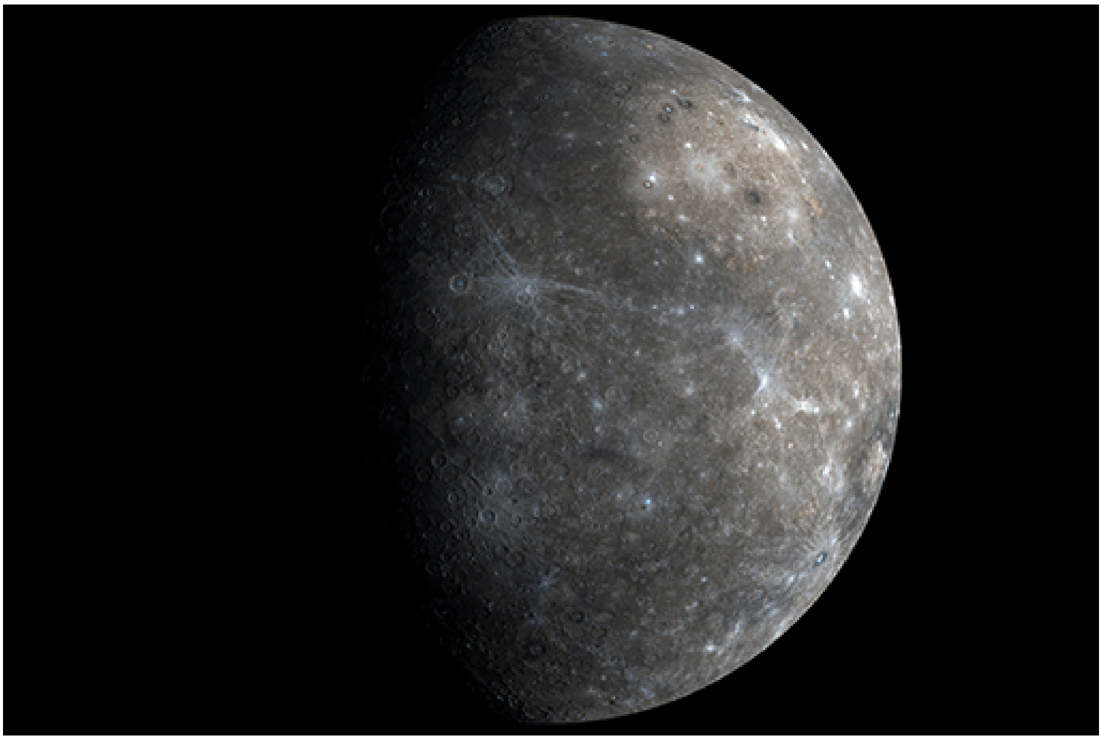


Figure 19 Mercury.

Europa's surface (Figure 20) has a much higher albedo than either the Moon's surface or Mercury's, but this is not apparent from individual images because each has been separately processed. (You may recall that the albedo of an object is the percentage of the incident light that it reflects.) However, you will make out few, if any, craters on this image.

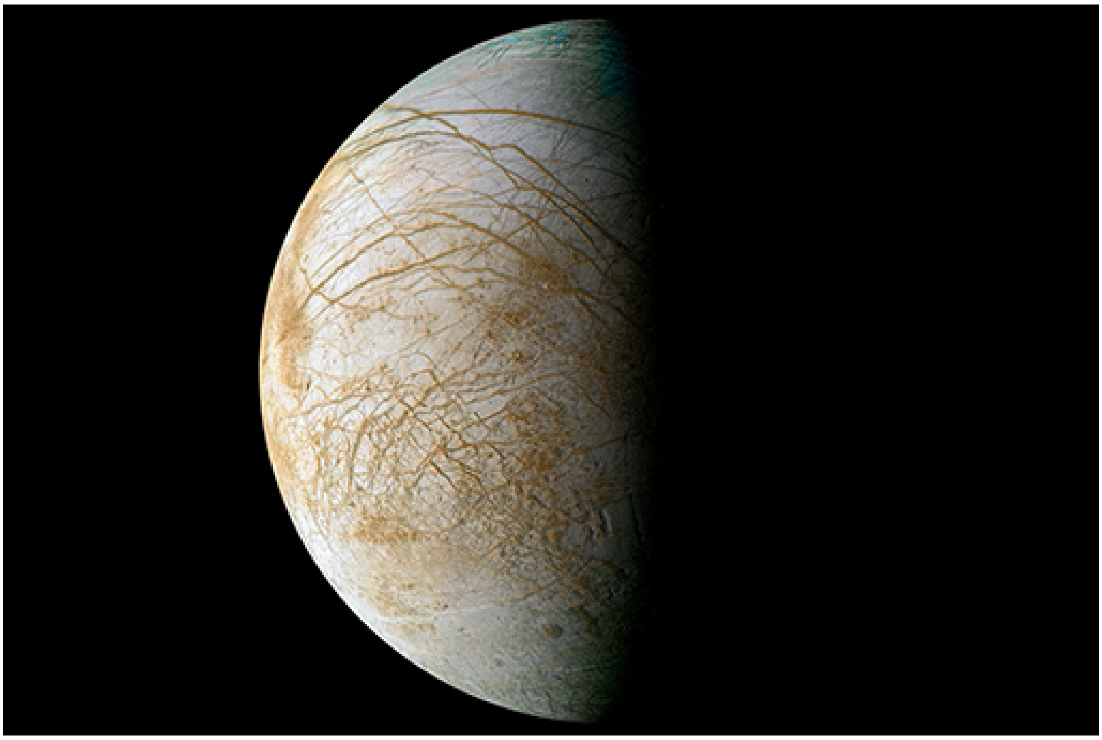


Figure 20 Europa.

The Voyager 1 and 2 spacecraft flew past Jupiter in 1979 and sent back our first pictures of Europa's smooth, bright surface, with barely any craters but mysterious dark fractures across its surface.

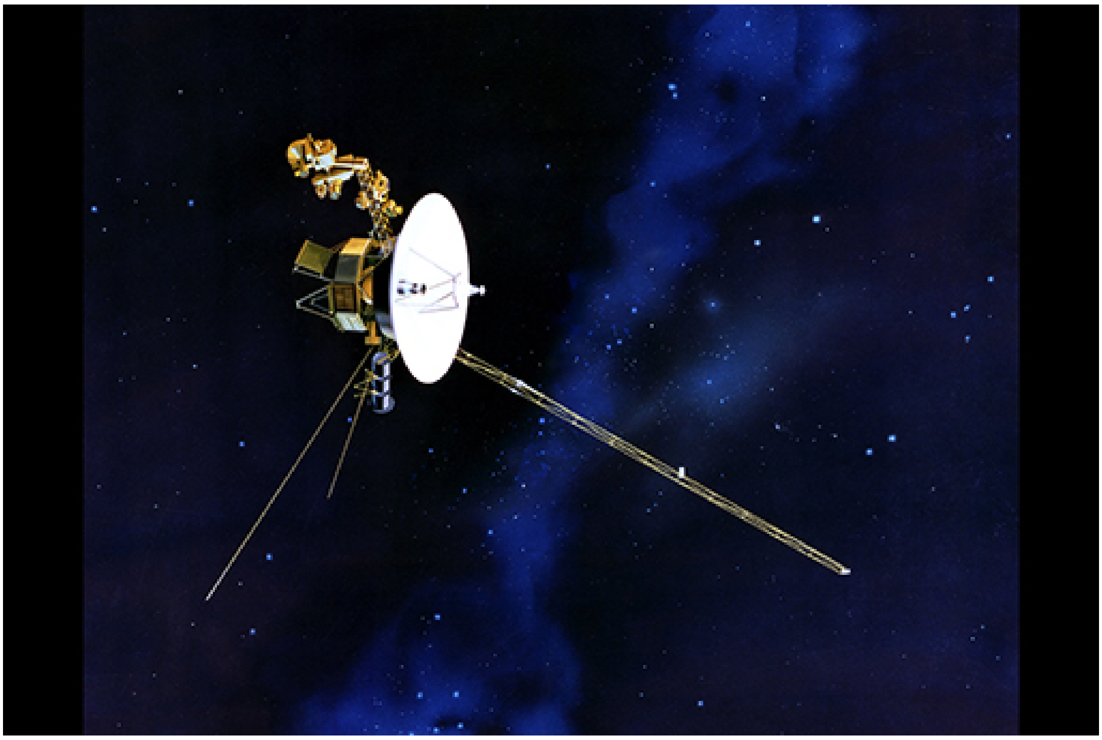


Figure 21 One of the Voyager spacecraft.

Figure 22 is of Europa taken by Voyager 2 at its closest approach. The lack of impact craters was surprising. This, along with the smooth, low topography suggests a much younger surface than Jupiter's other large icy satellites Ganymede and Callisto, where the scars of large, ancient impact craters dominate the landscape. From images like this, it was concluded that Europa's surface had been recently renewed, possibly by processes that are still taking place.

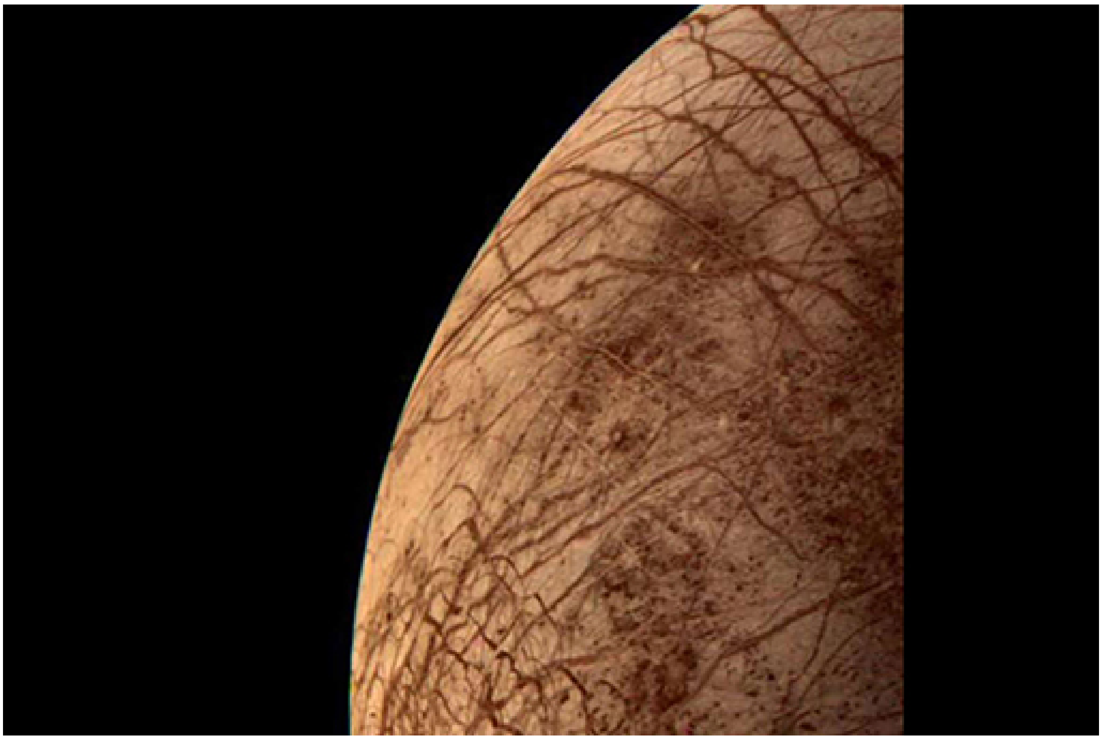


Figure 22 Voyager 2 image of Europa.

This artist's impression (Figure 23) shows that Galileo's orange parabolic high-gain antenna had failed to open correctly, rendering it useless for radio communication. All Galileo's data had to be sent back Earth using a less powerful low-gain antenna.

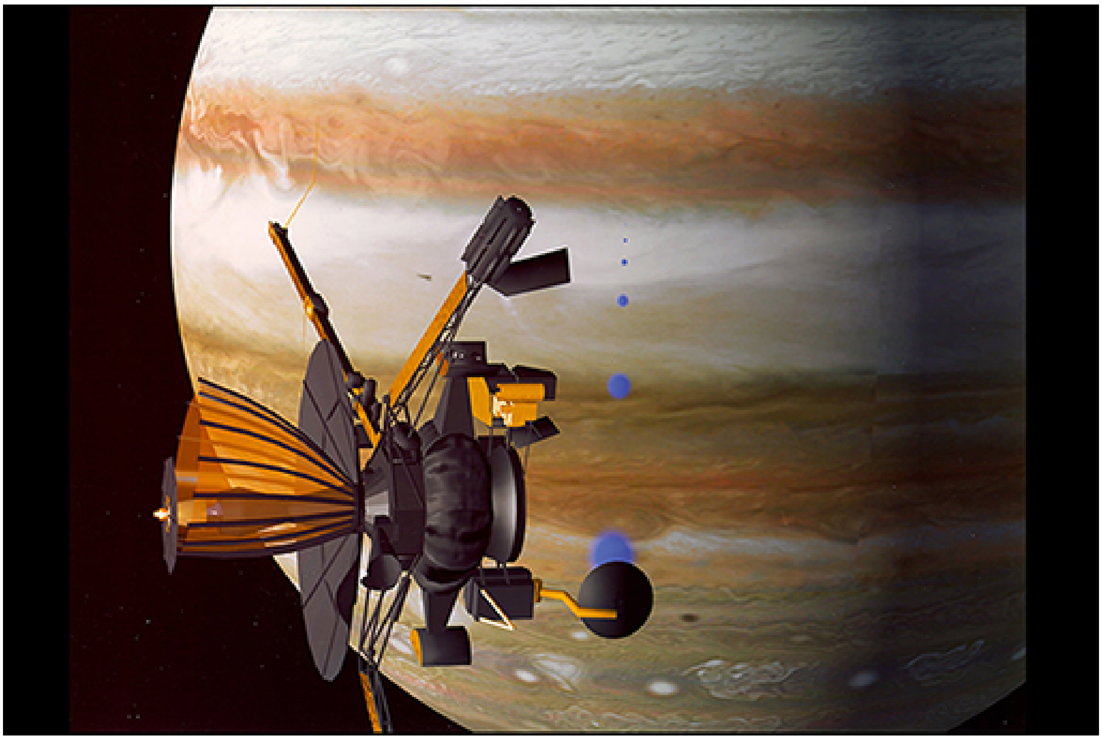


Figure 23 The Galileo spacecraft.

Europa is covered in ridges of various sizes that rise above the surface. It is thought that these ridges represent areas where liquid water has risen to the surface through cracks as they open, and has then been squeezed out as freezing slush as the cracks have closed. Most cracks are probably sealed shut, but a few could open and close tidally, perhaps twice during Europa's 3.6-day orbit. The ridge pattern is sometimes described as 'ball-of-string' terrain (Figure 24), because it makes Europa look like a giant ball of string. The area shown is 14 km by 17 km.

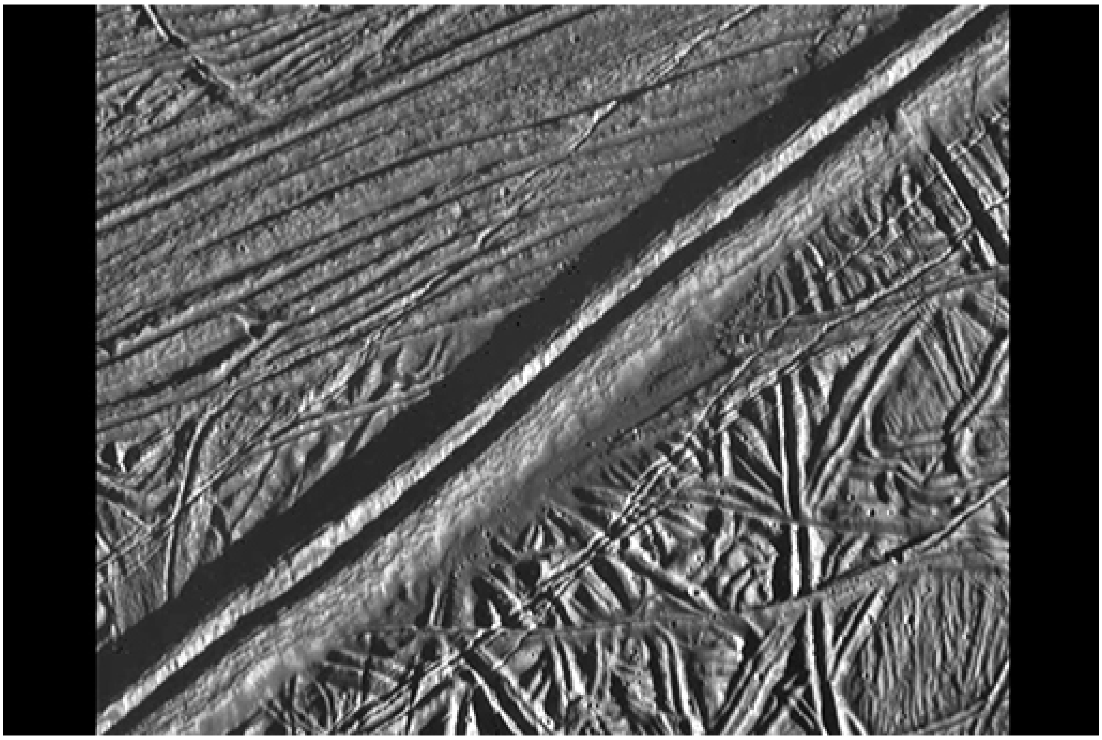


Figure 24 Ball-of-string terrain.

On Europa ridges can be seen crossing over one another, suggesting that the crust has undergone many episodes and directions of faulting and movement in response to internal heating. The ridged ('ball-of-string') surface appears to have been partly broken apart on the right in Figure 25. The three black sideways bands are gaps in the data, rather than features on the surface. The image covers an area of 108 km by 90 km.

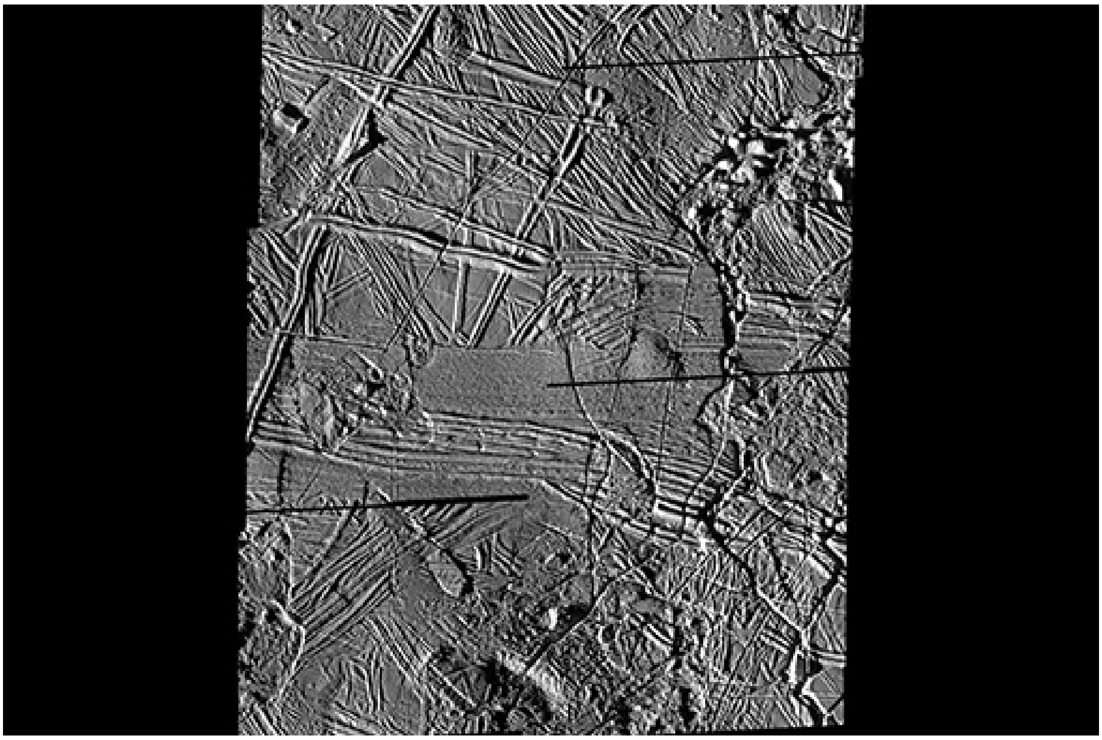


Figure 25 Ball-of-string terrain beginning to break apart.

Figure 26 shows a so-called chaos region on Europa. There are ice rafts containing ridged surfaces, which appear to have drifted apart before becoming refrozen in place. This resembles ‘pack ice’ in the Earth’s polar oceans. The area between the ice rafts that is lacking in ridges is referred to as ‘matrix’. The image is about 45 km across.

Figure 26 A chaos region on Europa.

Figure 27 is another image of a ball-of-string surface, disrupted into small patches of chaos terrain and with a few domes possibly overlying upwellings from below. The area shown is 140 km by 130 km.

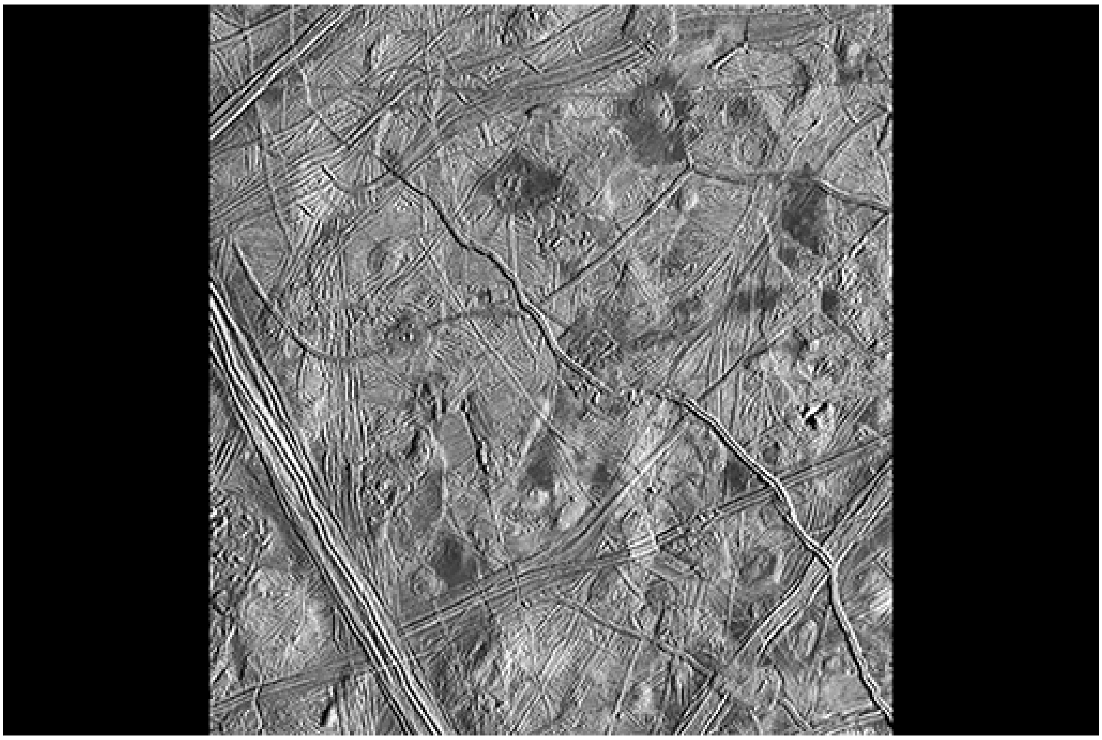


Figure 27 Disrupted ball-of-string terrain on Europa.

Figure 28 is a 200 km by 250 km area of Europa, where the icy surface has been cracked and broken apart many times. Most of the ice shows as blue. The red colouring beside some of the largest ridges and in some small regions of chaos is thought to be caused by salt or clay impurities. White patches are dustings of ejecta distributed from an impact crater 1000 km further south.

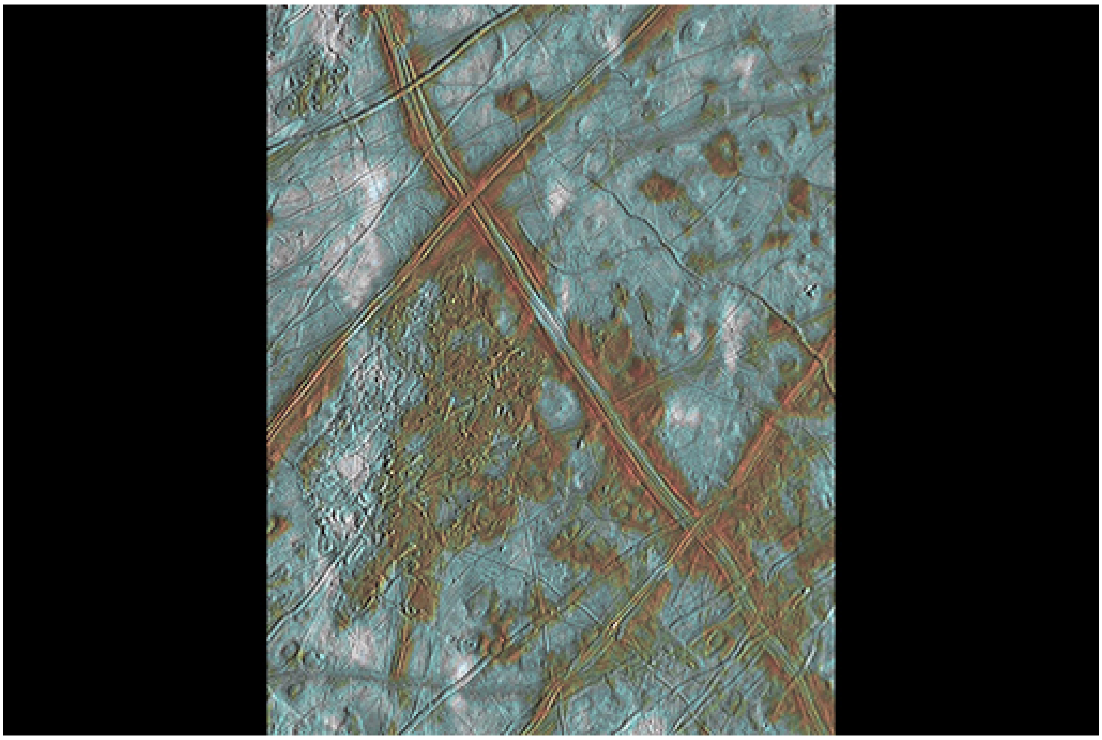


Figure 28 Exaggerated colour image of Europa.

2.4 What the images mean

Before spacecraft visited Europa, scientists were expecting its surface to be dark and highly cratered. This is characteristic of moons and planets that have been inactive for millions of years. Smaller bodies lose their internal heat sooner than larger bodies, resulting in cessation of tectonic activity and an ageing crust. Take another look at the planet Mercury and the Moon in the previous step. As Europa is smaller than our Moon, it should also be inactive and scarred by many craters.

The idea of the outer moons being dead, frozen worlds was dashed in 1979, when the Voyager mission captured images of Europa. As you've just seen, a smooth, bright surface, few impact craters and mysterious dark fractures were revealed. The surface was young, meaning that new surface was being created. On Earth, this occurs when magma from the mantle rises and cools at the surface along mid-ocean ridges. But on a tiny moon like Europa, a different process must be happening, as there is unlikely to be sufficient internal heat from radioactivity. So scientists turned to another explanation: tidal heating. But how would the tides be manifested on Europa's surface?

Figure 29 The Galileo spacecraft after it was released from the cargo bay of Space Shuttle Atlantis in 1989.

In 2003 the Galileo spacecraft captured more detailed images of the dark fractures imaged by Voyager 1 and 2. Rather than being flat features, they were revealed as belts of near-parallel ridges and grooves. This texture became known as the ball-of-string texture, representing extension of the crust, with gaps being filled in by rising water and freezing to form new crust. Possibly a crack somewhere on Europa opens and closes with every tide, which means twice per orbit. Higher resolution images show that some ridges cross-cut others, revealing many generations of crust extension. Some ridges are offset, suggesting lateral movement. In some areas, the ball-of-string texture is broken up into blocks called rafts and surrounded by matrix. The matrix represents now refrozen ocean that was uncovered when the rafts moved apart. There are also dome features, caused by upwelling of water underneath the crust. These features provide good evidence that there is an ocean beneath the surface, convecting upwards and freezing when exposed at the surface.

See also:

- Best ever view of Daphnis? Here is the best yet view of Daphnis, an 8 km long moon that orbits within one of the gaps in Saturn's rings. This was captured by Cassini on 16 Jan 2017. Note how it's gravity has produced a wave-like disturbance in the ring material.
- Close up of Epimetheus. Epimetheus imaged by Cassini on 30 Jan 2017.
- Another close up of Epimetheus. Another 30 Jan 2017 close up by Cassini. Do the fine, largely parallel, grooves on the surface remind you of any other moons?
- Best ever views of Pan. Superb extra detail on Pan, revealed on images recorded by Cassini 7 March 2017.

2.5 Is Europa habitable?

In this video several scientists explain why this moon is now the subject of so much interest. The video illustrates the surface features on Europa and discusses how they have led scientists to see Europa as a potentially habitable world. In this context, 'habitable' refers to suitability for simple, microbial, life to survive there. It does not imply that humans could live there without protection.

Bear in mind the following issues as you watch.

- What is the evidence for a young surface?
- Could you sketch the ball-of-string, raft and matrix textures?
- What features might Europa have that makes it potentially suitable for life? Give examples of where such features are found on Earth.
- What adaptations might life need to make in order to survive on Europa?

Video content is not available in this format.

See also: JUICE. The joint NASA-European Space Agency mission to Europa described as 'on hold' in this video has been replaced by an ESA mission in 2022 to study Ganymede, Callisto and Europa called JUICE (Jupiter Icy moons Explorer).

2.6 Is Lake Vostok like Europa?

The discovery of tidal heating and a potential global ocean on Europa is of great interest to astrobiologists, as the one requirement for all life (as we know it) is liquid water. Life is incredibly diverse on Earth and astrobiologists study the types of microbe (bacteria and similar organisms) that can survive in extreme environments, to better understand life's limits. So what does an astrobiologist do, and what makes Europa a potentially habitable moon?

Europa has three times the amount of water found on Earth. We can deduce from Europa's overall density that there is about a 100-km deep layer of H_2O overlying its rocky interior, but this doesn't distinguish between liquid (water) and solid (ice) because their densities are too similar. We can see that the outer part is frozen. Interpretation of the surface features has led most scientists to conclude that there is probably a liquid water zone beneath the frozen exterior, possibly in the form of a global ocean between the ice and the rocky interior. Episodes of tidal heating could heat the rock (or even cause submarine volcanic eruptions), warming the ocean to the extent that regions of the overlying ice melted, producing the rafts-and-matrix chaos areas that you have seen. In addition, tidal stressing of the ice shell could cause a few cracks to open and close during the tidal cycle, twice for every orbit around Jupiter.

All life as we know it needs liquid water to survive. As well as water, microbes need an active environment, where minerals and elements are cycled and concentrated.

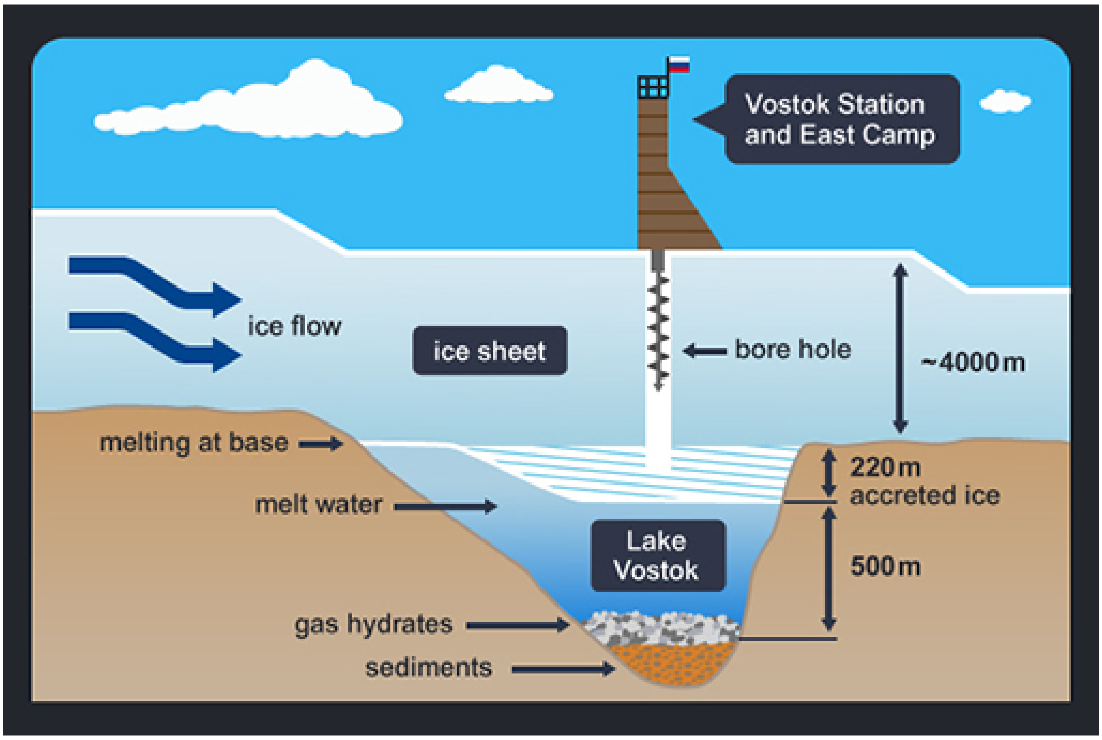


Figure 30 A schematic cross-section of Lake Vostok, which is in Antarctica.

Compare Europa with Lake Vostok in Antarctica, a lake that is buried beneath 3.2 km of ice and has been so for between 14 million and 34 million years. Scientists drilled through this ice and reached Lake Vostok in 2013. They claim to have found previously unidentified species of bacteria. Although some are questioning this claim as potential contamination, if life is found to exist in Lake Vostok then studying these organisms will improve our understanding of how microbes can survive in such isolated, cold, dark conditions.

2.7 Where might life be found on Europa?

If microbes do live on Europa, where might they occur?

The cracks on the surface are produced by tidal distortion. Such cracks may be the most likely place for life to occur on Europa, as they are at the surface, and so receive sunlight (unlike the water beneath the ice). They are also subject to currents as water is drawn upwards into opening cracks and then squeezed out of closing cracks. These currents can distribute nutrients and concentrate them at the surface in the cracks.

Life would need to avoid the top few centimetres because of intense radiation, but below that depth there would still be enough sunlight for photosynthesis.

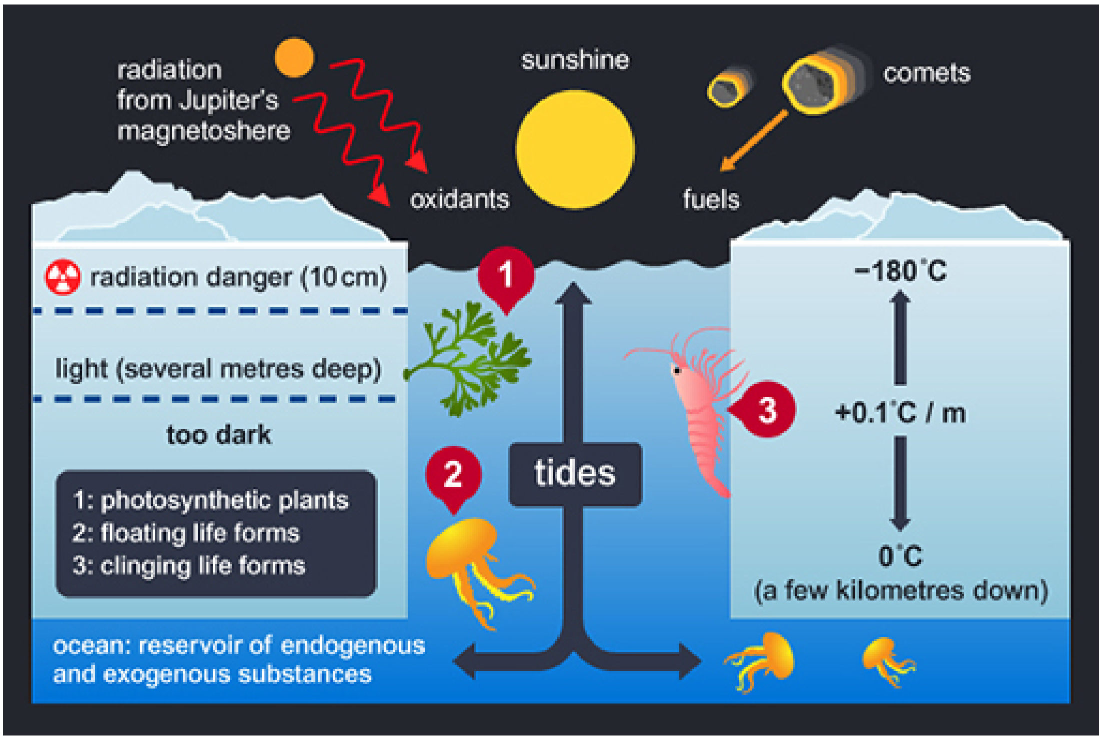


Figure 31 Cartoon of where life dependent on photosynthesis could inhabit Europa's cracks as they open and close.

The figure is a representation of a proposal by the American Richard Greenberg. Photosynthetic organisms occur near the surface in temporary cracks where they can receive sunlight. More complex organisms can float upwards when the tidal forces open the cracks. The squeezing and opening of these cracks in response to tidal forces moves organisms and nutrients up and down. This illustration shows large organisms, but there would surely be microscopic single-celled microbes too. Traces of life from this setting would be relatively easy to find, because some unlucky individuals would be squeezed out onto the surface along with the ridge-forming slush each time a crack closed.

2.8 Hydrothermal vents too?

On Earth, there are hydrothermal vents on the ocean floor, mostly around mid-ocean ridges. These are areas where hot magma is close to the surface. Water in the crust becomes heated and dissolves minerals from the crust. This hot water rises out of the crust and can precipitate the dissolved minerals to form chimneys. Examples like this one are called ‘black smokers’ on account of the black mineral particles that precipitate when the hot chemical-rich water meets the cold ocean-floor water.

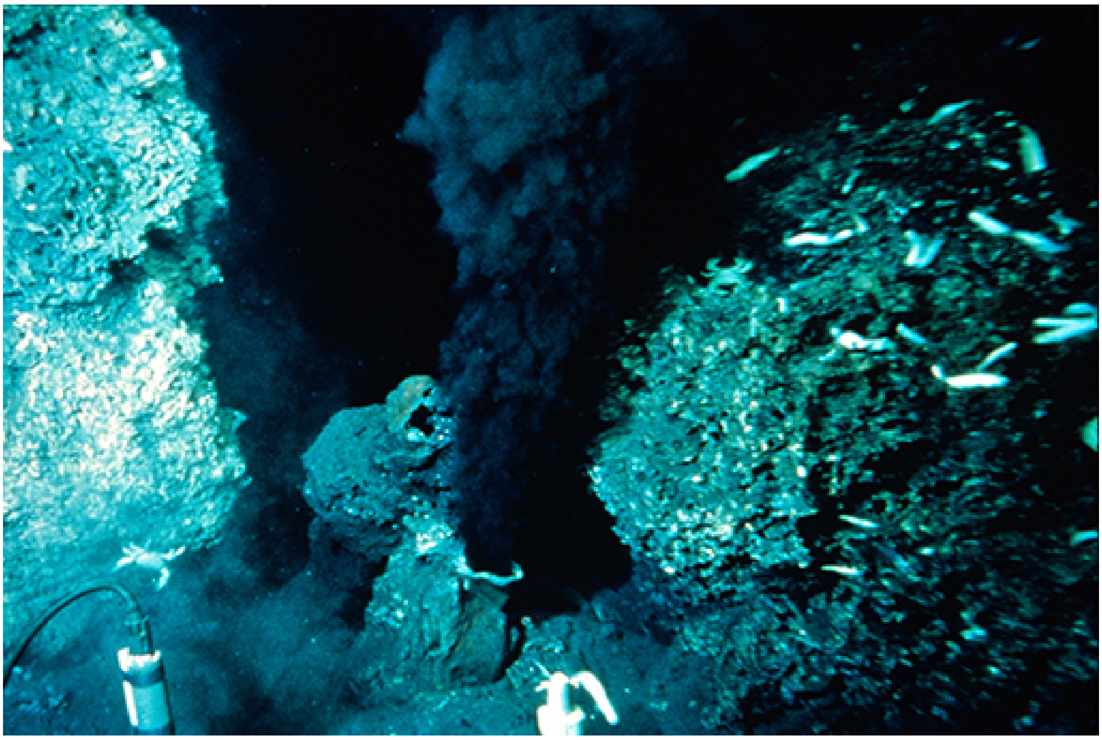


Figure 32 A hydrothermal vent.

Microbes have been found around these vents and they use hydrogen sulfide and other chemicals as their energy source. This is an example of ‘chemosynthesis’, using chemical energy to power life; sunlight is not used at all. These ecosystems also support more complex organisms such as tube worms and shrimps.

If hydrothermal vents exist on Europa’s ocean floor, life could exist there no matter how deep and dark. There is some evidence that life on Earth may have actually begun at hydrothermal vents, so could life have originated independently on Europa in the same way?

See also: More information on hydrothermal vents. An overview of where life could occur and a discussion of how we might explore Europa can be found in the article 'Searching for life where the Sun don’t shine (part 6): explorations to the seafloors of Earth and Europa' in Astrobiology Magazine.

2.9 Eruption plumes on Europa?

No visiting spacecraft has seen eruption plumes at Europa like those on Enceladus. However an exciting discovery was announced in December 2013. The Hubble Space Telescope, in orbit about the Earth, had found a faint ultraviolet glow caused by atoms of hydrogen and oxygen rising up to 200 km above Europa’s south pole in December 2012. This probably shows water molecules broken apart in the harsh space environment.

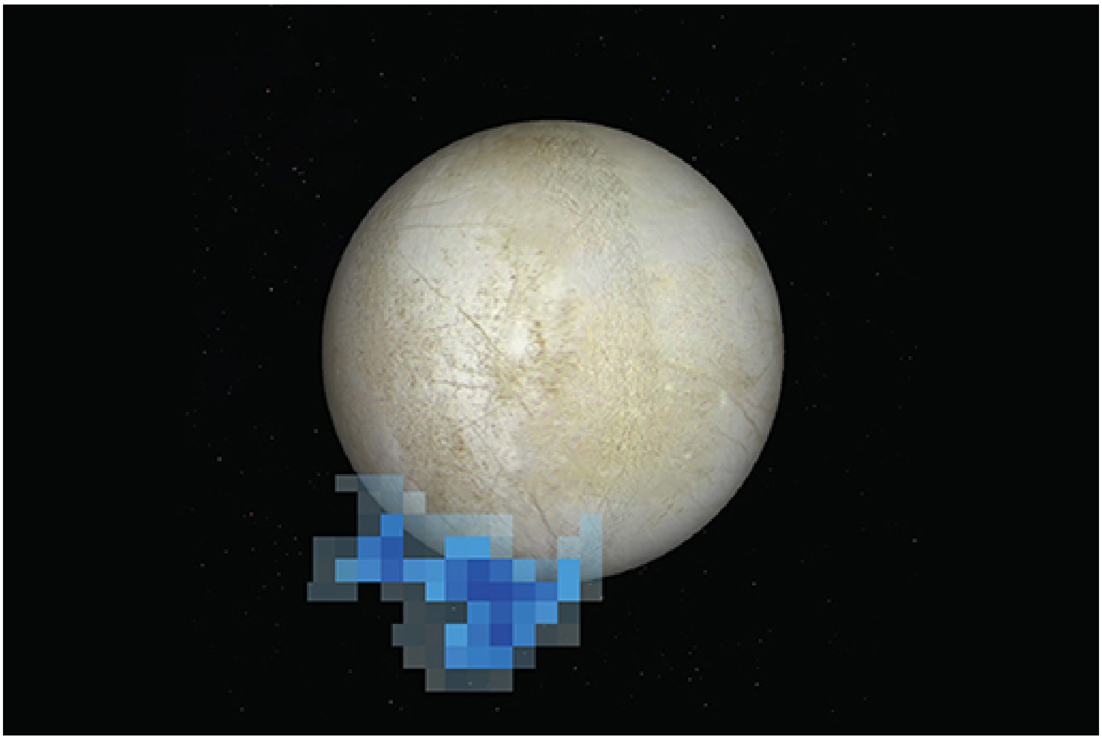


Figure 33 A plume of erupted water above Europa as imaged by the Hubble Space Telescope in Earth orbit (superimposed on a more detailed close-up image of Europa itself).

Europa's plumes are not persistent. Repeat attempts at detection using the same method throughout 2014 were blank. However in 2016 it was announced that by using the Hubble Space Telescope's ultraviolet camera to watch Europa as it crosses the face of Jupiter, absorption of the sunlight reflected from Jupiter could be detected as it passed parts of Europa's limb (the edge of its disc). This is most simply explained as plumes blocking out a tiny fraction of the light. The technique found plumes on three occasions out of ten during 2014.

If eruption plumes do indeed occur at Europa, they seem to be less persistent than those currently occurring at Enceladus. Perhaps water escapes in plumes only when certain special cracks in Europa's ice shell are open.

See also: Europa plumes seen by a new technique (2016 report). An account of plumes detected as Europa transits Jupiter's disc.

Activity 2 Identify features on Europa for yourself

Allow approximately 20 minutes.

Now explore these surface features of Europa.

Figure 34 Age relationships.

This is a 20-km wide image of part of Europa where the surface is made of ‘ball-of-string’ terrain. Which region do you think is older: the bright region or the dark ‘ball-of-string’ region?

Answer

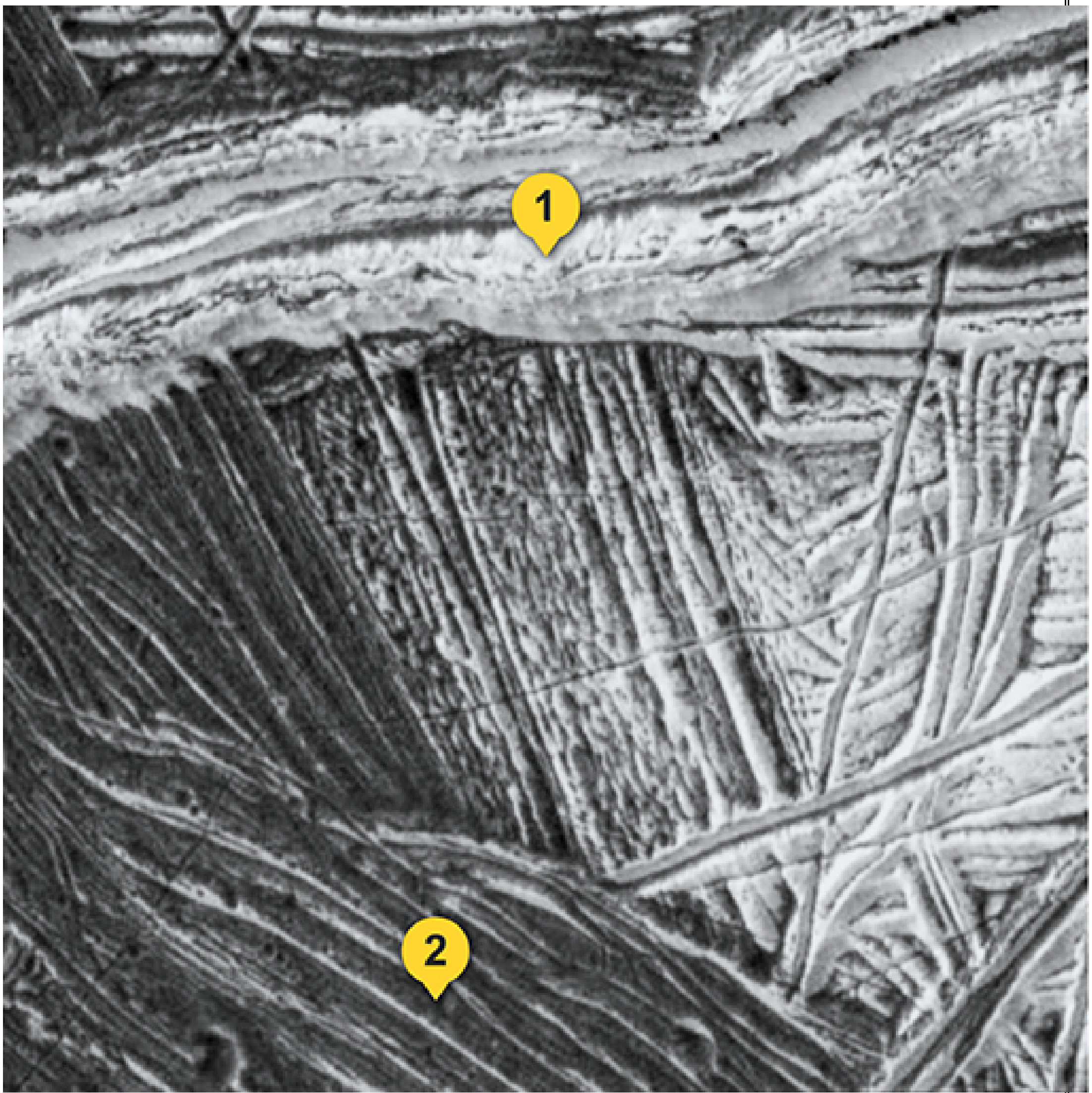


Figure 35

The brighter band (1) is younger than the darker 'ball-of string' textured area. It cuts across the darker area (2), showing that it must have formed later.

Figure 36 Domes

This is an 80-km wide region of Europa. It is mostly 'ball-of-string' terrain, but this has been warped or disrupted by doming from below. Most domes are 5–10 km across. See if you can identify some domes, and then see what we found.

Answer

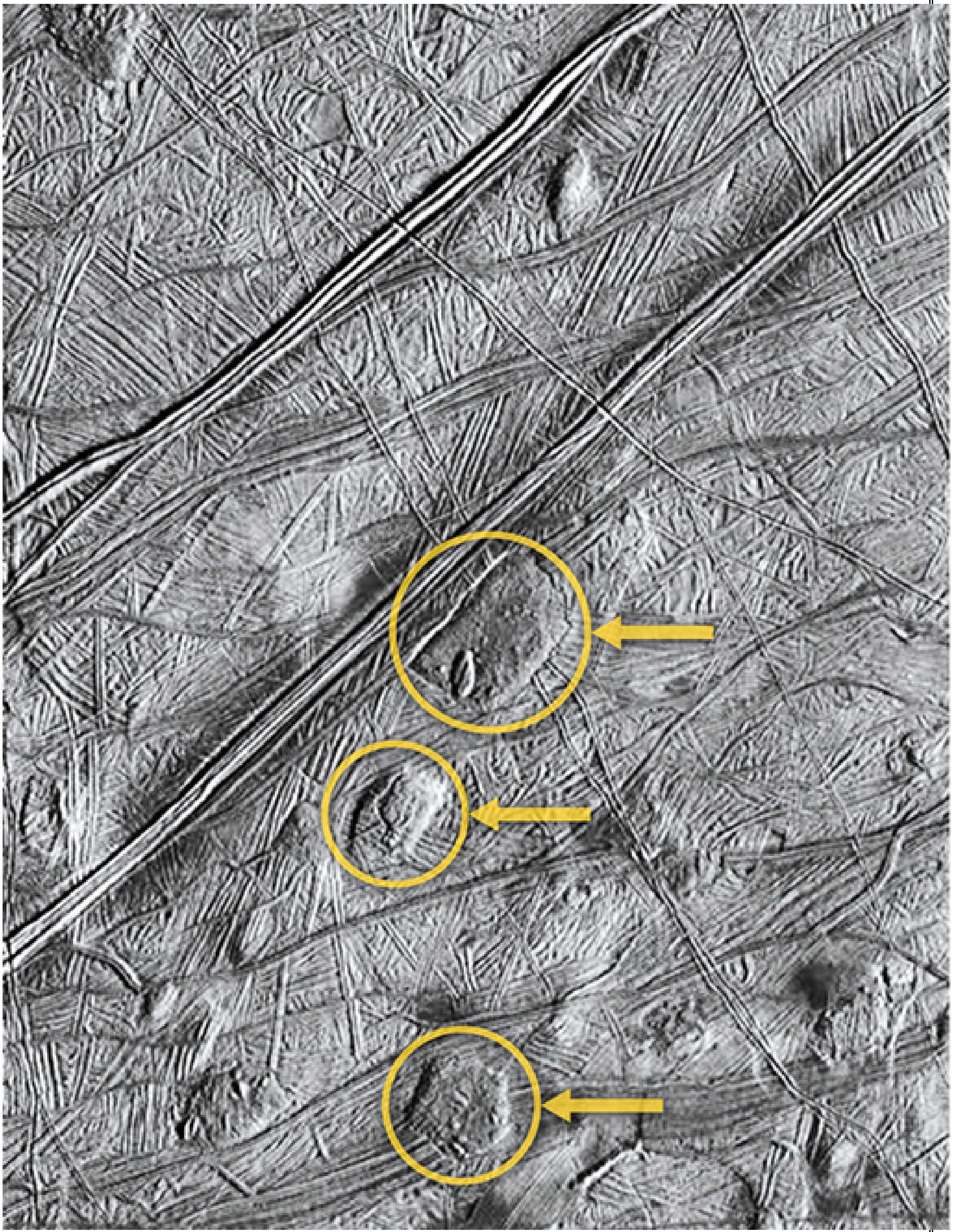


Figure 37

We have pinpointed the three most prominent domes in this image, but there are more.

Figure 38 Offset ridge.

This is a 15-km wide image of ‘ball-of-string’ terrain in Europa. There is one place where a ridge with a central groove has been offset by sideways slip along a fault. Try to find this, and estimate the amount of offset before you click to reveal the annotated version.

Answer

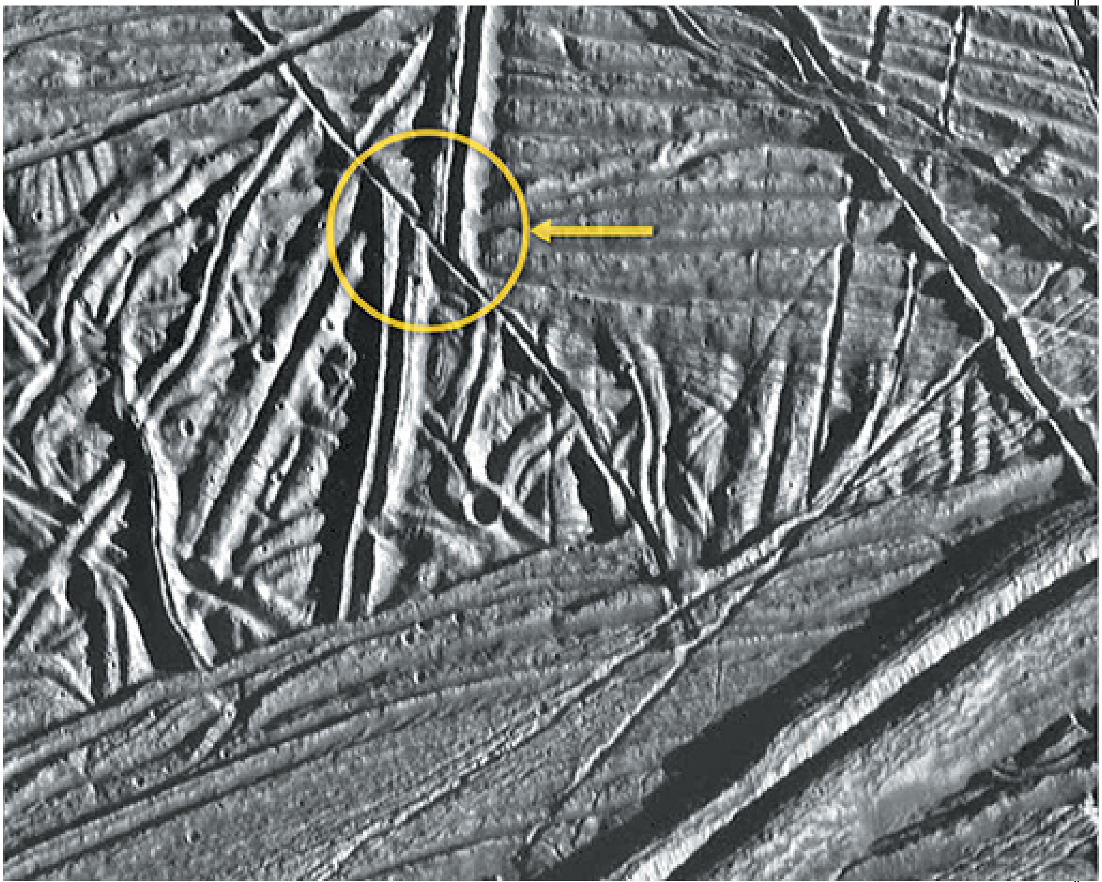


Figure 39

A ridge has been offset in the centre of the circle. This suggests lateral movement. Given that the image is 15 km wide, the offset is about 0.8 km.

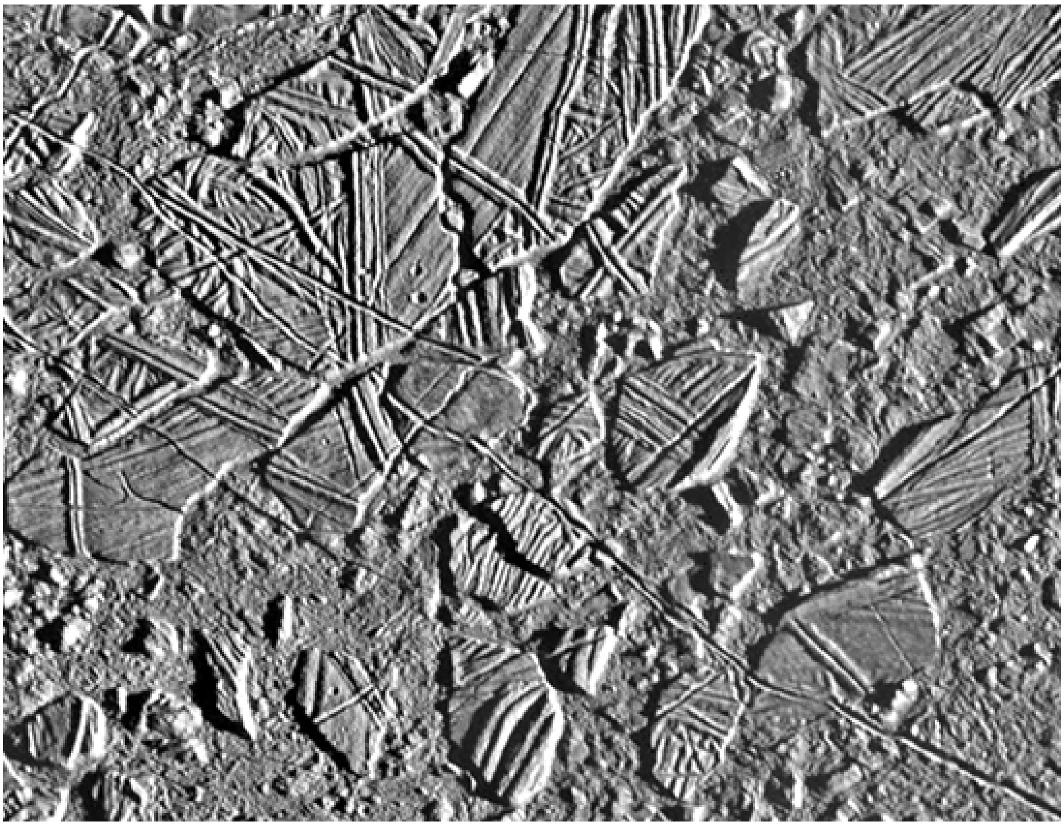


Figure 40 Raft features.

This image, roughly 34 km by 42 km, is part of a ‘chaos’ region consisting of rafts of ice that have broken apart and drifted into new positions before the slushy matrix between the rafts refroze. See if you can distinguish between rafts (still bearing ‘ball-of string’ texture) and matrix (representing the refrozen exposed ocean that was temporarily exposed as the rafts drifted apart), before you click to reveal the annotated version.

Answer

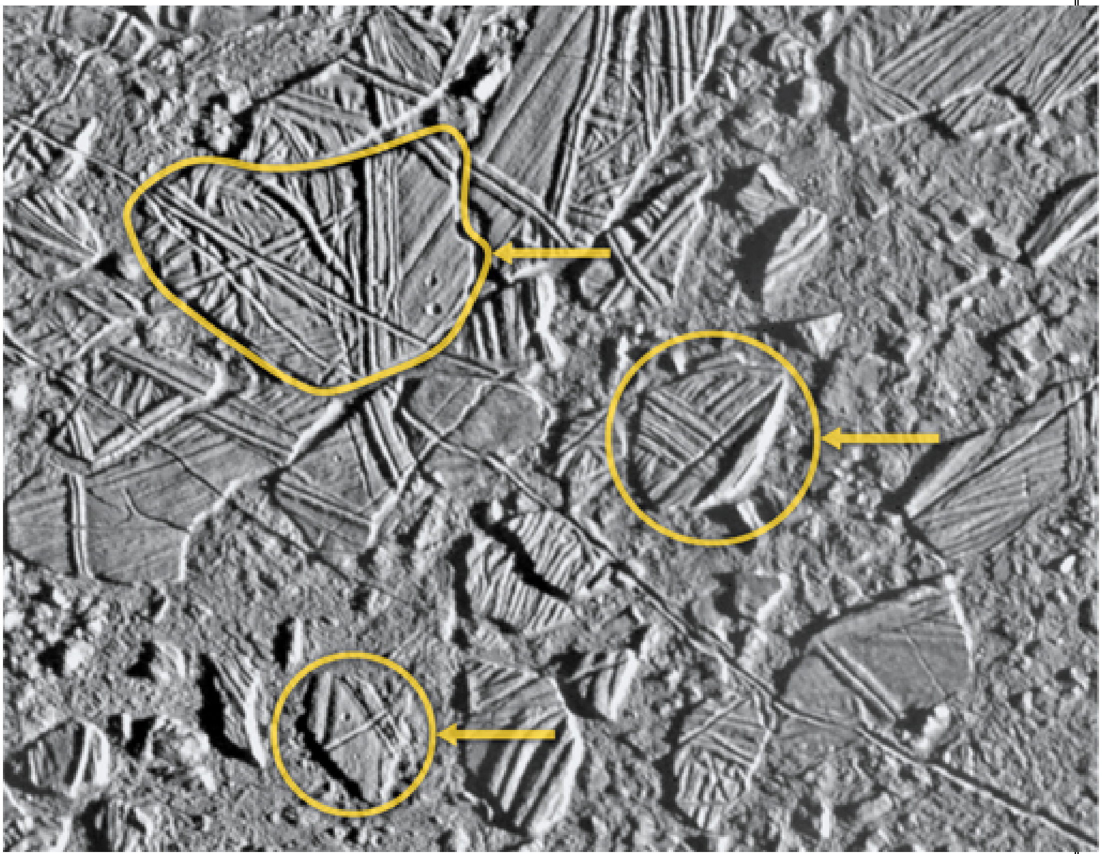


Figure 41

We have outlined the largest raft (which has neighbours close by to which it could be refitted without too much movement) and circled two other rafts that are more isolated. There are plenty of other rafts in this image. Shadows show that their surface is 100–200 m above the matrix. The matrix is a jumbled mess, lacking ‘ball-of-string’ texture, although there is a groove running through the matrix diagonally from the lower right corner that must have formed after the matrix refroze. Eventually, after many more grooves have formed, the matrix may become indistinguishable from ‘ball-of-string’ terrain.

2.10 Moon Trumps

Fancy a hand of cards? Have a go at our Moon Trumps game.

We’ve placed the same five attributes (radius, density, orbital period, orbital radius, potential for life) on cards for a number of different moons from throughout the Solar System. You win a turn by choosing an attribute that has a higher value than on the card held by your opponent, *except* for orbital period where the fastest orbit (lowest orbital period) wins. You can choose how smart the computer is. Normally whoever wins a turn plays first in the next turn, but you can give yourself an extra advantage by forcing the computer to always play second.

You will need to take an ‘educated guess’ from time to time, and we hope this will improve your feel for the nature and diversity of our Solar System’s moons. When you’ve had enough, move on to meet some small moons in more detail. You can come back any time you like and try to beat the computer as your knowledge grows.

You can play Moon Trumps online any time or pick up your own pack of Moon Trump cards on OpenLearn. If you experience any display issues with the exercise below, try this version instead.

3 Phobos and Deimos

Small moons have too little gravity to pull themselves into spherical shape. Meet the tiny moons of Mars, moons orbiting asteroids, Saturn's diverse moons (big and small), and gear up for the first visit to Pluto's moons.

Here you become better acquainted with some of the smaller moons in the Solar System. You begin with the best-known, which are the two moons of Mars: Phobos and Deimos.

Unfortunately Phobos-Grunt failed after launch in November 2011 (shortly after this video was made) when rocket failures left it stranded in low Earth orbit.

Video content is not available in this format.

See also: Although Phobos Grunt failed, the Japanese Space Agency (JAXA) plans to launch a probe to Phobos and Deimos in 2024, with a NASA instrument onboard. Read more here. MMX mission to Phobos.

3.1 The groovy moon

Figure 42 Left: Phobos (nearer and larger) and Deimos (smaller and further away) seen from the surface of Mars. Right: our own Moon, as it would appear in the martian sky if it were at the same distance from Mars as it is from Earth.

Test your understanding of John Murray's explanation for the origin of the grooves on Phobos as explained in the previous video. Which of the explanations below did he suggest as the cause of the grooves on Phobos?

- fractures associated with the impact onto Phobos that caused the crater Stickney
- Phobos passing through a hail of ejecta thrown out by an impact on Mars
- gases escaping from the interior of Phobos
- fractures caused by the distortion of Phobos caused by Mars' gravity.

Find out the answer to this question in the next section, and watch a short video of Phobos and Deimos shot from the surface of Mars.

3.2 Phobos seen from the surface of Mars

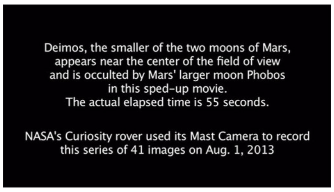
According to John Murray, the answer is that the grooves were formed when Phobos passed through ejecta flung out from an impact on Mars – like a car passing through a hail of machine-gun bullets.

Phobos is only about 6000 km above the surface of Mars, and this is close enough to be within range of ejecta flung out from large impacts.

This video was shot from the surface of Mars by NASA's Mars Curiosity Rover on 1 August 2013. It shows Phobos, the nearer to Mars of the two moons, passing in front of Deimos. Although Phobos is very much smaller than our Moon, its orbit is so low that in

Mars' sky it looks about half as wide as the Moon does in our own sky. The sequence has been speeded up from an actual elapsed time of 55 seconds.

Video content is not available in this format.



(Please note this video has no audio.)

See also: Phobos grooves as tidal stretch marks? An alternative explanation of Phobos's grooves from the November 2015 annual Meeting of the Division of Planetary Sciences of the American Astronomical Society.

3.3 The moons of asteroids

Find out about some moons of asteroids seen by spacecraft that have flown past, seen by optical telescopes and even imaged by radar when they pass very close to the Earth.

In March 2014 a particularly surprising discovery was announced concerning moons of asteroids. Seven southern hemisphere telescopes monitored a predicted occultation (hiding) of a star by the asteroid 10199 Chariklo, which is a 250 km diameter icy asteroid orbiting beyond Saturn (it belongs to a class of bodies known as Centaurs). The observations of this rare event were intended to refine our knowledge of Chariklo's size and shape (which they did). However, the light from the star dimmed twice very briefly a few seconds before the main occultation, and did so again a few seconds after. This shows that Chariklo has two rings (perhaps formed of debris resulting from a collision), 7 km and 3 km wide and separated by a 9 km gap. This is the first known ring system round anything other than a giant planet. Moreover, the only known way to confine the ring system so tightly is if Chariklo also has at least one shepherd moon, analogous to Saturn's Pan and Prometheus. Read more and see an artist's impression of Chariklo and its rings.

Video content is not available in this format.

Another moon of a near-Earth asteroid, even smaller than the moon of 1998 QE_2 that you saw in the video, was discovered using radar on 26 January 2015 when the 325 m asteroid 2004 BL_{86} passed at a distance of only 1.2 million km. Its moon is about 70 m in size making it the new record holder for the smallest known moon.

On 1 September 2017 during a close approach to Earth by the 4.5km asteroid Florence, two 100-300m moons were discovered orbiting it.

What about comets, could a comet have a moon? None has ever been found, however some comet nuclei are 'contact binaries' made of two lumps in contact. The comet famously visited by ESA's Rosetta Probe in 2014-16 is one of these. There is a short bonus video at the link given below, in which David Rothery discusses the issue with a member of the Rosetta camera team.

See also:

- A moon of a comet? A quick look at whether the two-lobed nucleus of a comet could have originated as a main body plus a moon (duration 2m 15s).
- A mission to 'Didymoon' Information (and a lovely video) about ESA's proposed 2023 mission to the moon of asteroid Didymos.

3.4 Exploring Saturn's moons with Cassini–Huygens

The Cassini–Huygens mission was launched in October 1997 as a joint mission between NASA, ESA (the European Space Agency) and ASI (the Italian Space Agency). It reached Saturn in July 2004, where it took the most detailed images to date of Saturn's small moons. These are all essentially icy bodies. Some of the smaller moons orbiting close to Saturn are known as 'shepherd moons' and actually help to stabilise the rings' edges through their tidal interactions.

Of the 62 moons discovered around Saturn, 53 have been officially named. Inner moonlets close to the primary body are likely to be formed at the same time as the primary or else they turn out to be fragments of larger moons that strayed too close. By contrast, outer irregular moons are more likely to be asteroids captured into orbit. In this image gallery you can view some of Saturn's larger small moons. As well as overall shape, look out for smoothness, crater types, overall texture, and any surface features such as valleys and grooves.

Hyperion (Figure 43) is 270 km across, and sponge-like in appearance due to the heavy cratering on its porous surface. Hyperion was the first non-round moon to be discovered (which was by telescope in 1848).

Figure 43 Hyperion

Helene (Figure 44) is 32 km in diameter and shares an orbit with Dione. Mysterious runnels can be seen crossing parts of its surface, carved into its regolith by an as yet unknown process.

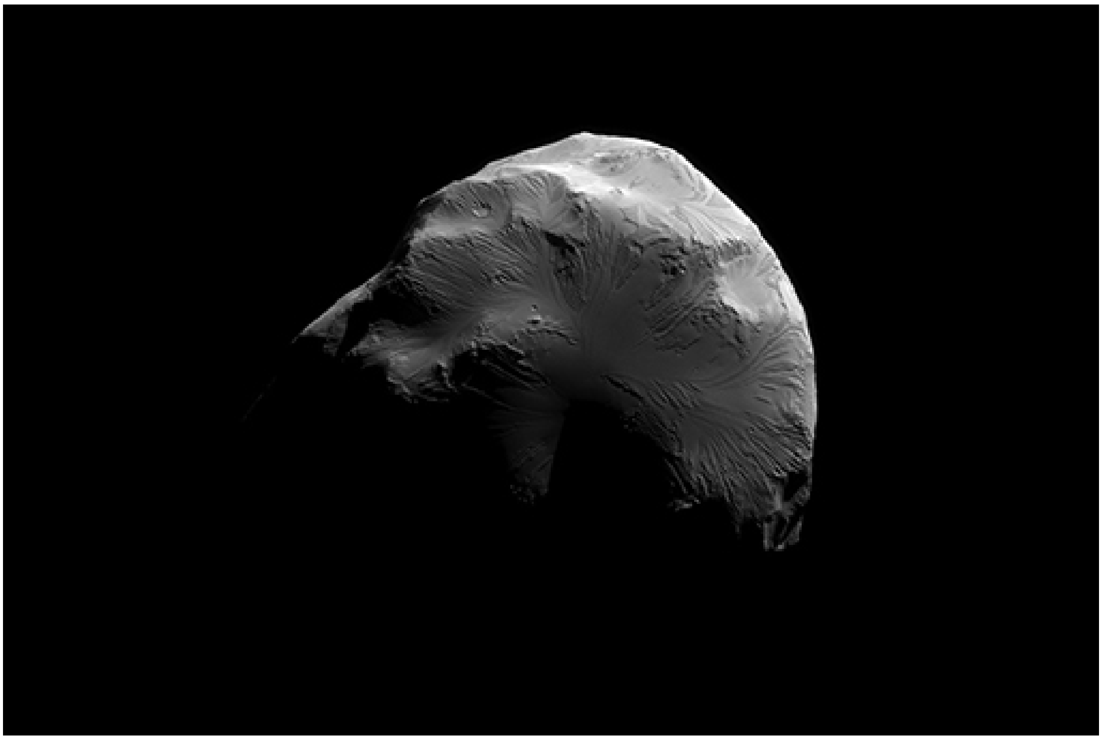


Figure 44 Helene.

Figure 45 is Enceladus (diameter 504 km), which was imaged in 2005 by Cassini, is thought to have liquid water under an ice surface, thus making it a candidate in the search for life. Water rather than lava is erupted from ice-volcanoes, and plumes of ice crystals mixed with nitrogen, methane, carbon dioxide and traces of hydrocarbons such as propane and ethane, have been seen being ejected into space.

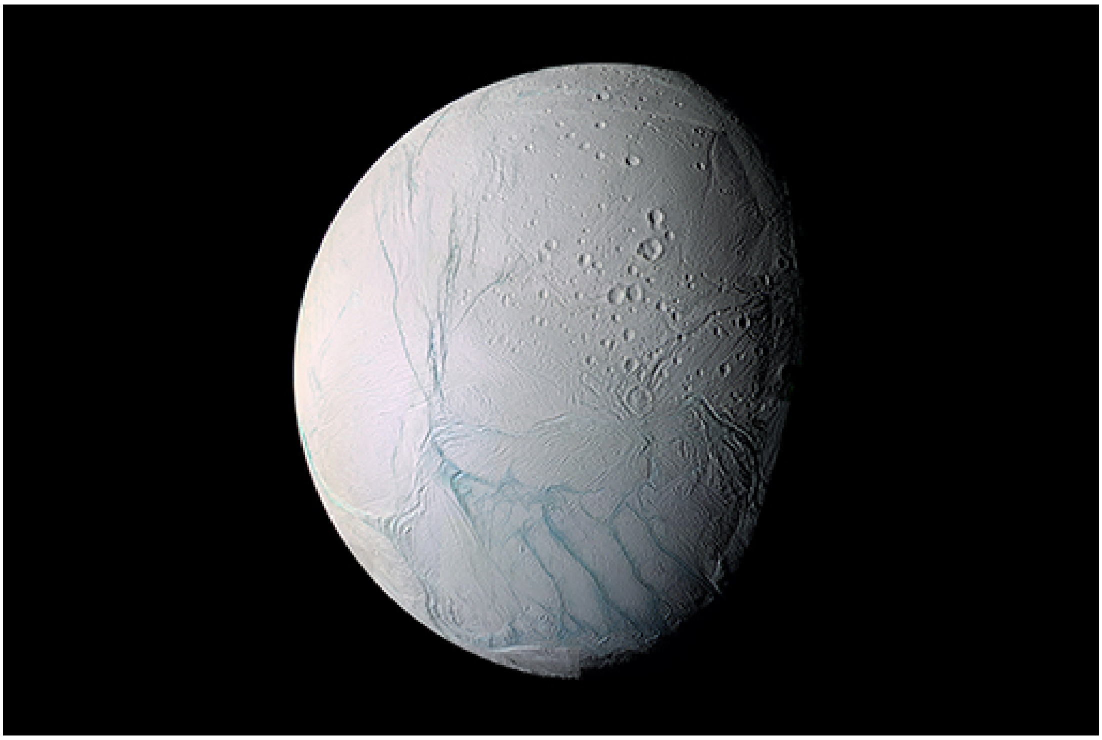


Figure 45 Enceladus.

A narrow crescent view of part of Enceladus, taken looking back towards the Sun. Scattering of the sunlight by particles in the eruption plumes renders the plumes visible (Figure 46).

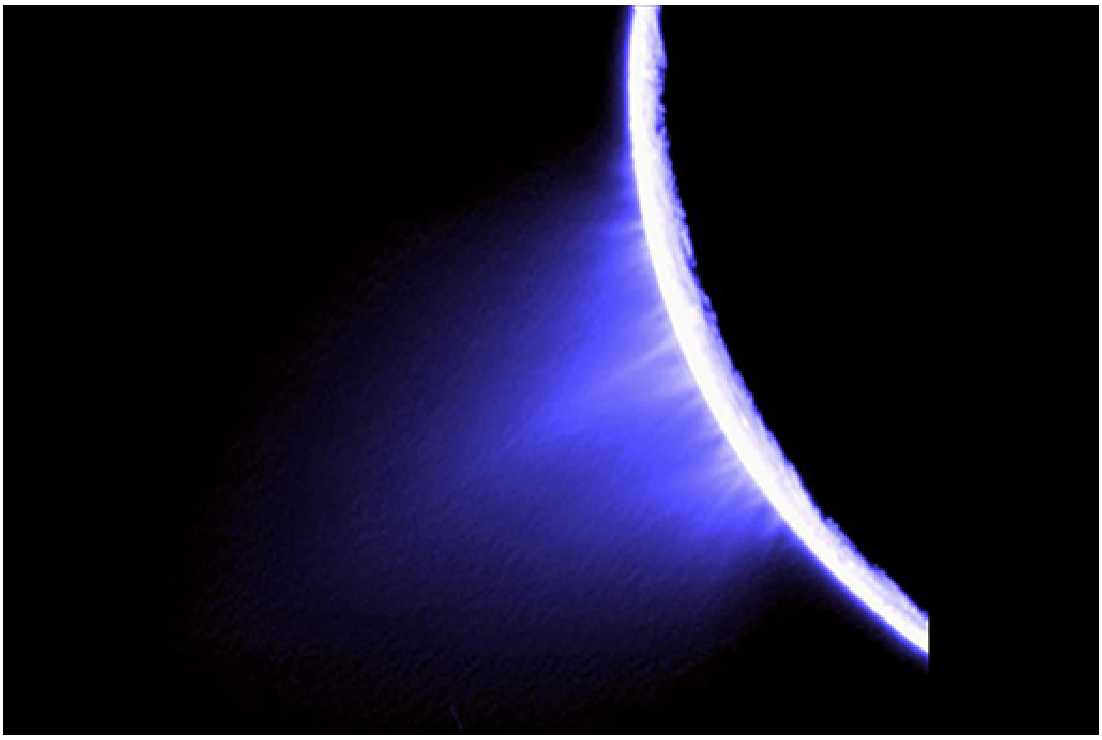


Figure 46 Plumes from Enceladus.

Mimas (Figure 47) is 396 km in diameter and is the smallest astronomical body known to be spherical in shape because of self-gravitation. Craters on Mimas are named according to IAU rules. In this case, they have used characters from the Arthurian legends (the crater on the lower left is named after King Arthur himself). The only exception to this is Mimas' largest crater, which is 139 km across and dominates the right-hand half of this view. It is named Herschel, in honour of Sir William Herschel, who discovered both Mimas and Enceladus.

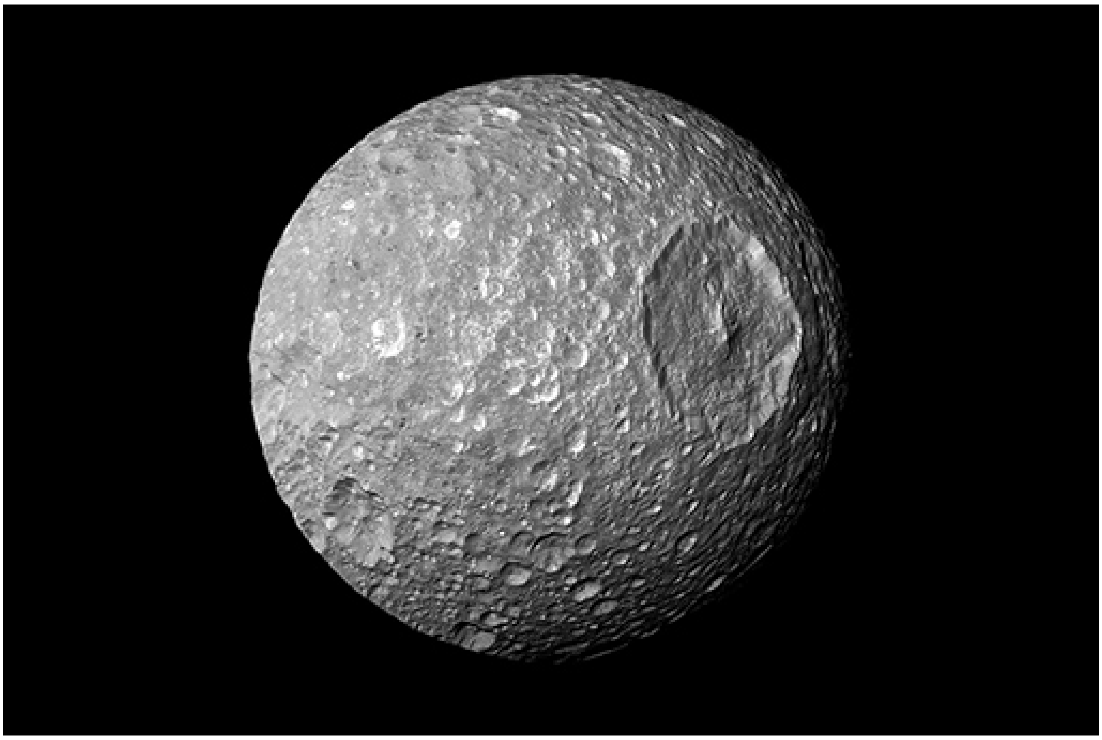


Figure 47 Mimas.

Dione (Figure 48) (diameter 1122 km) was discovered by Giovanni Cassini, along with Tethys, Rhea and Iapetus. Its icy surface features include complex craters and tectonic fractures.

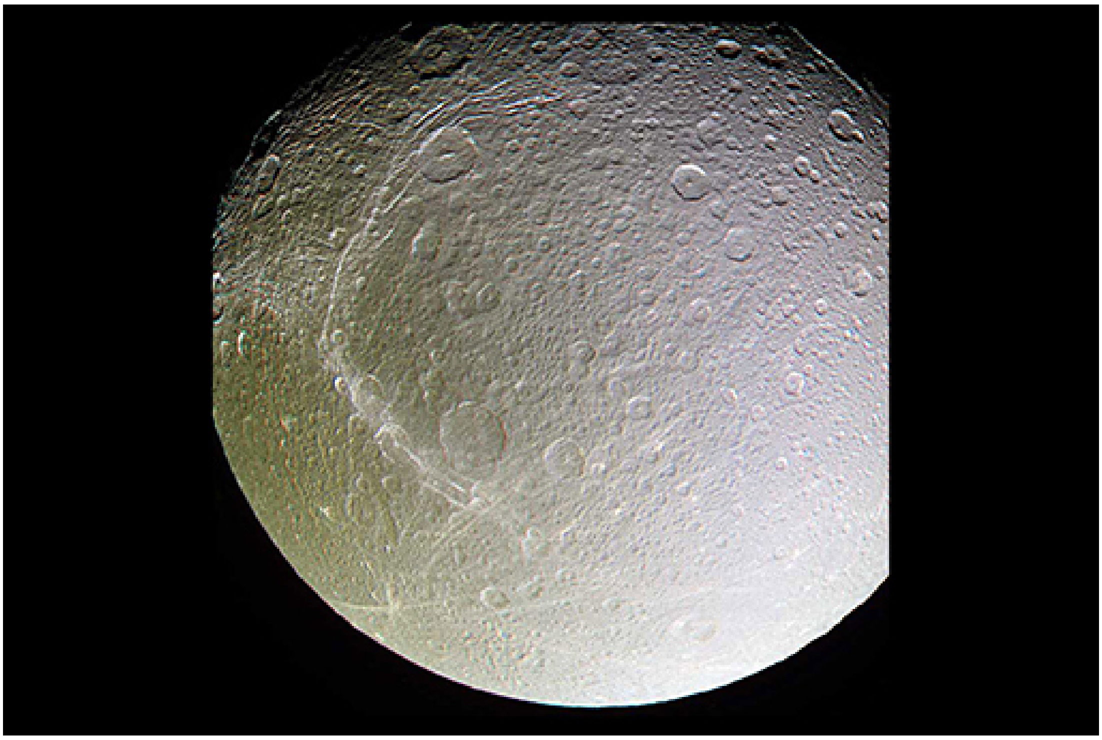


Figure 48 Dione.

Atlas and Pan (Figure 49) are small inner moonlets. Pan is the closest known moon to Saturn, and Atlas orbits not far beyond. Two views of each are shown. Along with Iapetus, each features a ridge along the equator, discovered during the Cassini mission. Such ridges are thought to be peculiar to Saturn's system, but it's not known how they formed.

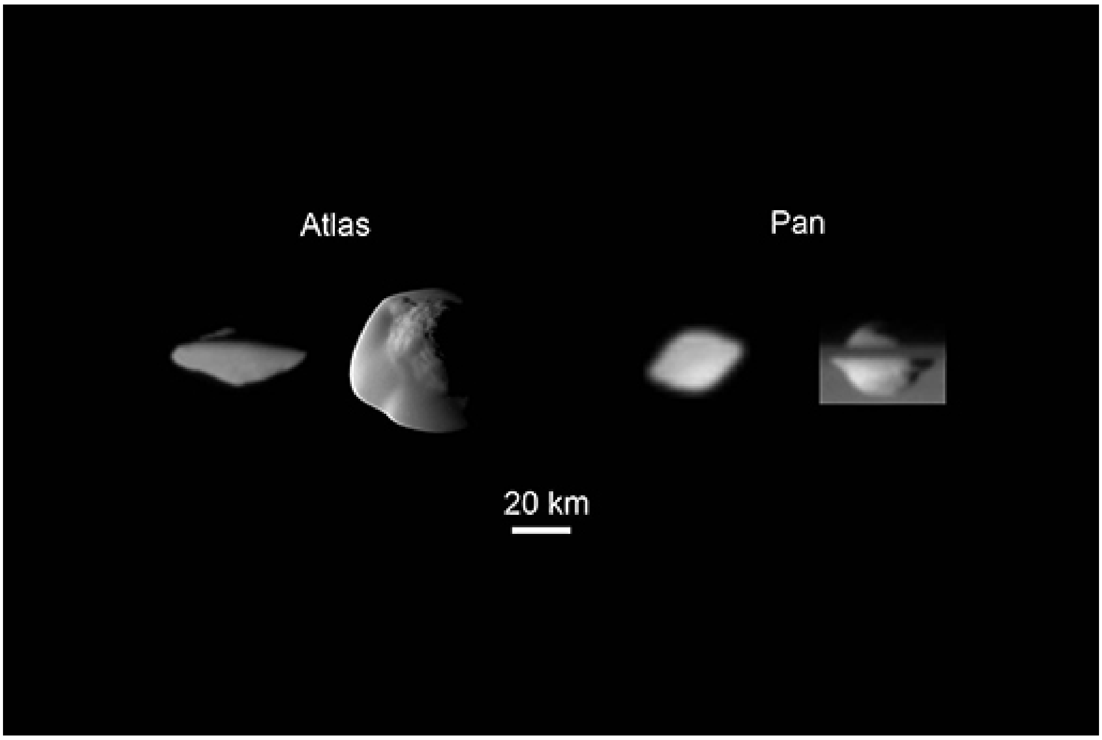


Figure 49 Atlas and Pan.

Iapetus (Figure 50, diameter 1492 km) shows a dramatic contrast, with one low albedo hemisphere and one high albedo hemisphere. The lengthy rotation period of about 79 days means that the dark side absorbs much more heat from the Sun than the bright side, resulting in increased sublimation (vaporisation) of ice on the dark hemisphere. The vapour migrates and tends to condense on the colder bright hemisphere. The high-albedo stuff is pure, clean ice, whereas the low-albedo stuff is probably carbon-rich impurities that have become concentrated at the surface where the ice has sublimed away.

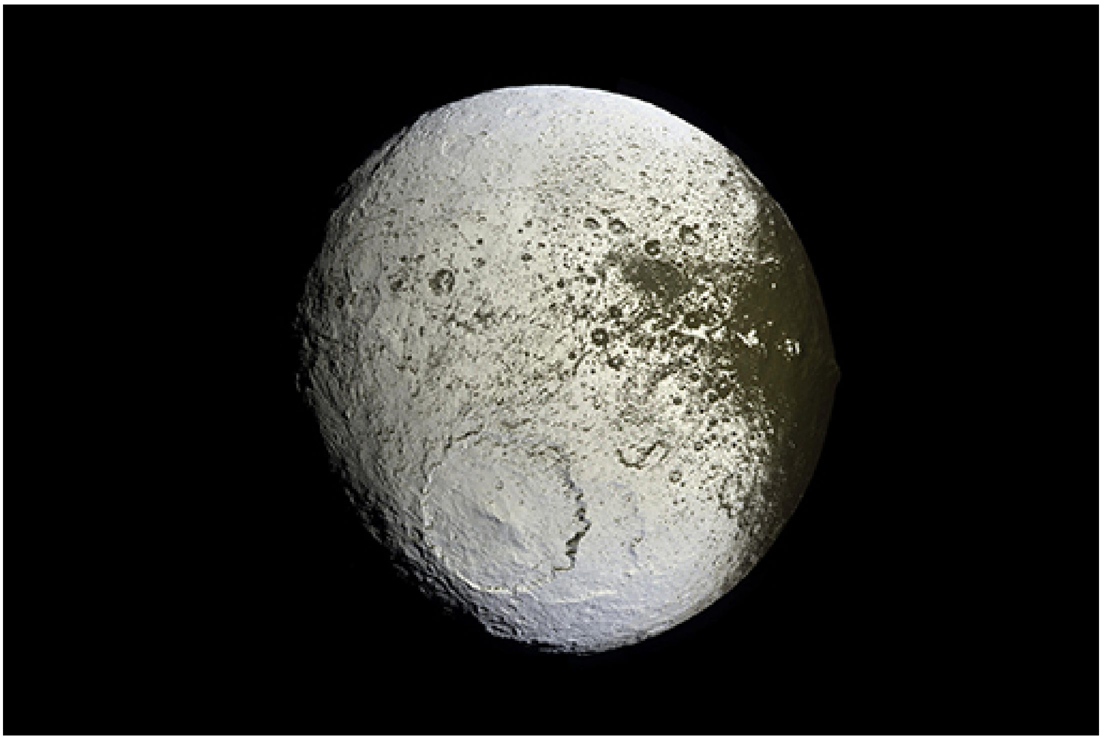


Figure 50 Iapetus.

Rhea (Figure 51, diameter 1526 km) has an icy surface that is more heavily cratered than Saturn's similar moons Dione and Tethys. The wispy lines are actually fractures in the surface, appearing brighter as they expose fresh ice.

Figure 51 Rhea.

Rhea is dwarfed by Saturn, because Saturn's diameter is nearly 80 times greater. The black diagonal stripes on Saturn are the shadow cast by its rings (Figure 52).

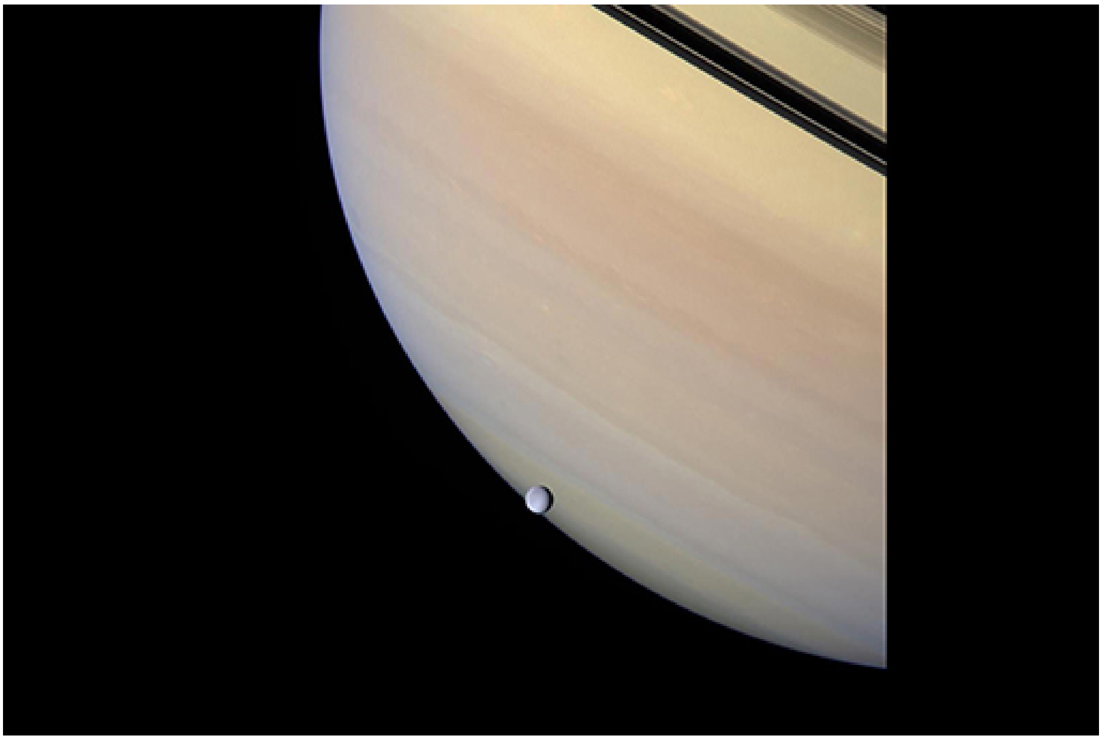


Figure 52 Rhea and Saturn.

Janus (Figure 53) is one of Saturn's inner moonlets and is about 200 km wide. It shares its orbit with Epimetheus. It has a low density, so it is presumed to be very porous.

Figure 53 Janus

Prometheus (Figure 54) is an elongated inner moonlet and is about 135 km long. Craters and ridges can been seen.

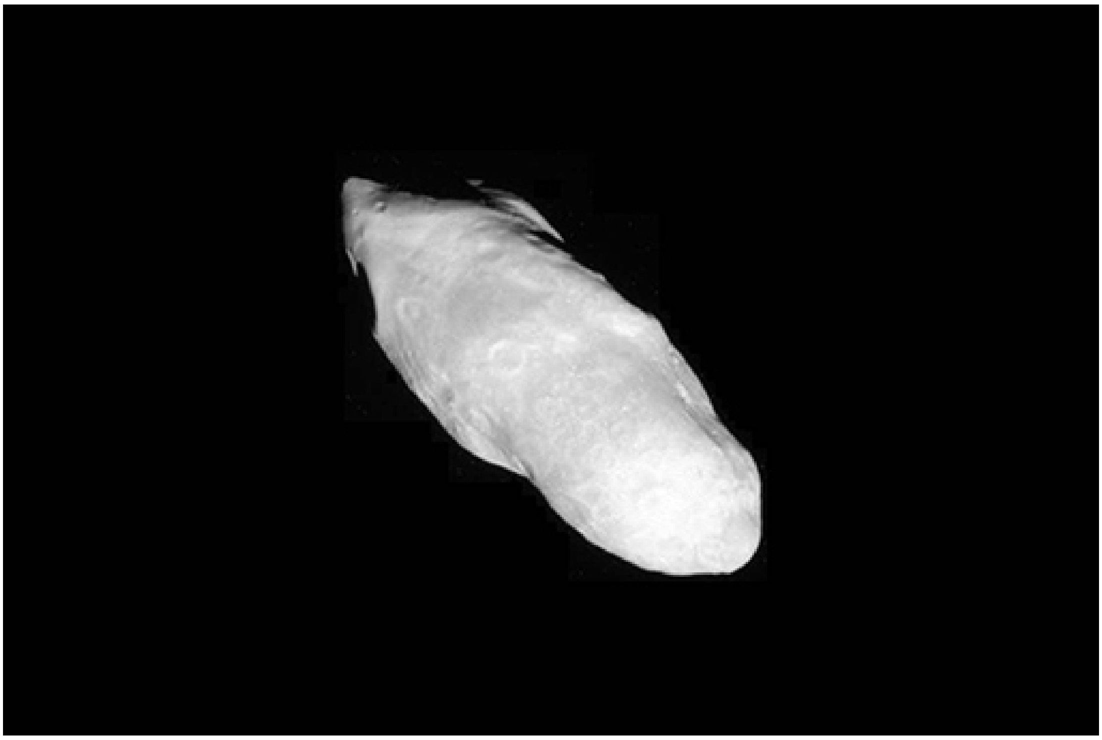


Figure 54 Prometheus.

Pandora (Figure 55) is an inner moonlet and is about 80 km wide. It is shepherd to one of the rings.

Figure 55 Pandora.

Epimetheus (Figure 56) is about 116 km wide. A large crater was observed on its southern face, which could be responsible for the flat edge.

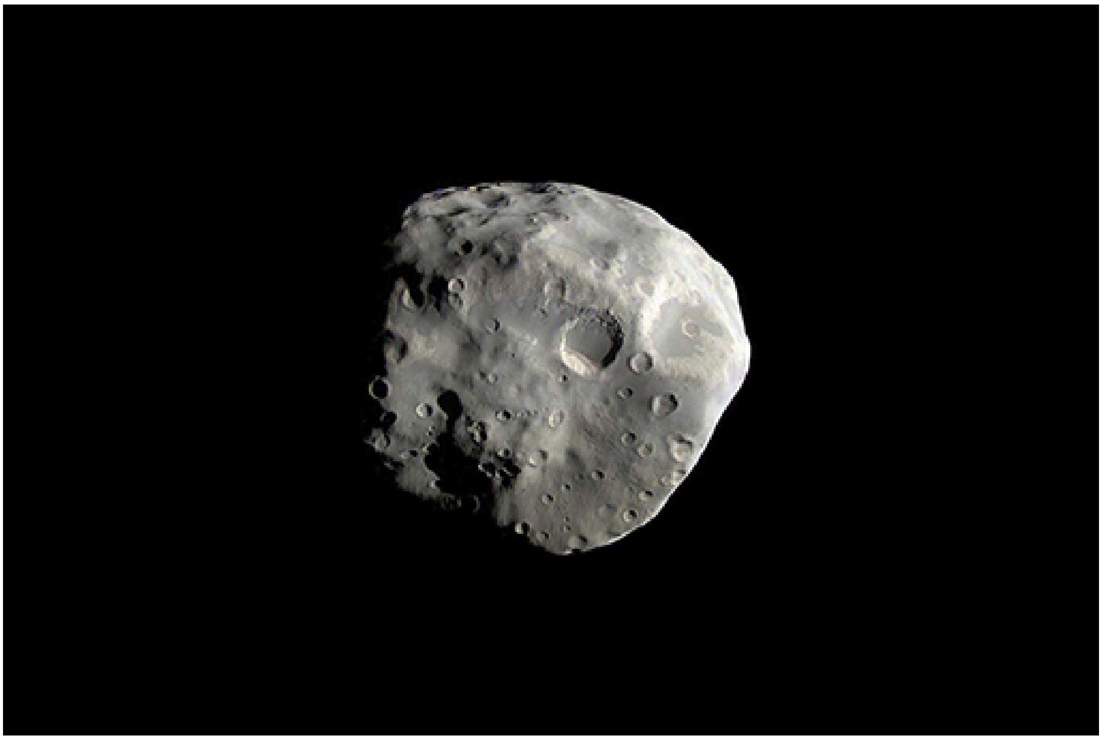


Figure 56 Epimetheus.

Phoebe (Figure 57) is an irregular outer moon of Saturn about 213 km wide and is thought to have been captured from the Kuiper Belt, as it has a retrograde orbit. It was the first moon to be observed at close quarters by the Cassini spacecraft.

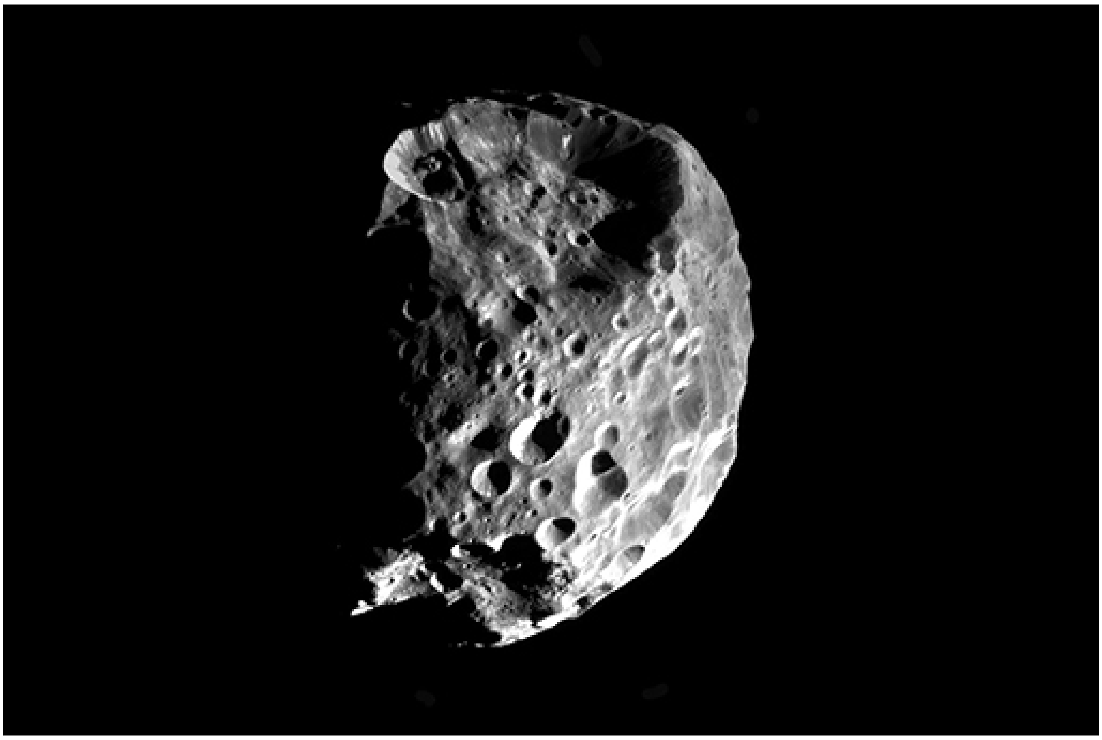


Figure 57 Phoebe.

See also:

- Best ever view of Daphnis? Here is the best yet view of Daphnis, an 8 km long moon that orbits within one of the gaps in Saturn's rings. This was captured by Cassini on 16 Jan 2017. Note how it's gravity has produced a wave-like disturbance in the ring material.
- Close up of Epimetheus. Epimetheus imaged by Cassini on 30 Jan 2017.
- Another close up of Epimetheus. A February 2017 close up by Cassini. Do the fine, largely parallel, grooves on the surface remind you of any other moons?
- Best ever views of Pan. Superb extra detail on Pan, revealed on images recorded by Cassini 7 March 2017.

3.5 Ordering Saturn's moons

Put the names of Saturn's moons in order starting with the closest to the planet by dragging the names up and down the list. The computer will tell you when you've got it right, and will offer you help after you've made a certain number of moves.

You can also view the data on Saturn's moons.

3.6 Naming Charon

Discovered in 1978 by James Christy, Charon was the first moon to be discovered orbiting Pluto. The name Charon was suggested after the mythological ferryman who carried souls across the River Styx from the world of the living to the underworld ruled by Pluto. This name was significant to the discoverer due to its similarity with the name of his wife

(Charlene) and is often pronounced ‘Sharon’, rather than the more Greek-sounding ‘Karon’.

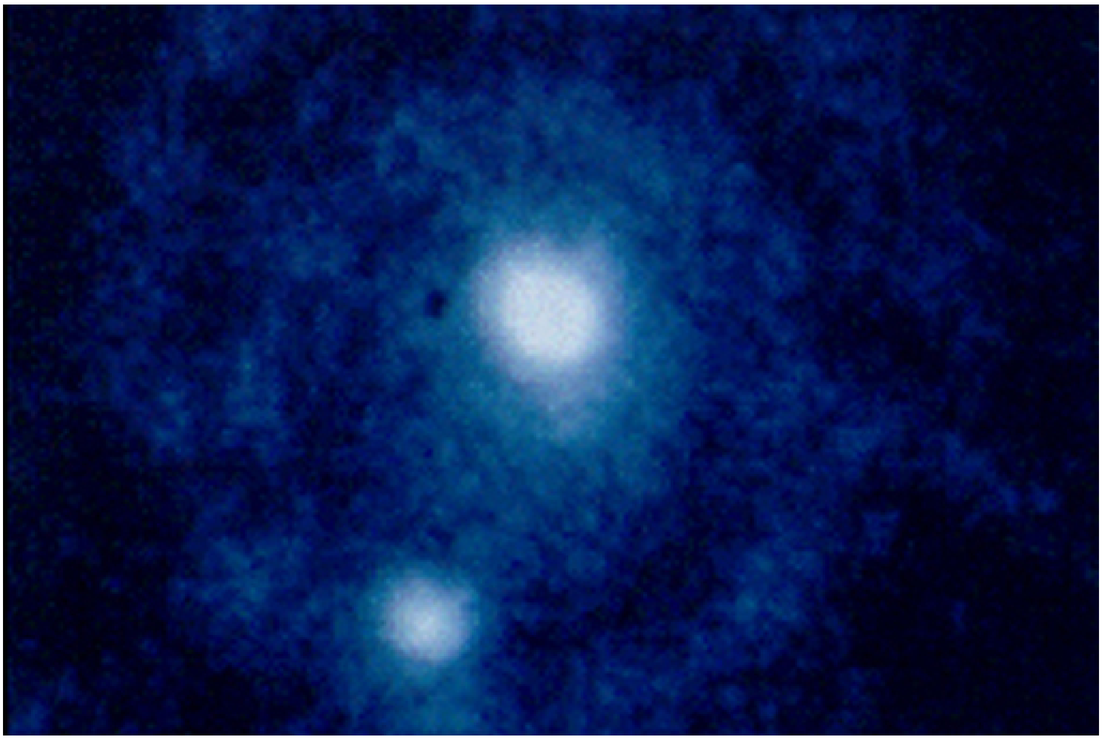


Figure 58 Pluto and Charon imaged by the Hubble Space Telescope.

3.7 Naming Pluto’s other moons

In 2005, two more moons were discovered orbiting Pluto from Hubble Space Telescope images. Originally referred to as S/2005 P1 and S/2005 P2, the moons were then named in 2006 as Hydra after the nine-headed beast, to reflect Pluto’s then-status as the ‘ninth planet’ (Pluto officially lost is status as a planet in 2006), and Nix after the Greek goddess of night and mother of Charon ‘Nyx’. The spelling change from Nyx to Nix was to avoid confusion with the asteroid 3908 Nyx.

Astronomers used new sets of long exposure images from Hubble to prepare for the upcoming New Horizons mission by looking for any rings that Pluto might have, and discovered two more new moons in July 2011 and July 2012. These were temporarily designated S/2011 P1 and S/2012 P1 respectively.

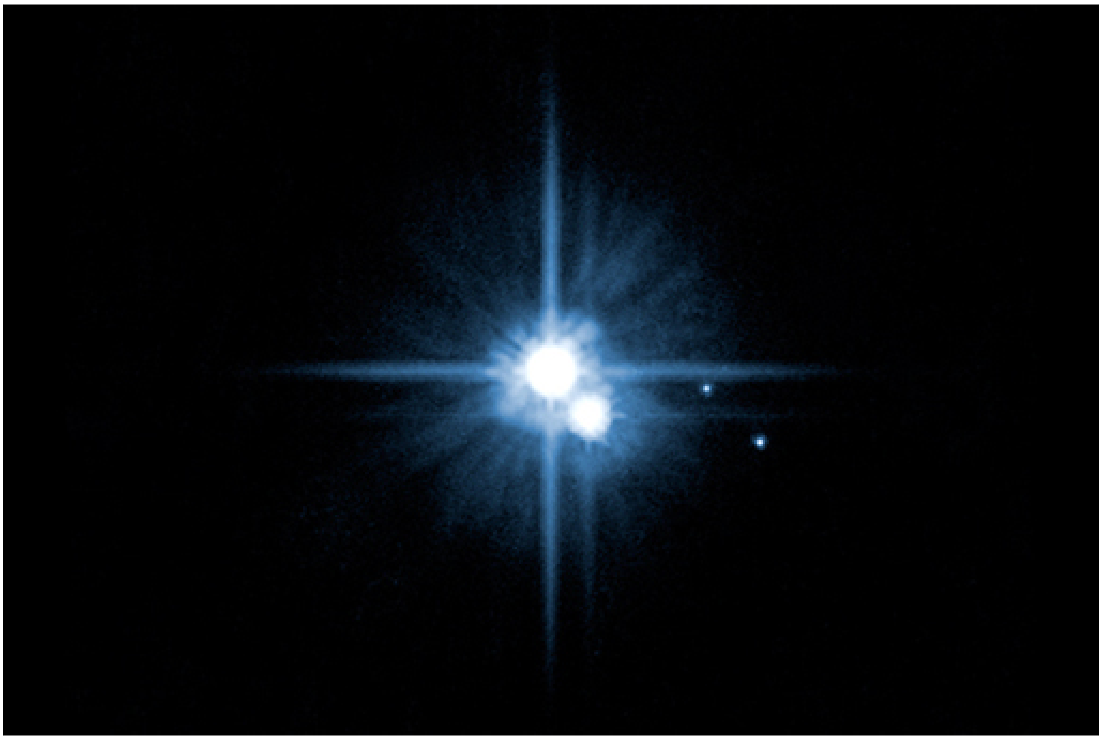


Figure 59 A Hubble Space Telescope image of Pluto and Charon, taken in 2005, from which Nix (the small dot closest to Pluto–Charon) and Hydra (the furthest dot) were discovered.

3.8 What's in a name?

The naming of S/2011 P1 and S/2012 P1 was open to an unofficial internet poll where the name 'Vulcan' won. However, the International Astronomical Union (IAU) could not accept this name. Vulcan is not connected with the underworld theme that has been adopted for Pluto, and had already been used to name the (hypothetical) vulcanoid asteroids. William Shatner, Star Trek's 'Captain Kirk', had tried to get Romulus added to the poll, but the organisers themselves ruled that out, because Romulus is already used for one of the two moons of the asteroid 87 Sylvia.

In the end, S/2011 P1 was named Kerberos, a Greek spelling of Cerberus, the dog that guarded the mythological underworld. S/2012 P1 was named Styx, after the river that bordered the underworld. Cerberus and Styx in fact came second and third in the poll, so the public did have a say in the official names.

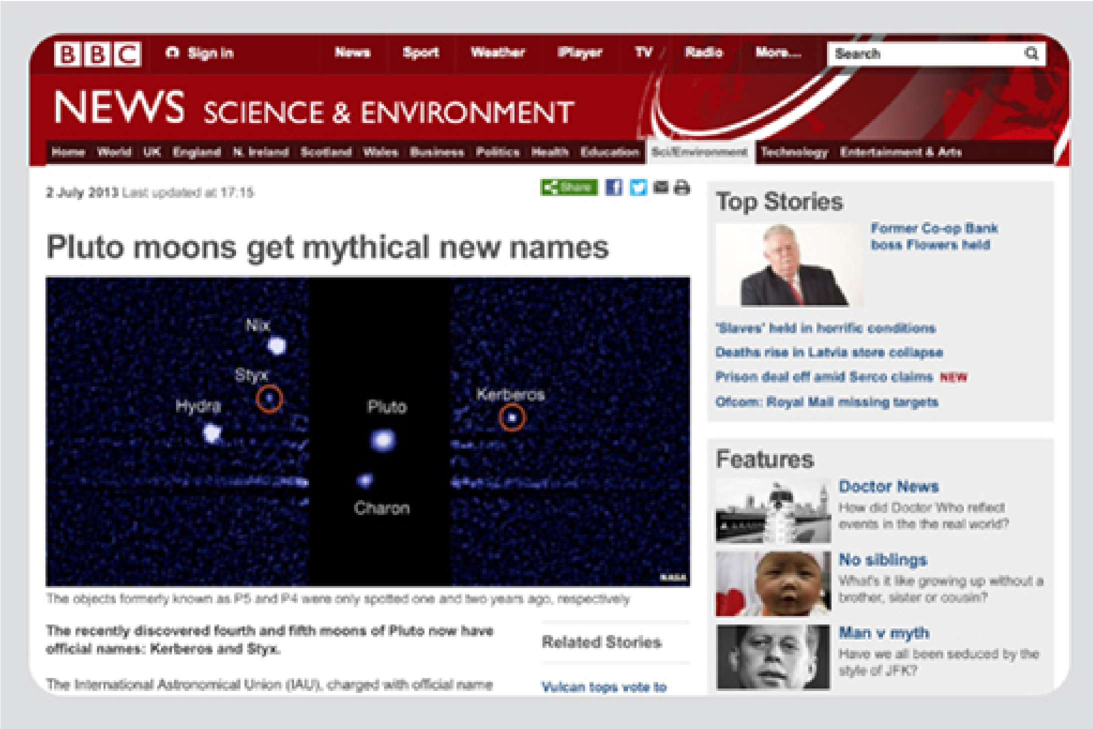


Figure 60 A screen grab of the BBC News website on 2 July 2013 in which Pluto's moons make the news.

See also: [BBC News - Pluto moons get mythical new names](). The recently discovered fourth and fifth moons of Pluto now have official names: Kerberos and Styx.

3.9 The New Horizons mission

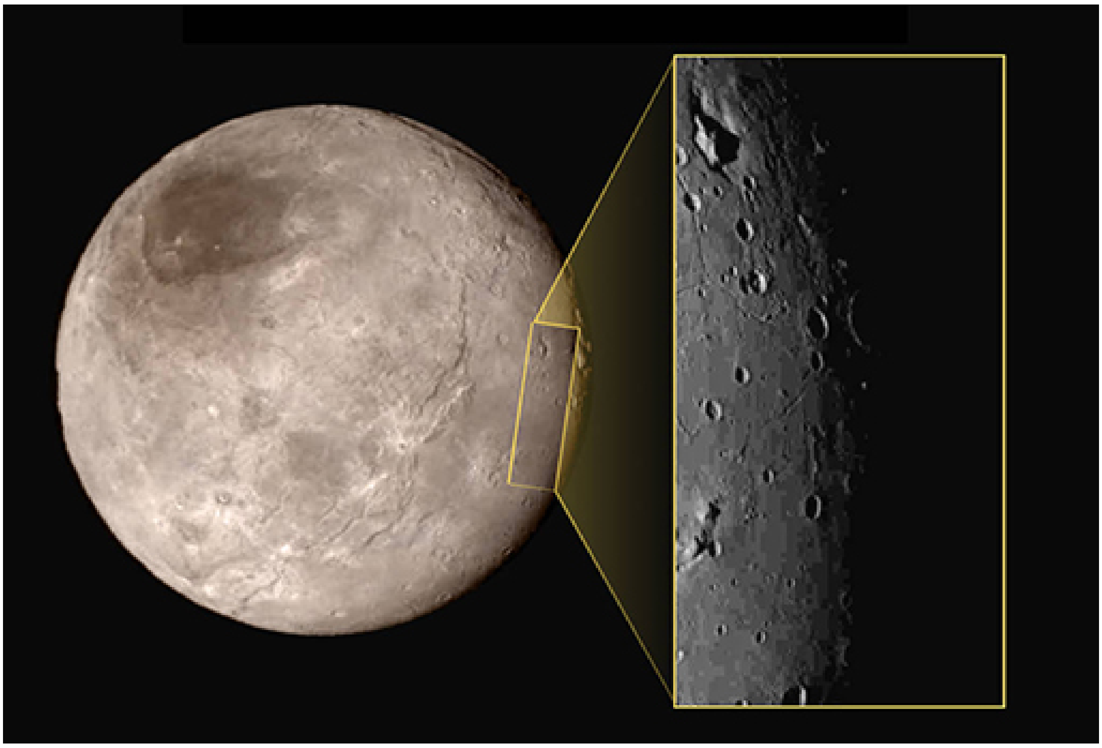


Figure 61 Global view of Charon and a close-up obtained at a range of only 79,000 km.

Pluto's moons were revealed in detail in 2015 when the New Horizons mission flew past Pluto. Launched in 2006, its journey to Pluto took nine years, and radio signals transmitted back to Earth took about three-and-a-half hours to reach us. It showed that Pluto's landscape is unlike that of Triton, even though they have similar compositions. Charon has a mixture of cratered (old) terrain and smooth (young) terrain that might have been cryovolcanically resurfaced, and is cut by major fractures.

Despite searching, New Horizons did not find any new small moons, but it did discover that the rotation axes of the four previously-known small moons point in various directions and that their rotation periods are much shorter than their orbital periods (so these are not in synchronous rotation, unlike Charon). Here are views of Nix and Hydra shown at similar scales.

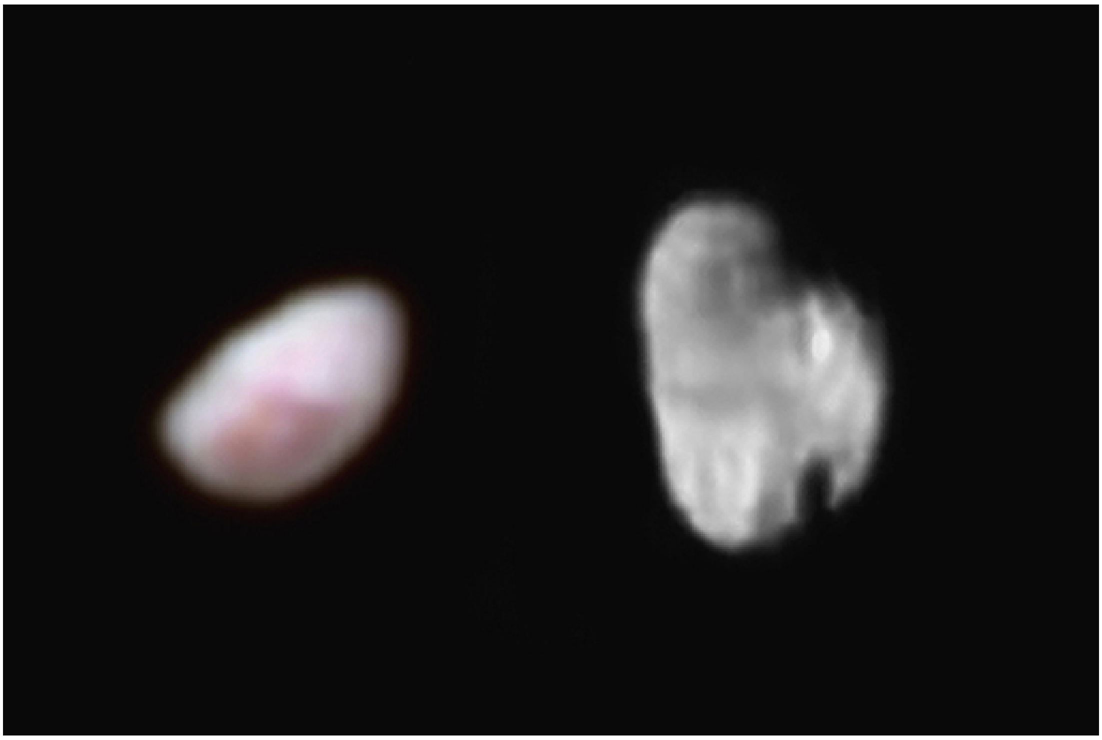


Figure 62 Nix (left), 42 km long and Hydra (right), 55 km long. The colour on Nix has been exaggerated to highlight an unexplained red area.

You can follow the mission at this link: New Horizons

See also:

- Pluto's weird small moons. Rapid spin and other weirdness among Pluto's small moons, including a nice animation.
- The best view of Nix. New Horizons' most detailed view of Nix.
- The best view of Charon. New Horizons' most detailed view of Charon.
- Tholins do not simply walk into Mordor Macula. A report of new results showing how methane escaping from Pluto stains Charon's poles red.

4 This week's quiz

This quiz allows you to test and apply your knowledge of the material in Week 3.

Complete the Week 3 quiz now.

Open the quiz in a new window or tab then come back here when you're done.

5 Summary

This week you learned about volcanic eruptions on moons; Galileo’s discovery of four large moons around Jupiter (one of which is arguably the place in our Solar System most likely to host extra-terrestrial life), and about various small moons. In contrast to Pluto’s moons, about which we still know relatively little, during the next three weeks you’ll be learning about the moon that we know most about – namely The Moon.

You should now be able to:

- understand the significance of volcanic activity on moons
- consider the importance of Galileo’s discovery of four moons around Jupiter
- consider the place in our Solar System that is most likely to host extraterrestrial life.

You can now go to Week 4: Our Moon.

Week 4: Our Moon

Introduction

Introducing the only moon you can see with the naked eye, how does it measure up against the others, what's under the surface and how far away is it? What did early missions to the Moon discover, and why would we want to return?

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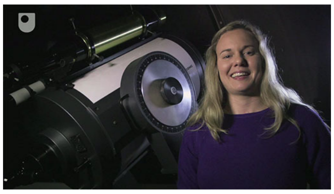

On Wednesday 15 March, 2017, Open University academic David Rothery and his colleague Ian Wright, who is a member of the Rosetta team that studied comet 67P, joined OU planetary science students in a live 'planets and moons' video webcast.

On Wednesday 15 November, 2017, David's guest in the next planets and moons chat was Monica Grady, an expert on meteorites and certain aspects of Mars. You may find it of interest to watch these webcasts, plus older ones and others to be added in the future. Those can be found easily from these links.

By the end of this week, you should be able to:

- recognise the many cultural references to the Moon, from music to art and literature
- understand more facts about the Moon
- calculate the distance to the Moon.

See also:

- Planets and moons chat 15 March 2017. Here is the link for the recording of live webcast that was made 1930-2015 on Weds 15 March 2017.
- Planets and moons chat link, for 15 November 2017. Click this link for the recording of the webcast with David Rothery and Monica Grady.

1 The Moon’s influence on us

Our culture is littered with references to the Moon, be it Shakespeare discussing the Moon in a sonnet, or a famous 1970s rock band using a certain unseen feature of the Moon as the title of one of their albums.

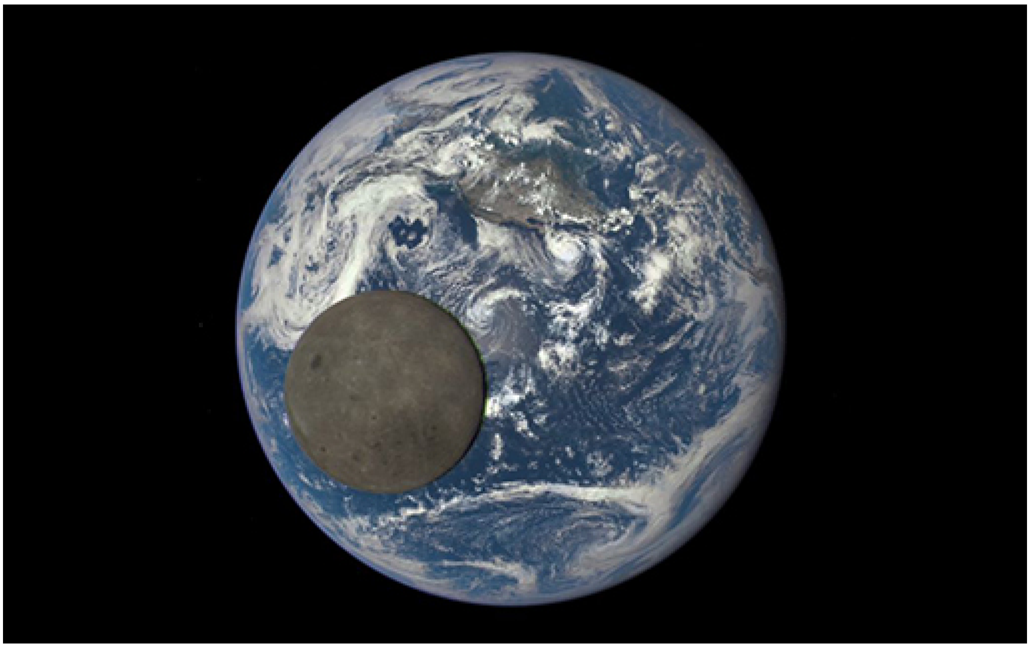

Figure 1 The Moon crossing the face of the Earth, seen from a range of 1.5 million km.

It’s not difficult to see why the Moon features so much in the arts. If you look up into a clear night sky, 25 days out of 28 you are likely to see it. The word ‘month’ is derived from the time (roughly) that the Moon takes to complete one orbit around the Earth. People have been fascinated by the Moon for millennia, with many ancient civilisations associating it with mental disorders: the word ‘lunacy’ is derived from ‘lunar’. This is reflected in popular culture – for example, the character Luna Lovegood in the Harry Potter books. Another rich area of cultural references to the Moon comes from the story of a simpleton trying to recover a large cheese, really a reflection of the Moon, from a lake. The story is present in the folk tales of many civilisations and gave rise to the metaphor that someone is so credulous ‘they’d believe that the Moon is made of green cheese’. In popular culture this fable is repeated, notably in the Wallace and Gromit adventure ‘A Grand Day Out’ produced by Nick Park/Aardman Animations.

Until Galileo identified four of the moons of Jupiter in 1610, Earth’s Moon was the only known satellite. Some of the features of the Moon’s surface can be seen from Earth with the naked eye and, as you’ll learn in the next few weeks, space missions have established that the Moon has no substantial atmosphere and no global magnetic field. No matter how much knowledge of the Moon scientists gain, it still captures the interest of people and inspires musicians, screenwriters, playwrights and artists.

The image at the top of this page shows the Moon passing in front of the Earth as seen by NASA’s Deep Space Climate Observatory (DSCOVR) satellite, which is stationed 1.5 million km from Earth. Notice how dark the Moon’s surface is compared to the Earth, even though most of the terrain on the lunar farside (which is what we see from this vantage point) is more reflective than the mare basalts that cover much of the nearside surface. You can see this image added to others to make a time-lapse video here.

1.1 Inspirational moons

What do you think is the main cultural significance of (a) the Moon and (b) other moons? What is your favourite Moon-inspired song, musical composition or artwork and why?

Figure 2 Vincent van Gogh, The Starry Night, 1889, painted in Europe and showing a C-shaped crescent, so this must be pre-dawn, not the evening sky. Or did van Gogh get it wrong?

Just for fun, we created a moons-inspired Spotify playlist here. Unsurprisingly, most music relates to the Moon alone, rather than to any of the others. You can enjoy the playlist and contribute your own selections by joining Spotify.

1.2 A moon among many?

In diameter, our Moon is the fifth-largest moon in the Solar System behind three of the Galilean moons of Jupiter (Ganymede, Callisto and Io) and Saturn's largest moon, Titan. To put its size in perspective, the diameter of the Moon is approximately the same as the distance between London and Cairo and it is less than an east–west crossing of Australia.

Figure 3 The Moon in context of other similar sized bodies

1.3 The Moon – some facts

The Moon is about 4.5 billion years old. Current thought is that it was most likely formed by a giant impact, as you saw in Week 1.

The distance to the Moon is known accurately due to reflectors that were placed on it during the Apollo missions. The reflectors, part of the Lunar Laser Ranging Experiment, allow lasers to be shone onto the Moon and the time taken for the laser light to get there and back can be measured. It is then possible, using a simple equation, to calculate the distance to the Moon. You can watch a four minute video of Brian Cox explaining just this.

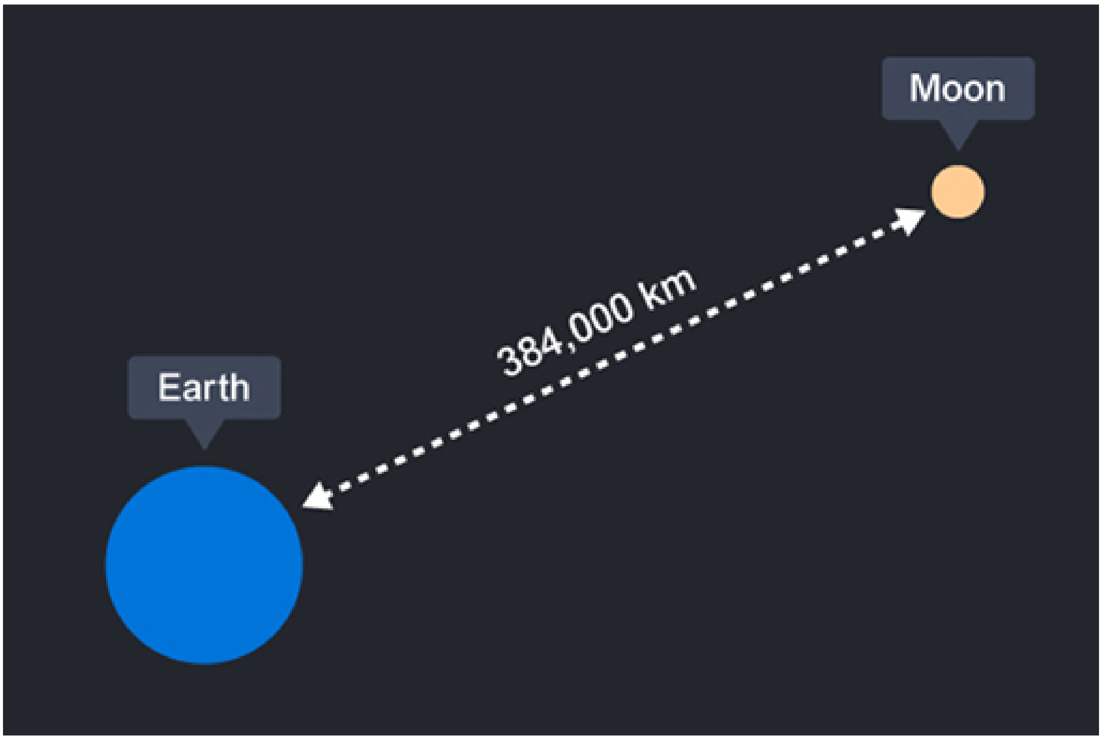

Figure 4 Distance between the Earth and the Moon.

Next, you have a chance to try calculating the distance to the Moon for yourself. It's a very basic non-scored quiz. Don't worry if you don't know some of the answers.

Activity 1 Calculating the distance to the Moon

Allow approximately 15 minutes.

Which is the correct equation for calculating the distance to the Moon? Note that 'time' refers to the time a laser pulse takes to get to the Moon and back to Earth.

○ distance = (time/speed)/2

That's incorrect, try again.

○ distance = (speed × time)/2

This is correct because speed = distance/time. Multiplying both sides by time gives: distance = speed × time. Then speed × time is divided by 2 because the time obtained by shining the laser is the time for the light to go to the Moon and back to Earth, whereas all you want to know is the time for the light to reach the Moon.

○ distance = (speed/time)/2

That's incorrect, try again.

What is the speed of the laser light?

○ The speed of light

This is correct. Since a laser is simply a light source so laser light travels at the speed of light, independent of the frequency of the laser.

○ The speed of sound

That's incorrect, try again.

○ It is different depending on the laser

That's incorrect, try again.

What is the distance to the Moon?

○ ~770 000 km

That’s incorrect, try again.

○ ~260 000 km

That’s incorrect, try again.

○ ~390 000 km

This is correct. The speed of light is approximately 3 × 10⁸ m s^{−1} and the time taken for the light to go to and from the Moon is about 2.6 seconds. Using the equation given above, distance = (speed × time)/2, you get distance to the Moon ~390 000 km.

1.4 Inside the Moon

Experiments performed by Apollo astronauts on the Moon have shown that its internal structure is similar to that of the Earth. It has a crust, a mantle and a core but, unlike the Earth, has no magnetic field. This is because the Moon’s core is now solid (even an iron core cannot create a magnetic field if it is solid, it has to be molten and churning around so that it acts like a dynamo). The Earth’s crust is also very different because it is made up of plates that slowly form at mid-ocean ridges and collide to produce mountain chains, changing the crust at the surface of the Earth. The atmosphere and climate combined with plate tectonics lead to erosion of mountains, thus destroying evidence of meteorite impacts. The geological features seen on the Moon, however, are different because the crust does not move: there is no plate tectonics.

If you look at the Moon with the naked eye you can see pale highlands and some of the larger craters, as well as dark areas that are by convention called seas or maria (plural of mare). The lunar highlands are the Moon’s original crust, which has suffered many billions of years of bombardment, as explained in Week 2. The darker mare areas are large craters that later filled with extensive lava flows.

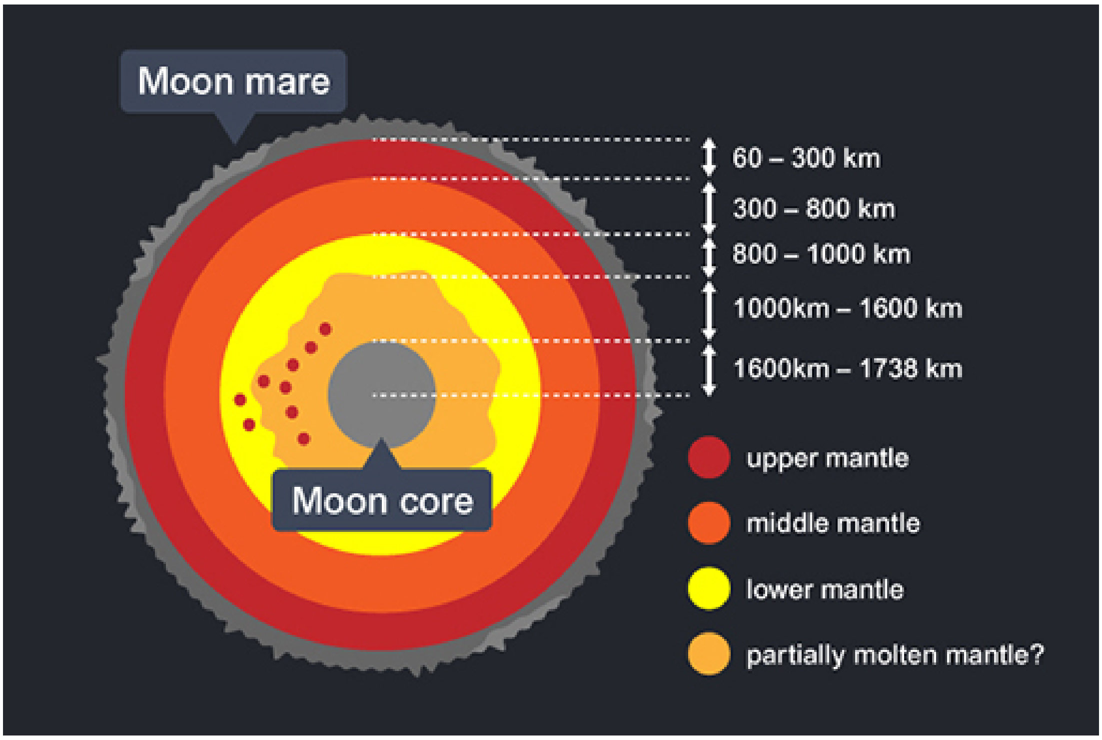

Figure 5 A speculative cross section of the Moon. Red dots indicate the locations of moonquakes recorded by Apollo experiments.

It used to be thought that the Moon lost its magnetic field about 3 billion years ago. However a new study of a Moon-rock dated at 1-2.5 billion years old shows that it formed in the presence of a magnetic field, suggesting that the Moon's core remained molten for up to 2 billion years longer than previously assumed.
When did the Moon's core become solid?.

1.5 Looking at the Moon

As mentioned in Week 1, we observe the same side of the Moon at all times due to synchronous rotation in which the Moon takes almost the same amount of time to complete one rotation on its axis as it does to complete one orbit around the Earth. If the orbit of the Moon was completely circular around the Earth, we would only see exactly half of the Moon. In fact, the orbit is not completely circular: it is elliptical. This causes the Moon to be closer to the Earth at some points in its orbit than at other points. Because the orbit is elliptical, the Moon's orbital speed is not the same all the way round. The result of the changing speed is that the Moon appears to wobble slightly during its orbit, a process known as libration. This libration allows us to see about 60% of the Moon's surface, as demonstrated in the animation.

Video content is not available in this format.

Please note this video has no spoken audio.

See also: Moon phases and libration. If you want to explore the Moon’s orbital relationship with the Earth more fully than in this video, you can find explanations and other videos at this link.

1.6 Going to the Moon

Later this week you’ll learn more about the Apollo missions and earlier missions to the Moon. Although Apollo 11 was the first mission to put humans on the Moon, it was not the first spacecraft to land. Two earlier Apollo missions had orbited without landing and several unmanned probes had landed. The Soviet Union had crash-landed a probe as early as 1959. On the American side, the Mercury (1961–63) and Gemini (1964–66) programmes confronted the problems that needed to be solved before a trip to the Moon could be launched.

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2 Race to the Moon

Learn about the space race, and one of the iconic moments in history when humankind first stood on the Moon. See what it was like to walk on the Moon and some experiments the astronauts undertook, like the ‘hammer and feather'.

Listen to the story of the Space Race, part of the Cold War, in which the two most powerful nations on Earth battled for supremacy in sending a manned mission to the Moon.

There was genuinely a race, starting with the earliest Soviet success, Sputnik, that orbited the Earth in 1957. Soviet dominance of the early Space Race in the late 1950s and early 1960s included launching the first man, Yuri Gagarin, into space in 1961. The USA reaction included establishing the National Aeronautics and Space Administration (NASA), and President Kennedy’s famous speech setting out the aim of landing a man on the Moon and returning him safely to Earth (and yes it was specifically a man) by the end of the decade.

The Space Race continued apace for the rest of the decade and even in the final few days, spacecraft from both nations were in the race to the Moon. Neil Armstrong and Buzz Aldrin fulfilled Kennedy’s promise and landed on the Moon on 20 July 1969. (The Soviet Luna 15, referred to near the end of the video, was an unmanned mission. It attempted to land on 21 July after completing 52 orbits of the Moon, but contact was lost 3 km before it reached the surface.)

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2.1 What’s it like on the Moon?

The environment of the Moon is very different from that of the Earth. The force of gravity is a lot less, and temperatures are extreme, varying between −153 °C at night and +123 °C in the day.

Gravity is an attractive force between all objects, but is only noticeable if at least one of the objects is significantly large. For two objects, the force of gravity exerted on one object is proportional to the mass of the other and inversely proportional to the square of the distance between the two objects. If you (one object) are standing on a planet or moon (the other, more massive object), this distance is the radius of the body. The Moon has a mass around one-eightieth the mass of the Earth. Combining this with the smaller radius of the Moon, the force of gravity on an object on the Moon’s surface is around one-sixth of the force of gravity on an object on the surface of the Earth.

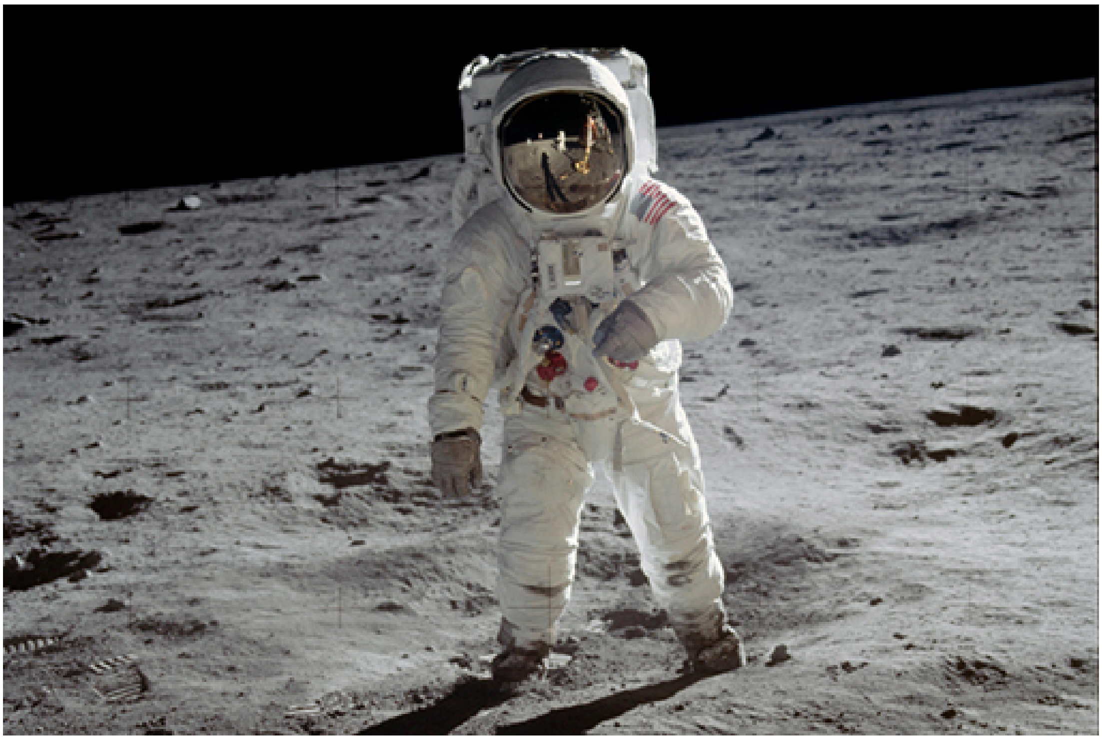

Figure 6 Buzz Aldrin on the Moon.

2.2 Weighing objects on the Moon

Figure 7 The hammer and feather experiment from the Apollo 15 mission.

Because the force of gravity experienced at the Moon's surface is around one sixth of the surface of the Earth, try to work out how much the following items would weigh on the Moon.

- A Yourself
- B A bag of flour (typically 1.5 kg)
- C The largest Moon rock returned to Earth (11.7 kg)
- D The spacesuit worn on the first Apollo missions (96.2 kg)

In each case your answer should be the weight on Earth divided by six. We don't know your weight on Earth, so we can't tell you the answer to A, but B a 1.5 kg bag of flour taken to the Moon would weigh 1.5 kg/6 = 0.25 kg, C the 11.7 kg rock would weigh 11.7 kg/6 = 1.95 kg, and D the spacesuit would weigh 96.2 kg/6 = 16.03 kg. (*Note*: we are well aware that in scientific usage kg is a measure of mass, not of weight. You should be too if you have studied science before. If you want to be strictly correct, 'Weight in kg on the Moon' should be taken to mean 'The mass in kg on Earth that would have the same weight (on Earth) as this mass does on the Moon'.)

If you want to take this further, find out what it would be like to play sports on the Moon by competing in the Moon Olympics.

2.3 Falling objects on the Moon

The force of gravity determines how long an object will take to fall to the ground. In the absence of air resistance, all objects will accelerate towards the ground at a rate denoted by g, which is measured in metres per second squared (m s^{-2}).

On Earth, g = 9.8 m s^{-2} but on the Moon g is only 1.6 m s^{-2}. Hence an object dropped from a given height will take longer to fall to the surface on the Moon than it would on the Earth.

This experiment on the Moon was a recreation of a legendary experiment performed by Galileo in 1589. He is supposed to have dropped two balls of different masses off the Leaning Tower of Pisa and demonstrated that they hit the ground at the same time because they were both subject to acceleration due to gravity, which is independent of mass. If you tried this experiment on Earth with say a hammer and feather, the hammer would hit the ground first because the feather would be slowed down more by air resistance. However, when the experiment was done on the Moon, the feather and the hammer both hit the ground at the same time because, in the absence of air resistance, all objects do in fact accelerate towards the ground at the same rate. As the Moon has virtually no atmosphere, there is virtually no air resistance. The lack of atmosphere is also responsible for the extreme temperatures on the Moon, whereas the atmosphere of the Earth acts like a blanket trapping heat. When the Sun sets on the Moon, the temperature drops very rapidly to −153 °C.

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2.4 Experiments on the Moon

The astronauts didn't just drop feathers and hammers; they also performed some more complex experiments. You have already learnt about the laser ranging reflectors. Some of the others are shown here.

Figure 8 is an active seismic experiment.

- Why? To determine the internal structure of the Moon.
- How? It was composed of three geophones that could detect movement from controlled explosions. The movement gave information about the Moon's internal structure.

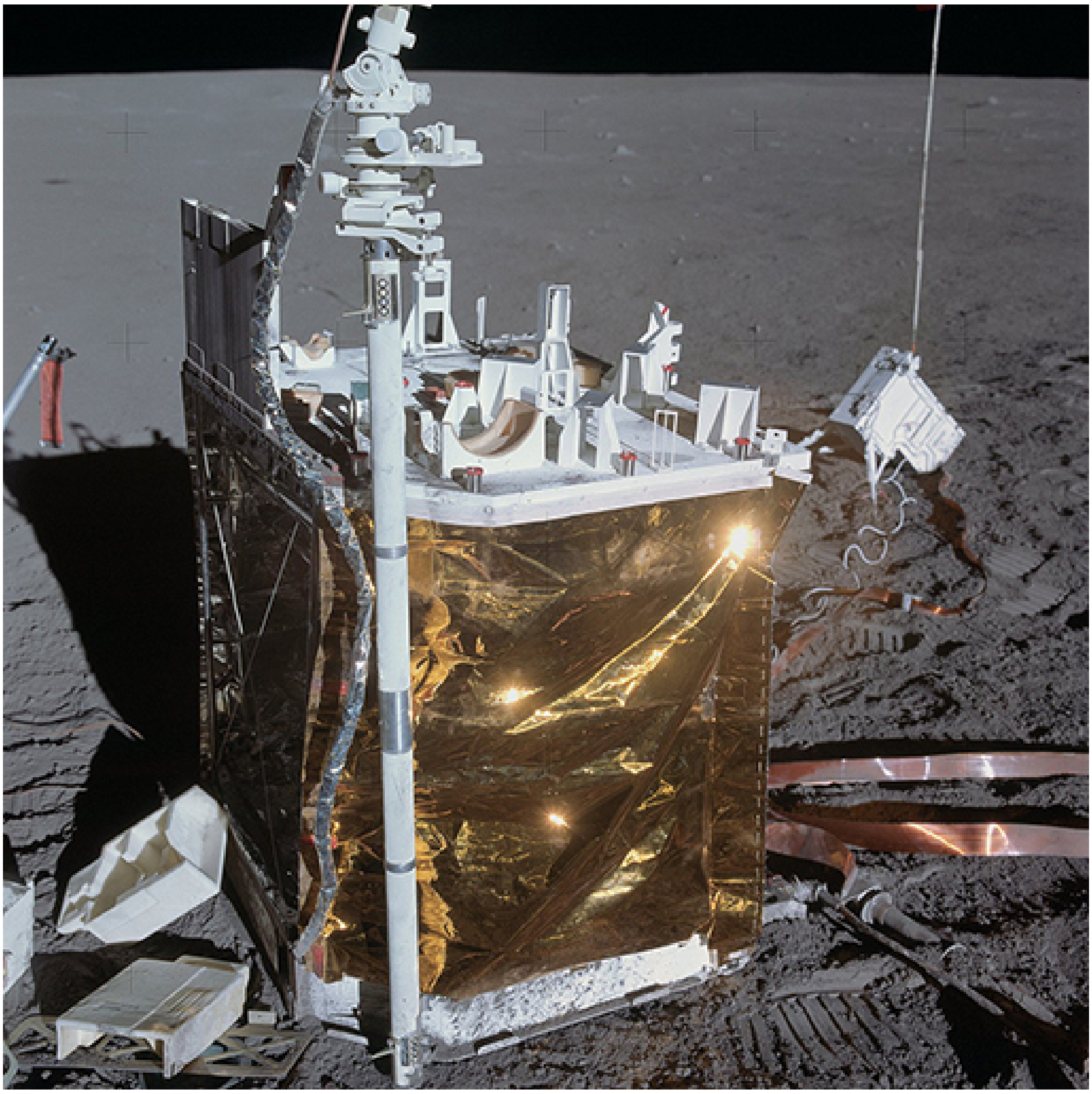

Figure 8 Active seismic experiment.

Figure 9 is a solar wind spectrometer experiment.

- Why? To study solar winds and their effects on the Moon's environment.
- How? Solar wind is composed of electrically charged particles from the Sun. A sheet of aluminium or platinum foil was placed on the Moon for a number of hours to collect the solar wind particles. The foil was brought back to Earth for analysis.

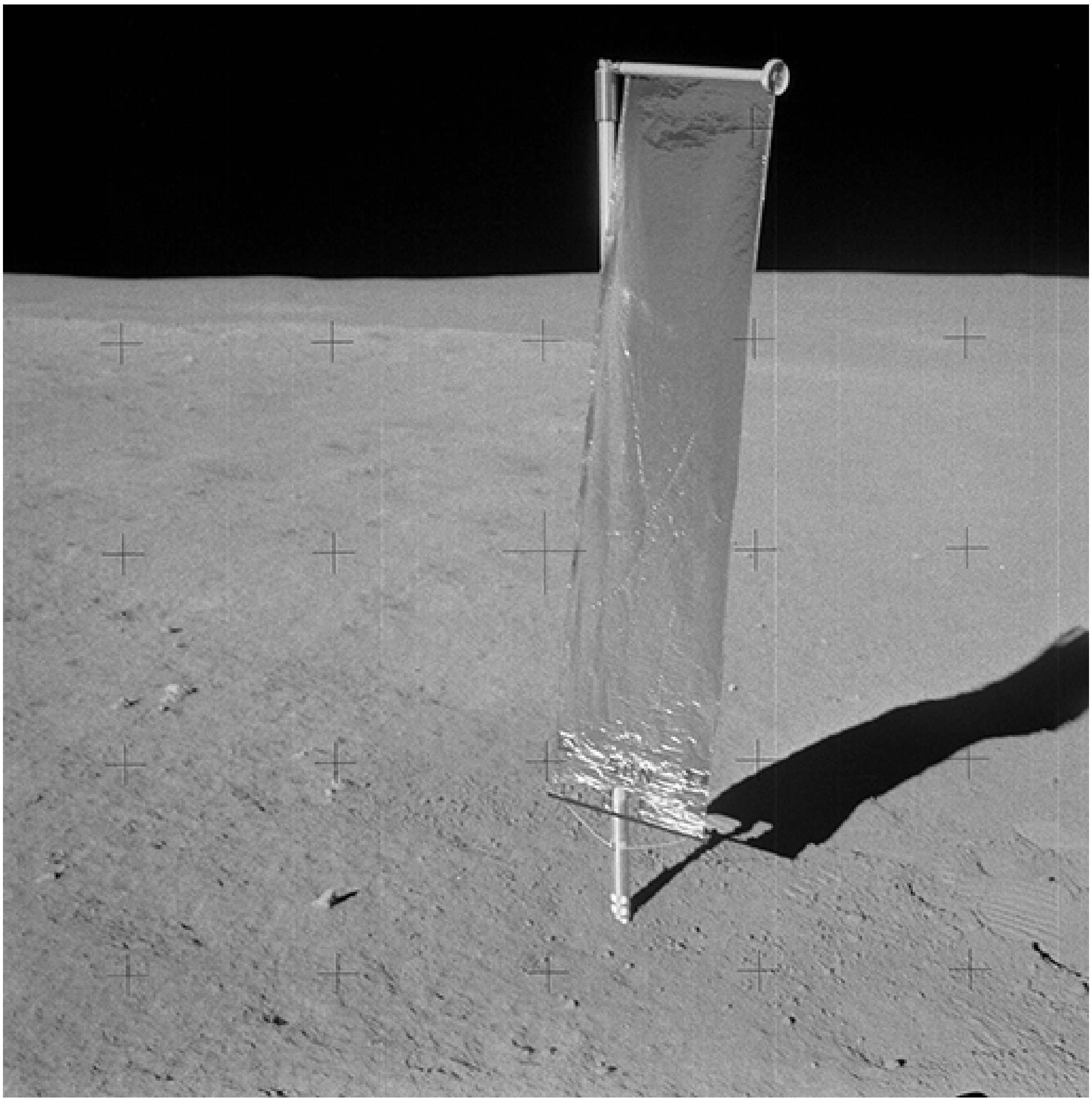

Figure 9 Solar wind spectrometer experiment.

Figure 10 is a lunar surface gravimeter.

- Why? To measure the gravity on the surface of the Moon precisely.
- How? A sensitive spring balance. Reliable data could not be collected because of a design error.

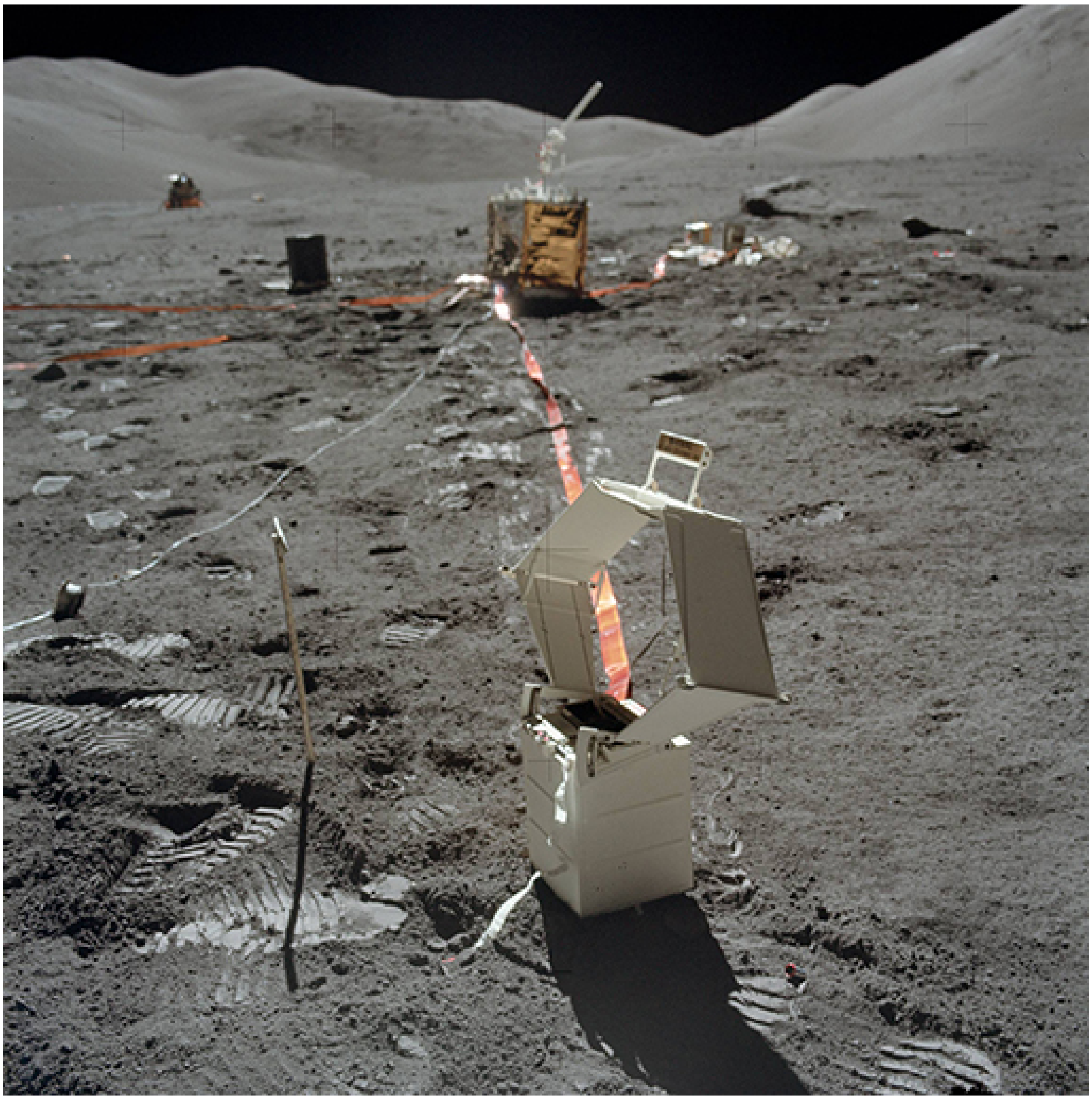

Figure 10 Lunar surface gravimeter.

Figure 11 is a lunar ejecta and meteorites experiment.

- Why? To study dust ejected from the surface due to meteorite impacts and to study micrometeorites.
- How? Three sensors detected the movement of small particles from the east, from the west and from above. Large numbers of particles were seen each lunar morning, but the experiment would overheat a few hours after each lunar sunrise.

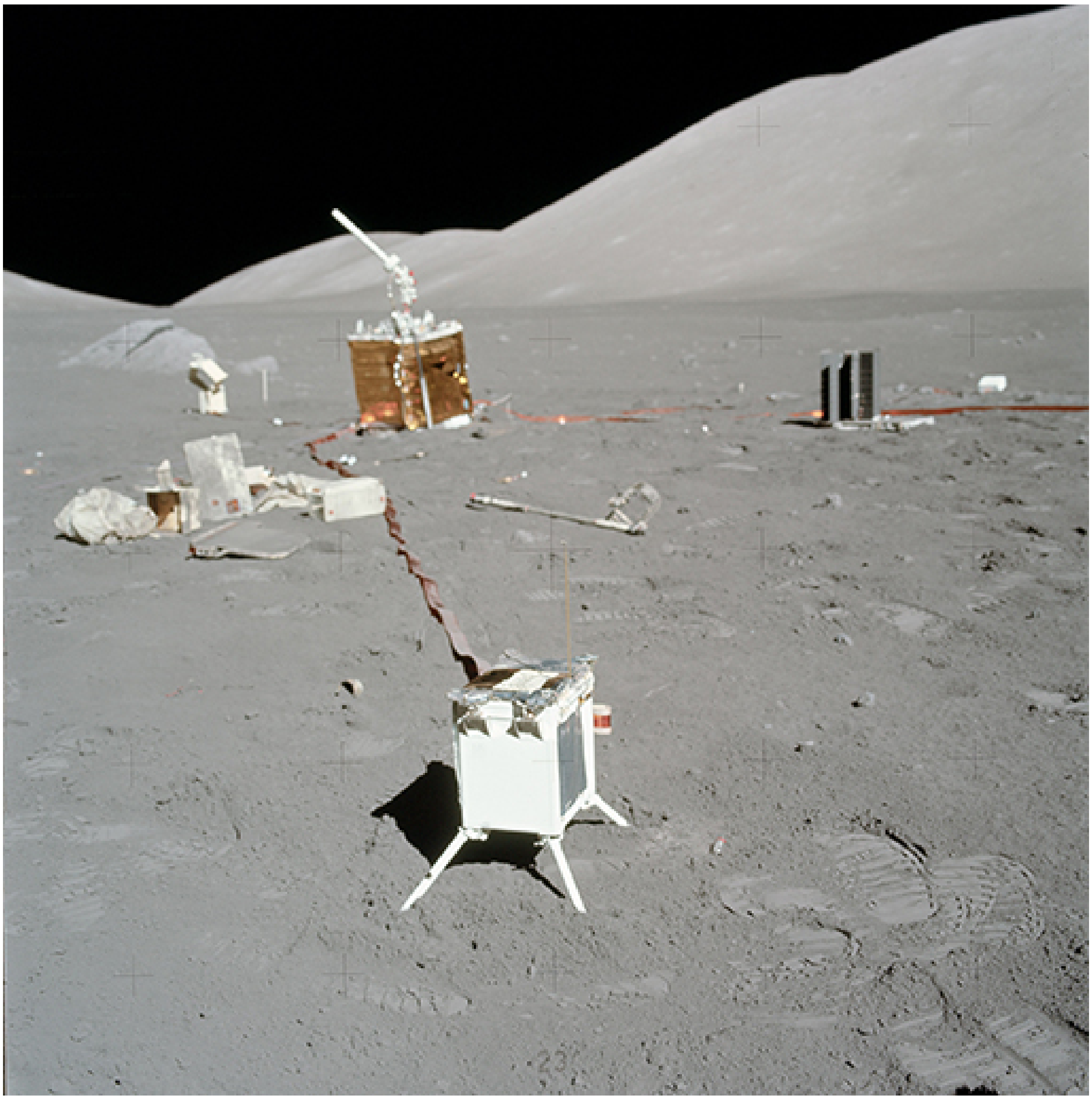

Figure 11 Lunar ejecta and meteorites experiment.

Figure 12 is a cold cathode ion gauge.

- Why? To measure the tiny pressure of the Moon's atmosphere.
- How? Typically used for very low-pressure measurements, a cold cathode ion gauge traps electrons which are used to ionise any atoms or molecules present. These ions travel to the cathode and create a current.

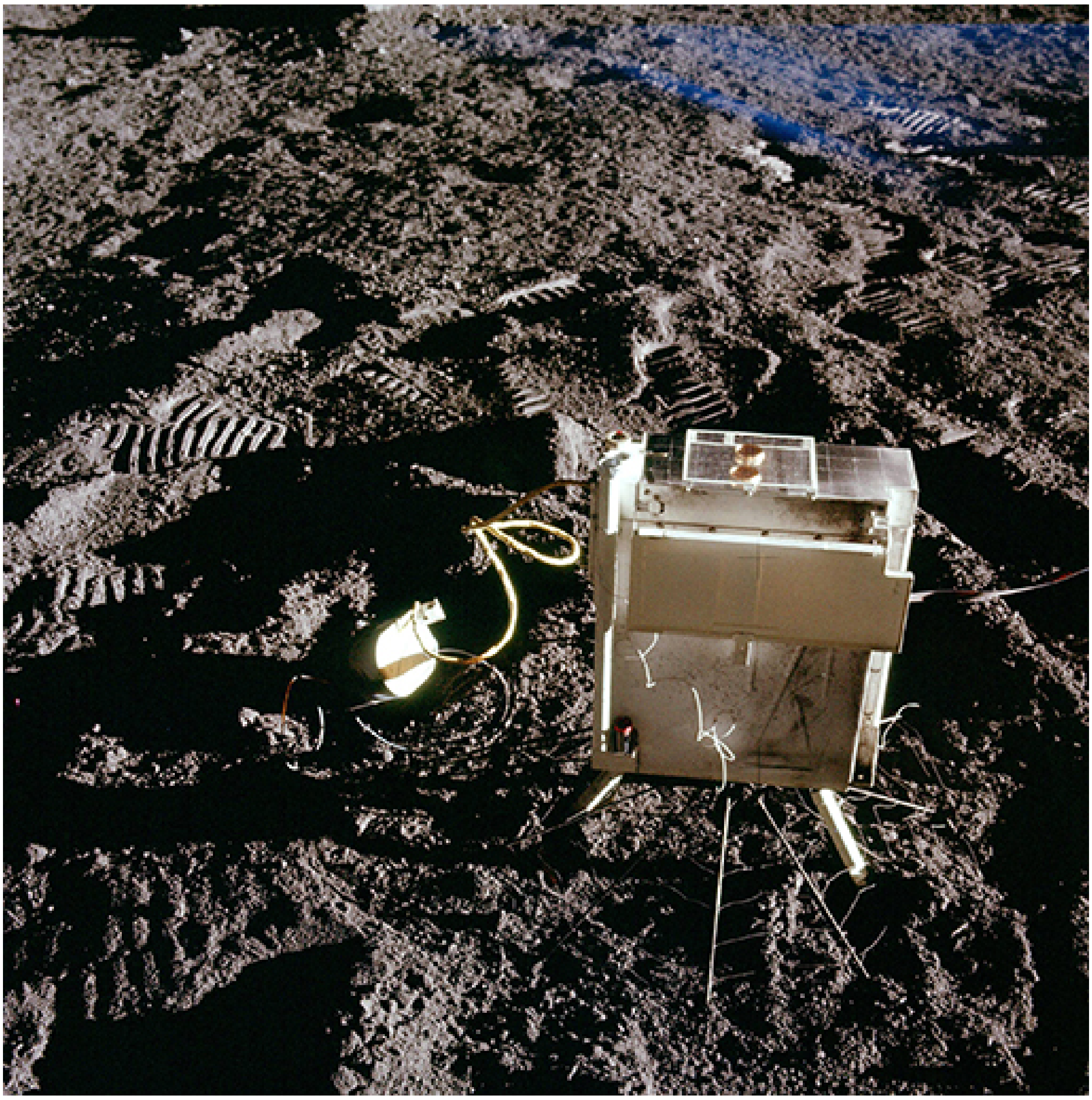

Figure 12 Cold cathode ion gauge.

See also: Apollo 16 third-stage crash site identified. The crater made when the 3rd stage of the Apollo 16 rocket was deliberately crashed into the lunar surface at 2.6 km per second in 1972 has recently been found on high resolution images from orbit. The impact acted as a source of seismic waves to probe the Moon's interior with the aid of seismometers placed on the surface by earlier Apollo missions.

2.5 Where next?

All six manned missions that landed on the Moon returned safely to Earth, having explored the Moon, conducted experiments and achieved a significant milestone in history. Later, you will see how the astronauts returned to Earth and what they brought back with them.

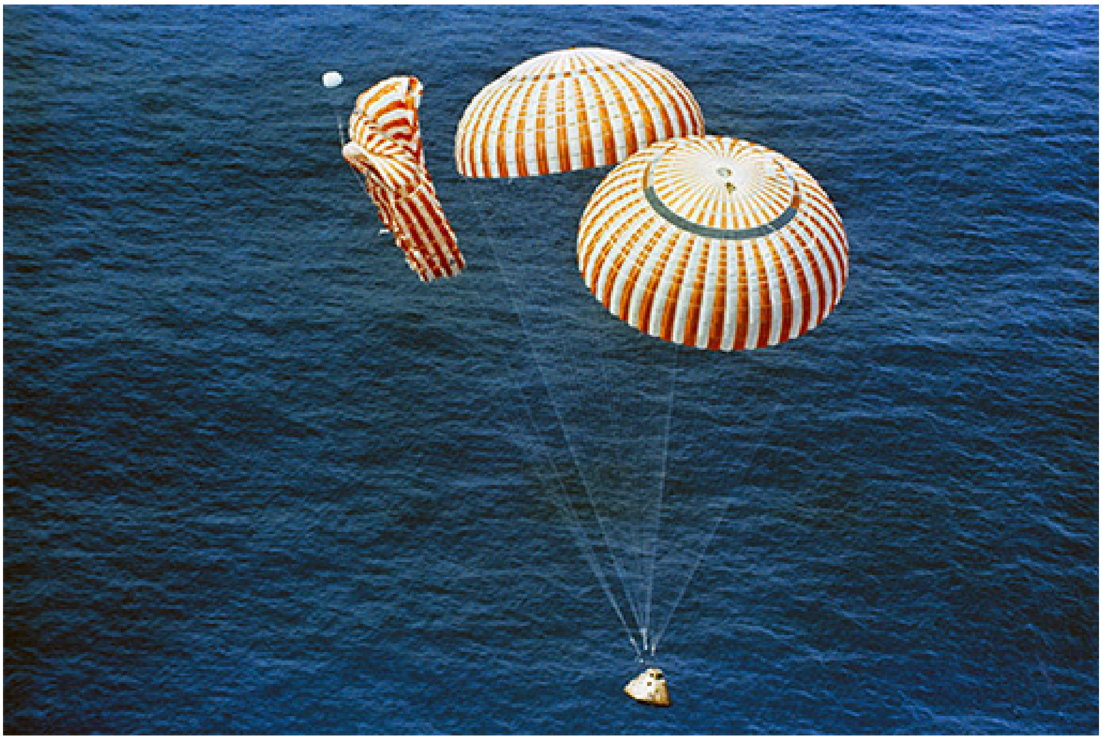

Figure 13 Apollo 15 splashdown.

To find out more about the Apollo Moon landings, visit Google Moon.

3 Departure from the Moon

The astronauts really did risk their lives, as Apollo 13 demonstrated, but they successfully landed and returned six times. Moon rock amounting to 382 kg was returned to Earth and stored in special conditions for scientific study.

The video shows the view from the window of Apollo 14 as it departed the Moon on 6 February 1971. Sadly there is no footage from when Apollo 11 did the same in 1969.

By landing humans on the surface of the Moon, NASA had achieved its main goal, set out by President John F. Kennedy in 1961. Proving that manned space exploration was technologically possible, the Apollo astronauts went on to conduct scientific experiments on the Moon, giving the world an important first insight into the Moon's internal structure, gravity and other physical properties. Media coverage of these historic achievements inspired people watching back on Earth, all across the globe. But despite all of this, the Apollo programme could only be considered a true success if it ended with the safe return of these astronaut explorers to Earth. Successful completion of the mission was not certain and several different disasters were envisaged that might have resulted in Neil Armstrong and Edwin 'Buzz' Aldrin being marooned on the lunar surface; there was even a speech written for such an event. Later in the Apollo programme there was a brush with disaster, but not on the lunar surface.

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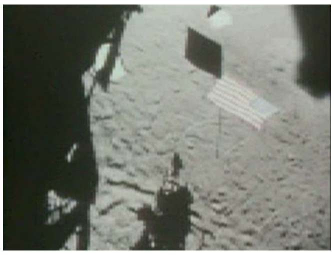

3.1 Re-entry

As you saw earlier, objects such as hammers and feathers fall to Earth at different rates. The reason for the difference in rates of fall is air resistance. An additional factor is that because falling objects experience air resistance, then if they are travelling fast enough, they can heat up noticeably.

The Apollo command modules re-entered the atmosphere at more than 11 000 m s^{-1}. During re-entry, the shock compression of the air in front of the spacecraft moving at such high speeds generated a great amount of heat (sometimes mis-described as 'frictional heating'), with the outside surface reaching temperatures of up to 2800 °C. It took specially designed heat shielding to protect the astronauts inside from this inferno until they reached the lower part of the atmosphere where the command module's huge parachutes were deployed.

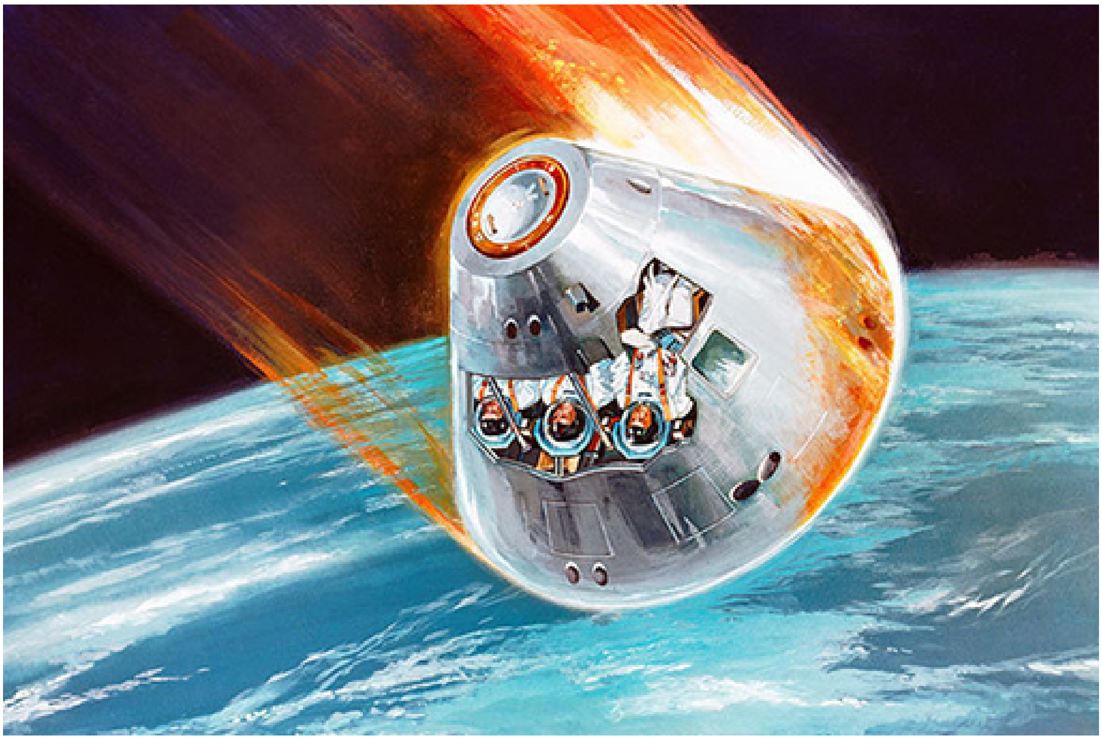

Figure 14 Artist’s impression of the Apollo command module’s atmospheric re-entry (1968)

3.2 Apollo 13

The third manned mission that was intended to land on the Moon was Apollo 13, launched on 11 April 1970. While still on their way to the Moon, about 300 000 km from Earth and almost 56 hours into their mission, the crew heard an explosion coming from one of the oxygen tanks inside the service module. This prompted one of the most famous Apollo quotations, uttered by astronaut Jack Swigert: ‘Houston, we’ve had a problem here’.

The fuel cells which powered the spacecraft needed oxygen to combine with hydrogen to generate electricity and water; with the ruptured oxygen tank losing its contents to the vacuum of space, the main power supply to the command module soon ran out, leaving only the limited-supply back-up batteries to provide power. The crew were forced to shut down the main command module and instead rely on the lunar module, which was able to act like a lifeboat.

With the planned Moon landing now out of the question and the spacecraft rapidly approaching lunar orbit, the crew and mission controllers back on Earth faced a stark choice: either opt for a direct return to Earth, which would mean jettisoning the crew’s only source of life-supporting resources – the lunar module; or try to use the Moon’s gravity to ‘fling’ the damaged spacecraft back towards Earth. Although it would mean travelling further away from Earth first, passing behind the Moon, the latter option was chosen.

With dwindling oxygen supplies and reduced power, which left the inside of the spacecraft at a chilly 4 °C for the duration of the return flight, Apollo 13 limped back to Earth, safely splashing down in the Pacific Ocean on 17 April 1970.

As the crew had proved, returning to Earth could be a perilous experience.

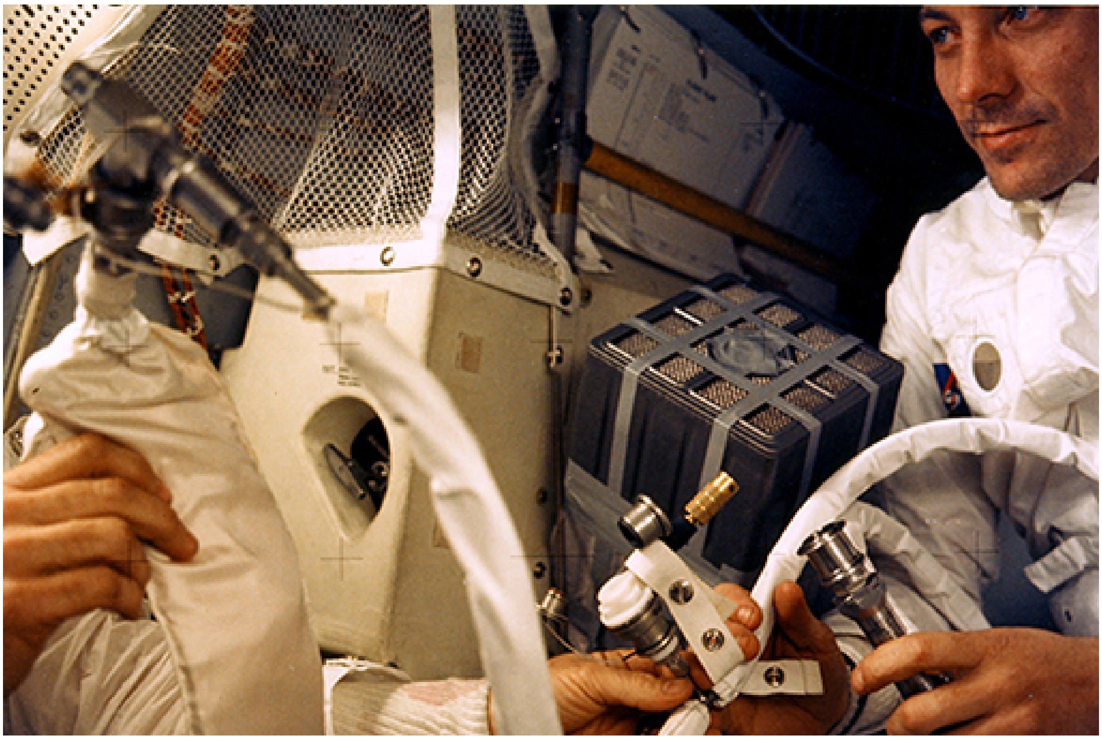

Figure 15 View of Apollo 13 astronauts changing one of the modified LiOH cannisters.

See also: Apollo 13: Houston, We've Got a Problem. This film depicts attempts to return the crewmen of the Apollo 13 mission safely to earth following an explosion onboard the service module. The film emphasises the Mission Control and spacecraft teamwork that overcame the life-or-death problems of Apollo 13, as well as the worldwide reaction to the crisis. Listen out for the famous quotation by Jack Swigert at 4:43 into the video. Warning: this video is 150mb in size. For this reason, we recommend that you access the link over a WiFi connection rather than a 3G or 4G connection, which could prove costly depending on your mobile data tariff.

3.3 Bringing Moon samples to Earth

But it wasn't just astronauts that NASA brought safely back to Earth. The six Apollo missions brought back a total of 382 kg of Moon rocks and fine dust (regolith) from the lunar surface, which is roughly equivalent to five extra astronauts.

Three unmanned Soviet Luna missions (Luna 16, 20 and 24) also brought back a total of 0.326 kg of lunar regolith samples. By comparison, one of the largest rocks collected by Apollo astronauts was sample 15555, from the Apollo 15 mission; this single sample had a mass of 9.614 kg, about 30 times the total mass of all the Soviet Moon samples put together.

Video content is not available in this format.

3.4 Why bother bringing rocks back to Earth?

The Apollo astronauts collectively spent a total of 12.5 days on the lunar surface, during which time they were able to set up and conduct some quick, basic experiments to explore the lunar environment.

However, to answer some of the bigger questions about the Moon, such as what it is made of, how old it is and how it formed required much more time and access to large specialist laboratory machines that could not be flown to the Moon with the astronauts. Also, while the Apollo crew members had received some geological training before their missions, they were originally test pilots by profession and only one was a fully-trained geologist (Harrison 'Jack' Schmitt on Apollo 17). Therefore, if the scientists couldn't go to the Moon, pieces of the Moon had to be brought to the scientists.

Figure 16 A lunar rock in the lab at Houston.

Another important reason for returning samples to Earth was the understanding that techniques for studying rocks are always improving over time and there is no way of knowing what may be possible in the future. So, bringing back samples and storing them for posterity, while waiting for new, better techniques has meant that those six missions that ended over 40 years ago are still yielding cutting-edge scientific data, and are even now transforming ideas about how the Solar System formed.

Figure 17 Collecting lunar samples.

The returned Moon rocks are not only a wonderful scientific legacy of humankind's first steps into exploring other worlds; they also form a political and cultural legacy, with 'goodwill' samples being sent to many countries around the world and placed on display in national museums for the global public to see. In the UK there are three institutions that house and display Moon rocks (in London, Leicester and Cardiff), where they serve to inspire new generations to explore beyond our home planet.

See also: 2014 Masursky Lecture by Cmdr David Scott. If you can spare 40 minutes, this excellent and entertaining lecture by David Scott of Apollo 15, given in Houston in March 2014, is well worth it.

3.5 Handling pieces of the Moon

As the only extraterrestrial rocks to be deliberately brought to Earth, great care was taken when packaging the samples before they left the Moon. Samples were placed into separate, individually labelled bags and then packaged in batches into larger sample boxes for the return journey to Earth.

To protect them from coming into contact with any terrestrial atmospheric gases, some samples were placed inside specially designed, airtight containers (named SESC, or Special Environmental Sample Containers). These were then opened inside vacuum chambers in the newly established Lunar Receiving Laboratory, at the Lyndon B. Johnson Space Center in Houston, Texas.

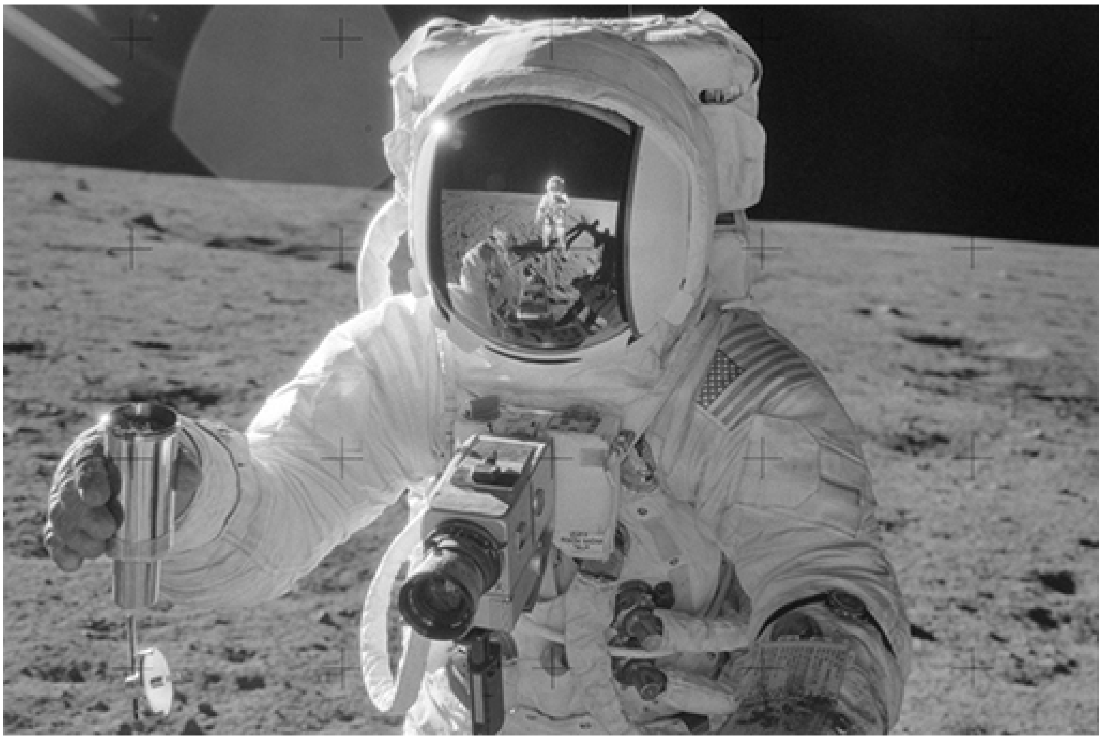

Figure 18 Apollo 12 Special Environmental Sample Container, containing lunar regolith (lunar 'soil') held by astronaut Alan Bean.

3.6 Storage on Earth

Another reason behind the careful return and handling of the lunar samples was the fear that the Moon rocks might be carrying potentially harmful contaminants back to Earth and so the Lunar Receiving Laboratory was both a sample handling and a quarantine facility. Apollo 11, 12 and 14 astronauts were also quarantined for several weeks after their return to Earth, although this rule was later dropped when it became apparent that there was no threat of back-contamination of the Earth from any lunar microbes.

Today, most lunar samples (apart from those given out as goodwill samples, those on display around the world and those currently being used for research) are stored, prepared and curated in the purpose-built Lunar Sample Laboratory Facility at the Johnson Space Center in Houston.

Although these samples have been extensively studied in the decades since they were brought back to Earth, scientists return their allocated Moon material to this facility, ensuring that precious material is not lost over the years. In addition, several containers have never been opened and they remain in their original pristine lunar condition for use in the distant future.

Figure 19 Apollo 14 samples being processed in glovebox protective chambers at the Lunar Receiving Laboratory.

4 This week's quiz

Now it's time to complete the Week 4 badge quiz. It is similar to previous quizzes, but this time instead of answering 5 questions there will be 15.

Remember, this quiz counts towards your badge. If you're not successful the first time, you can attempt the quiz again in 24 hours.

Complete the Week 4 badge quiz now.

Open the quiz in a new window or tab then come back here when you're done.

5 Summary

This week you considered the cultural references to the Moon, from music, art and literature. You also learned basic facts about the Moon and how to calculate the distance from Earth to the Moon. Next week looks at missions to the Moon and the investigations which took place there.

You should now be able to:

- recognise the many cultural references to the Moon, from music to art and literature
- understand more facts about the Moon
- calculate the distance to the Moon.

You are now half way through the course. The Open University would really appreciate your feedback and suggestions for future improvement in our optional end-of-course survey, which you will also have an opportunity to complete at the end of Week 8. Participation will be completely confidential and we will not pass on your details to others.

You can now go to Week 5: What we learned from the Moon.

Week 5: What we learned from the Moon

Introduction

Rocks are the key evidence for the Moon's story. The meteorite-battered lunar highland rocks are more ancient than anything on Earth, and the ancient volcanoes on the Moon are better preserved than many modern volcanoes on Earth.

Jess introduces the week, which continues the story of the Moon and lets you get up close to Moon rocks using The Open University's virtual microscope.

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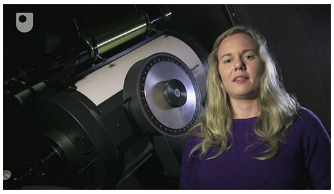

By the end of this week, you should be able to:

- understand the significance of the Apollo 11 and Apollo 17 missions to the Moon, and what was investigated there
- consider what Moon dust and rocks brought back to the Earth tell us about the Moon.

1 What we've learned about the Moon

Dave Vaniman reflects on his experience of seeing rocks brought back from the Moon, the importance of the interaction with the Moon for the history of life on Earth and what we've learned about the Moon.

Last week you learned about the unique characteristics of the surface of our Moon and its exploration by Apollo astronauts. Now you will look in more detail at the rocks on the Moon's surface and what they can tell us about the formation of the Moon.

It may surprise you to learn that the Moon rocks returned by the Apollo missions are still being analysed today. Unlike rocks on Earth, these samples have not been subjected to terrestrial alteration caused by water (on Earth, even in the desert, rocks on the surface become altered in a few years); neither have they been subjected to contamination by soils and windblown dust. The sophisticated analytical techniques of today allow us to find out more about these amazing samples than we could when they were first returned to Earth and one particularly exciting discovery (water) will be explored next week. This week, you will be introduced to the geology of the lunar surface and the rock types returned by the Apollo missions. You will also be introduced to how planetary scientists examine rocks under the microscope and how these are dated, in order to piece together the structure and formation of the Moon.

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1.1 An ocean of magma

In Week 1 you learned that the giant impact hypothesis is the most commonly accepted model for the formation of our Moon (although there are challenges). The impact of a body about the size of Mars into the Earth soon after the formation of the Solar System ejected melted and vaporised material into orbit, which accreted to form small bodies. These smaller bodies gradually combined to form our Moon. The hypothesis predicts that huge amounts of heat generated by this accretion process resulted in the whole surface of the Moon becoming molten at one time and forming one enormous magma ocean (the 'melt' referred to below) on the young Moon.

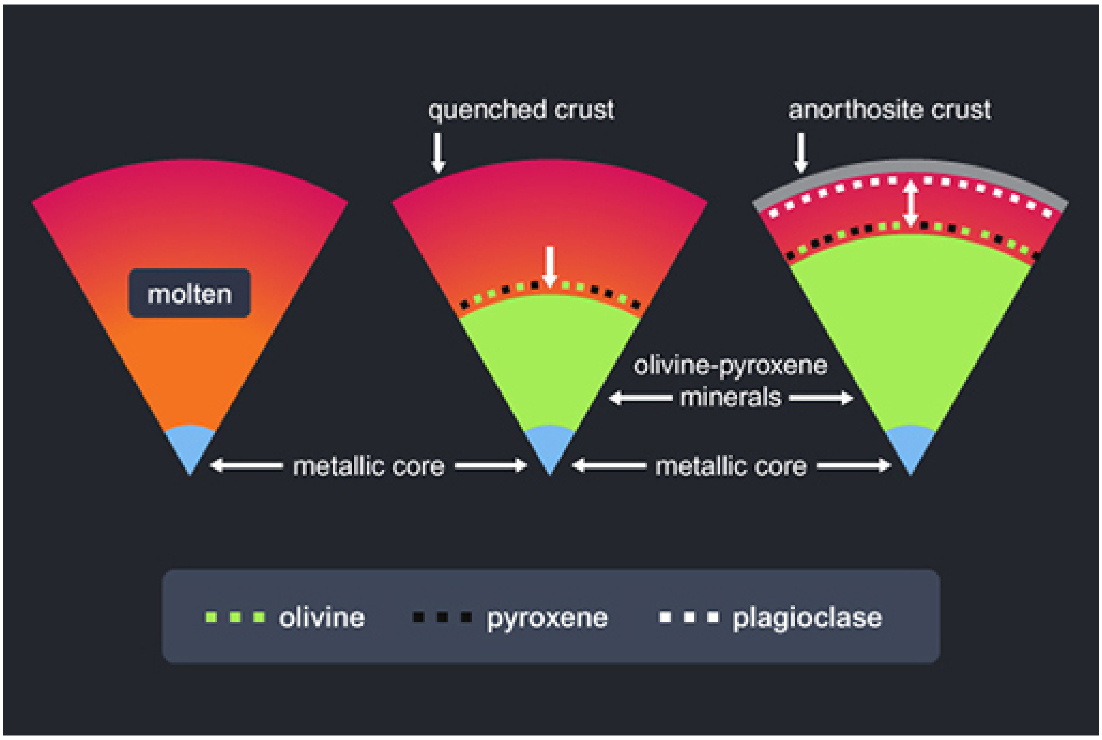

Figure 1 Differentiation and fractional crystallisation result in layers of different composition. That's why the lunar highlands on our Moon are rich in plagioclase.

In this scenario, iron and nickel quickly separated from the melt and sank to form a small dense metallic core (left-hand image) and a temporary crust formed on the surface as a result of quenching, i.e. rapid surface cooling (middle image). In time, the magma ocean cooled and minerals began to crystallise. During this process, which probably happened over millions of years, dense minerals sank in the magma ocean and less dense minerals floated upwards to grow a chemically-distinct crust. This density differentiation produced a core, mantle and crust of different compositions: the core (iron rich), the mantle (olivine and pyroxene minerals) and the crust (plagioclase feldspars such as anorthosite – right-hand image). This geochemical and physical process that results in mineral separation is known as fractional crystallisation. The same process occurs on Earth in large magma chambers (located within the crust) and beneath the mid-ocean ridges.

Evidence to support this hypothesis for the formation of the structure of the Moon has come from rocks brought back to Earth by Apollo astronauts and from lunar orbiting spacecraft – for example, the Japanese SELENE mission.

1.2 The Genesis Rock – a key find

The Genesis Rock was the first sample of early crustal material to be found on the Moon. It is an anorthosite, a rock composed almost entirely of the mineral anorthite, a type of plagioclase feldspar. As you saw in the previous step, anorthosite was predicted to have collected at the top of the magma ocean (low density), so its discovery was very significant in supporting the magma ocean hypothesis; it represents early crustal material that floated to the surface. We now know that the lunar highlands are mostly anorthositic in composition.

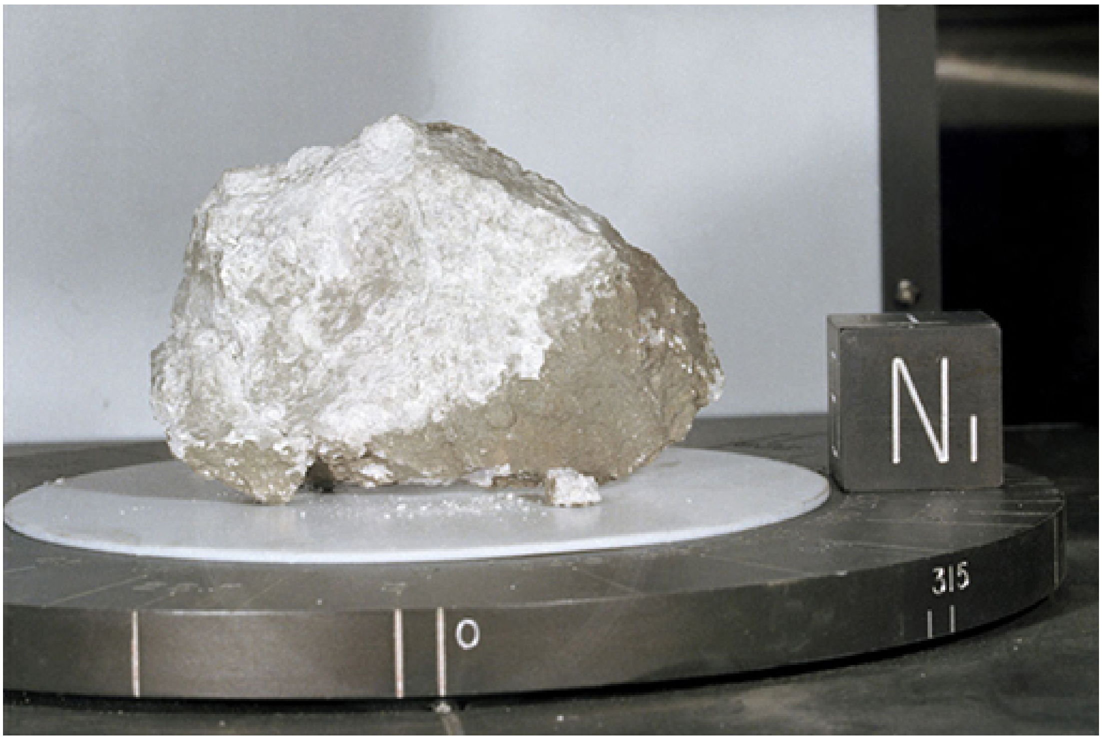

Figure 2 The plagioclase rich Genesis Rock: a key find.

1.3 The Genesis Rock – how it was found

The Genesis Rock was found by astronauts James Irwin and David Scott of Apollo 15. These two astronauts knew the significance of what they had found: it was the first sample of the early lunar crust. Watch the video from the *Apollo Lunar Surface Journal* website, showing the discovery of anorthosite by the Apollo 15 astronauts. The other voice is Joseph Allen, the Capsule Communicator back in Houston. As some of the dialogue in this video is indistinct, you may wish to read the transcript below.

Video content is not available in this format.

Next, about those golf balls …

1.4 Anyone for golf?

Discoveries and experiments on the Moon weren't all serious. On the Apollo 14 mission, as you see here, Alan Shepard demonstrated how far a golf ball can travel on the Moon.

Video content is not available in this format.

1.5 Lunar mantle fragments at the surface

The SELENE mission was a Japanese lunar orbiter, launched 14 September 2007. The scientific objectives included obtaining information about the chemical composition of the lunar surface and studying the formation and geological evolution of the Moon. You will learn more about the SELENE mission next week.

The spacecraft measured the reflectance spectra of the lunar surface over a broad range of wavelengths and with a spatial resolution of around 500 m, in order to map the global distribution of the mineral olivine. The magma ocean hypothesis predicts that the mineral olivine should dominate the upper mantle and therefore should not be common in the lunar highlands. However, 34 olivine-rich sites were identified and all were concentrated around large impact basins located in thinner parts of the lunar crust. The presence of olivine is believed to be a result of exhumation of upper mantle material during large impacts, suggesting that olivine does occur in the upper mantle. No olivine was found in the thicker highlands crust.

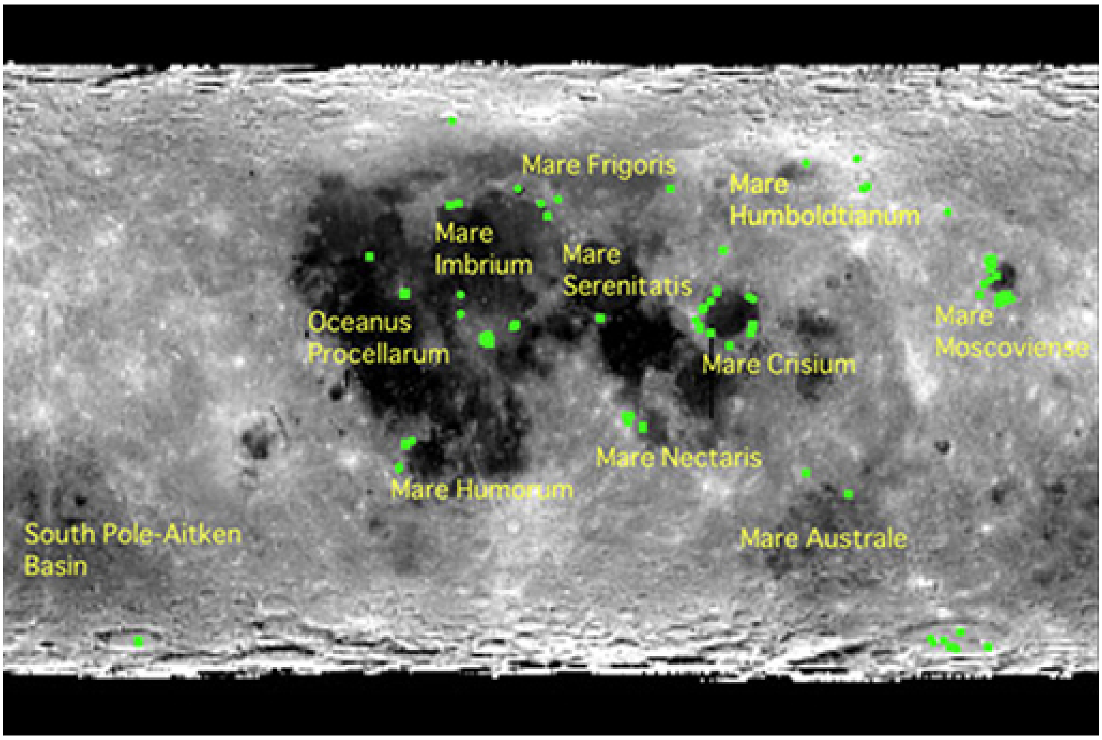

Figure 3 An image of the lunar surface showing the sites where mantle olivine was detected. The high olivine sites are marked in green.

Activity 1 Test your knowledge on the structure of the Moon

Allow approximately 15 minutes.

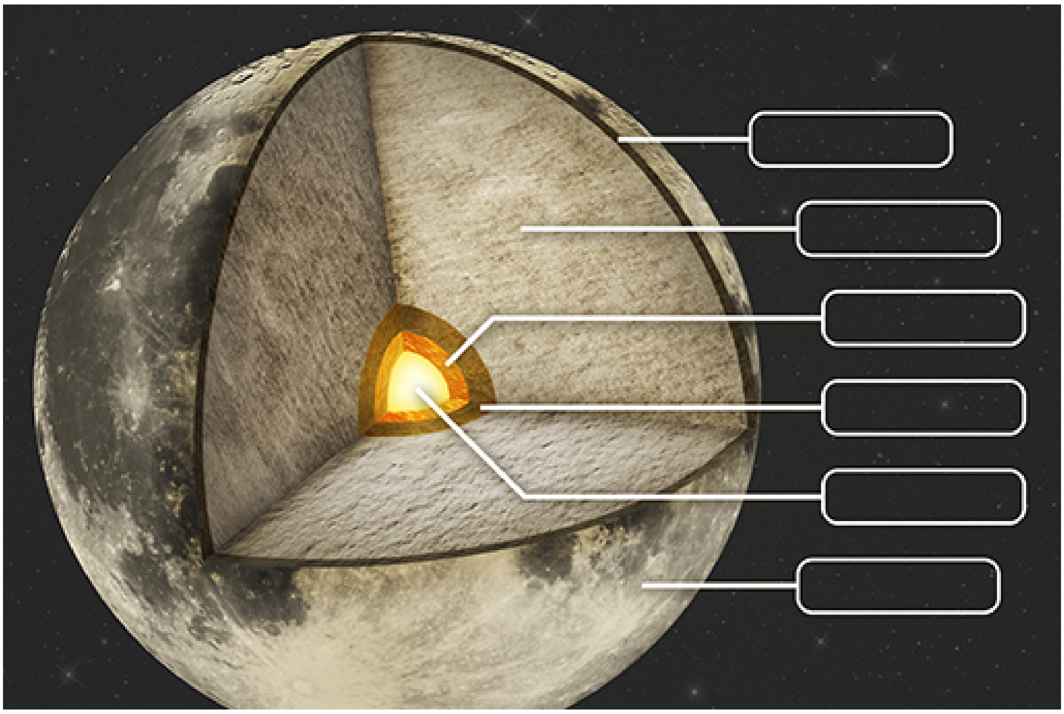

Figure 4 The Moon's interior.

Try to work out which layer each empty label refers to.

When you're ready, select 'Reveal answer' to see a fully labelled version.

Choose from these options:

- inner core
- outer core
- mantle
- lunar surface
- partial melt
- crust.

Answer

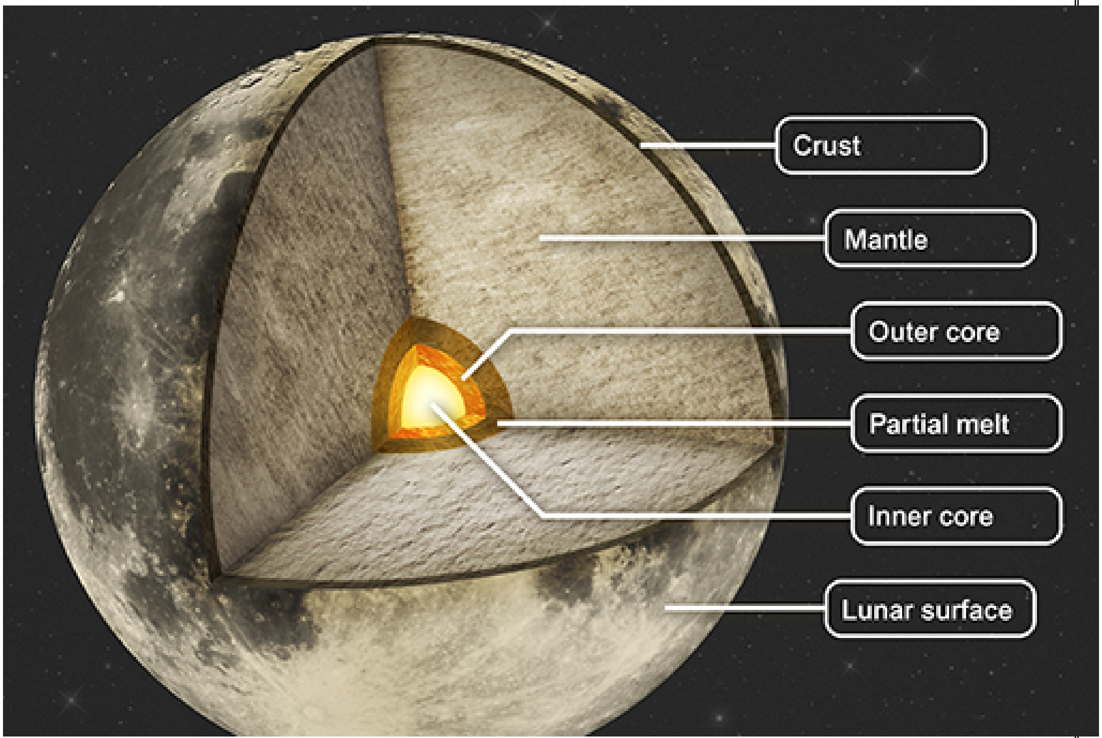

Figure 5 The Moon's interior, with labels.

See also:

- Chang'e 4 landing The China National Space Agency landed its Chang'e 4 probe on the far side of the Moon on 3 Jan 2019. This is the first ever far side landing. The landing site is in the South Pole Aitken basin, and there is a chance that Chang'e 4's rover (Yutu 2) may find fragments of mantle. Read David Rothery's article here.
- Misleading red colour in the first Chang'e 4 images A demonstration of why the early colour images from Chang'e 4 showed the lunar surface looking too red (later images from the science cameras were correct).

1.6 Rocks that form the Moon's surface

When you look at the Moon on a clear night with the naked eye, you can see colour variations. The overall pattern that they make is sometimes called 'the man in the Moon' because some people think they see a face. The lighter areas are the highlands and the darker areas are maria (mare is the singular form).

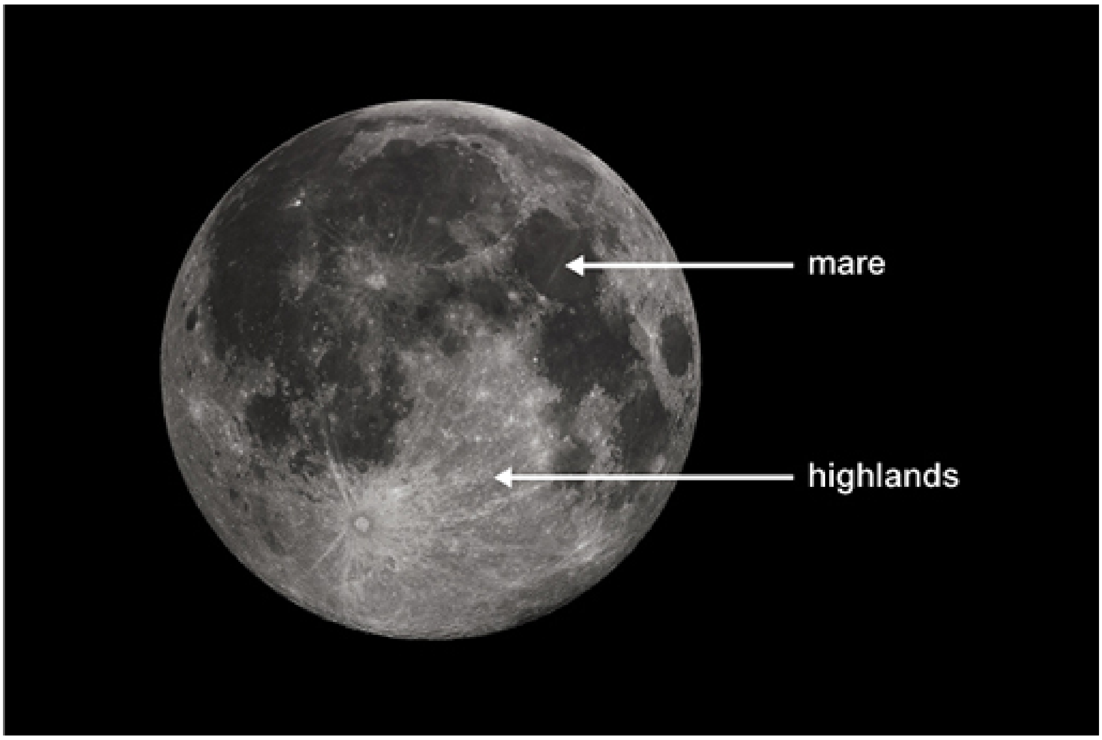

Figure 6 Two different regions of the near side of the Moon.

The lunar highlands represent the original lunar crust, as seen in the previous step. The oldest highland rocks are more than 4.15 billion years old and sometimes as old as 4.4 billion years, which is older than any rock found on Earth. They are mainly anorthosite, but also include dunite and gabbro with increasing depth. These are the oldest rocks on the Moon and are evidence for a magma ocean, as discussed earlier.

In contrast, the maria are basins filled in with basalt and were formed mostly between roughly 3.0 and 3.5 billion years ago. However, there are some small patches that are thought to be as young as around 1.0 billion years. The mare basalts are secondary to the Moon's formation, in the sense that they did not form from the magma ocean stage like anorthosite, but by later heating and melting of the mantle in the same way that volcanoes are formed on Earth.

Two other types of deposit are found on the surface of the Moon:

- regolith: the crushed remains of other rock types that coat much of the surface
- breccia: a rock formed of regolith that has been welded together at high temperature and pressure.

Regolith is the mixture of dust, mineral fragments and rock fragments that lies on the surface. Breccia is formed by the fragmentation and re-welding that occurs as a result of impacts onto hit the Moon.

The Moon has no atmosphere, so even the smallest meteorites just millimetres across reach the surface and form craters. (Such meteorites are called micrometeorites.) Some of the Moon rocks returned to Earth by the Apollo astronauts have small pock marks formed when tiny particles hit them. Each is filled by a thin layer of rock that melted in the impact and then re-solidified.

1.7 Mare basalt formation

The mare basalts were formed by volcanic eruptions on the Moon, extruding low-viscosity basaltic lava which flowed to fill basins and craters. The lava flows are hundreds of metres thick and similar to basalt lava flows on Earth on Hawaii and Tenerife.

Figure 7 An active basalt lava flow in Hawaii.

The lava was generated by melting deep within the Moon's mantle. The heat source was radioactive decay of elements such as uranium, thorium and potassium. Lunar basalts have similar features to those found on Earth. The low-viscosity basaltic lava produces domes, made up of successive layers of lava flows. Lava channels, known as rilles, can also be observed on the Moon.

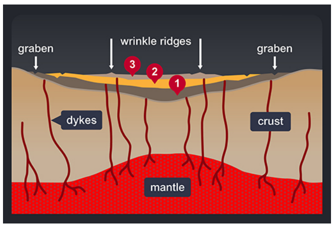

Figure 8 Sagging of a basin, causing structures known as graben to form around the rim.

As mare basalt layers accumulated in the basins, the weight caused subsidence of the basin floor (successive lavas are labelled 1, 2 and 3 in the image). In turn the subsidence meant that later basalts tended to flow inwards, filling low-lying areas such as large impact crater scars. Two tectonic features accompany mare basalt fields. First, there are wrinkle ridges which form in areas of compression, often in the centre of basins where the surface buckles around features beneath the lavas, such as old impact craters. Second, there are grabens, which are areas of extension where the surface pulled apart along faults, creating parallel-sided valleys; these are more commonly formed at the edges of basins.

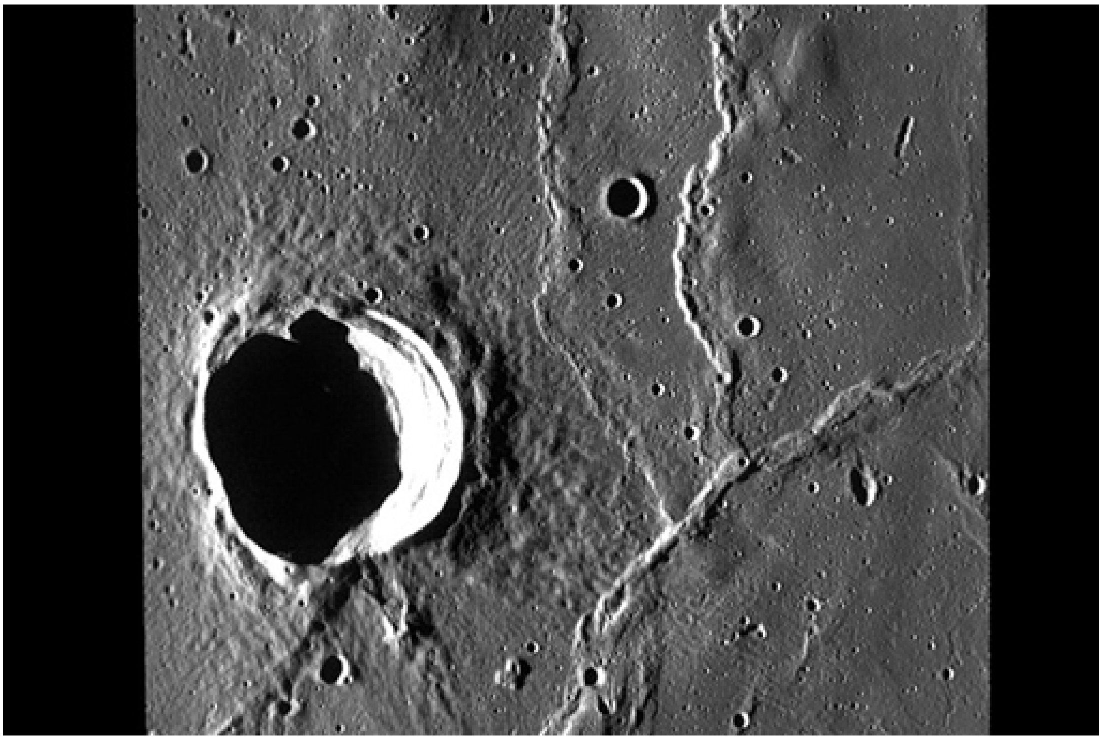

Figure 9 Wrinkle ridges in Mare Tranquillitatis. The crater on the left is 26 km in diameter.

Activity 2 Test your understanding of the Moon's surface features

Allow approximately 15 minutes.

For each image try to work out which features the empty labels refer to.

When you're ready, select 'Reveal answer' to see a fully labelled version.

Volcanic features

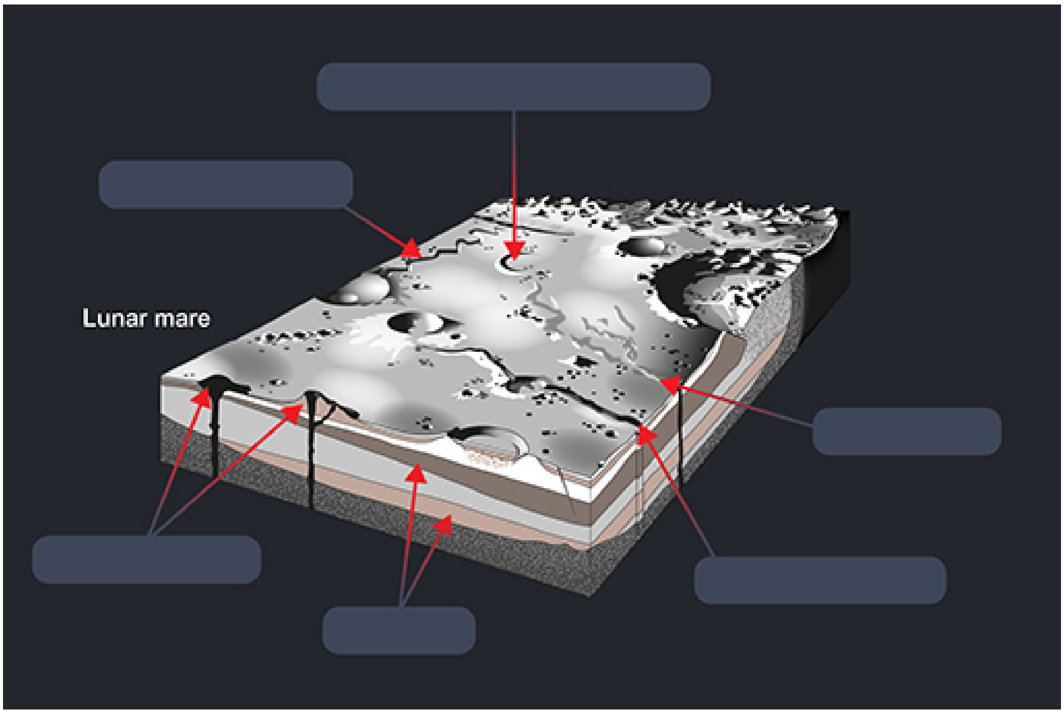

Figure 10 The Moon's surface and shallow subsurface.

Choose from these options:

- old, lava-flooded impact crater
- lava channel (rille)
- volcanic domes
- lava flows
- linear rille (graben)
- wrinkle ridge.

Answer

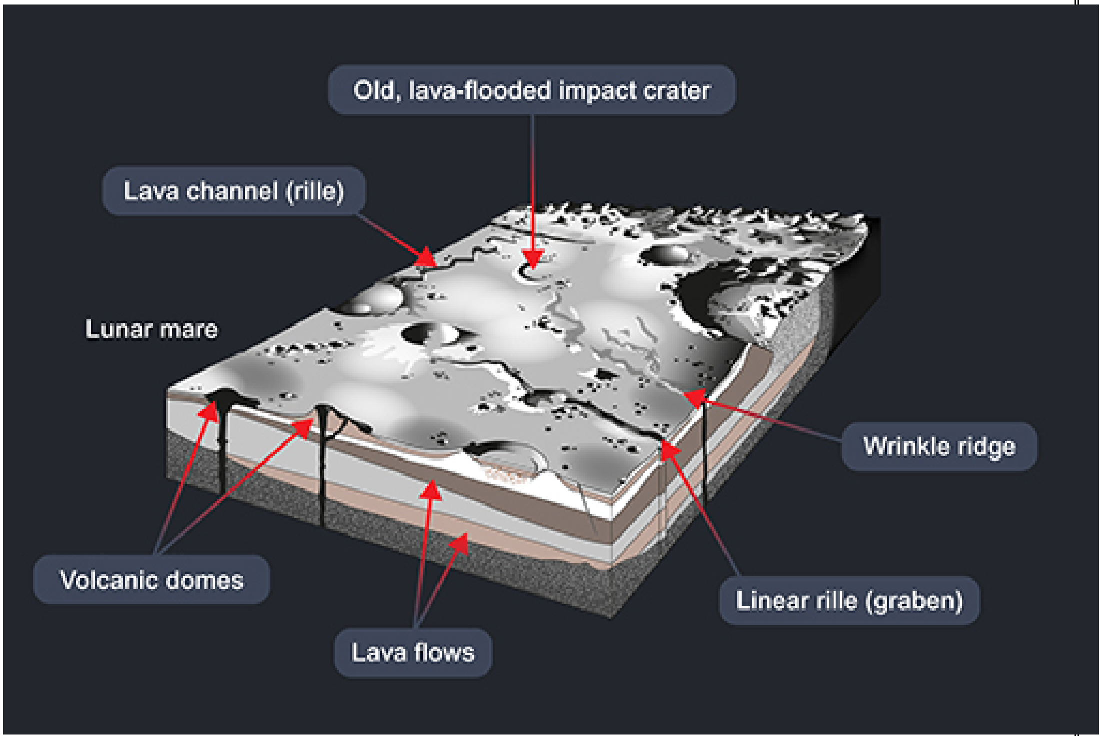

Figure 11

Impact features

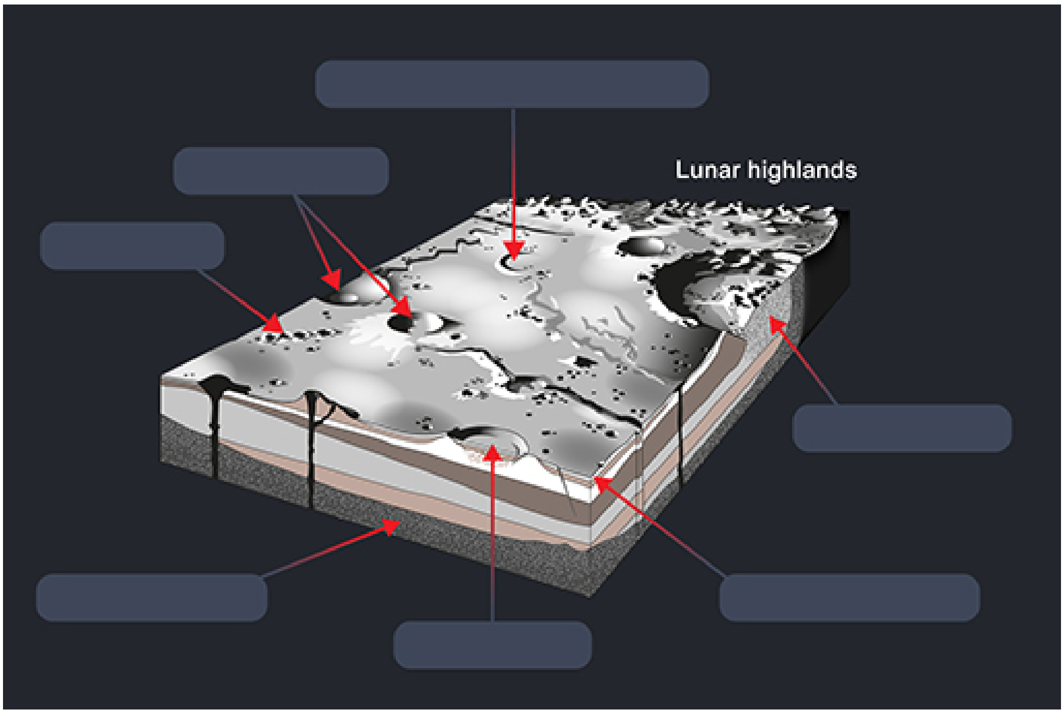

Figure 12 The Moon's surface and shallow subsurface.

Choose from these options:

- old, lava-flooded impact crater
- crater chain
- youthful craters
- brecciated rocks (formed by meteorite impact before lava flows)
- impact crater
- thin layer of regolith
- impact breccia.

Answer

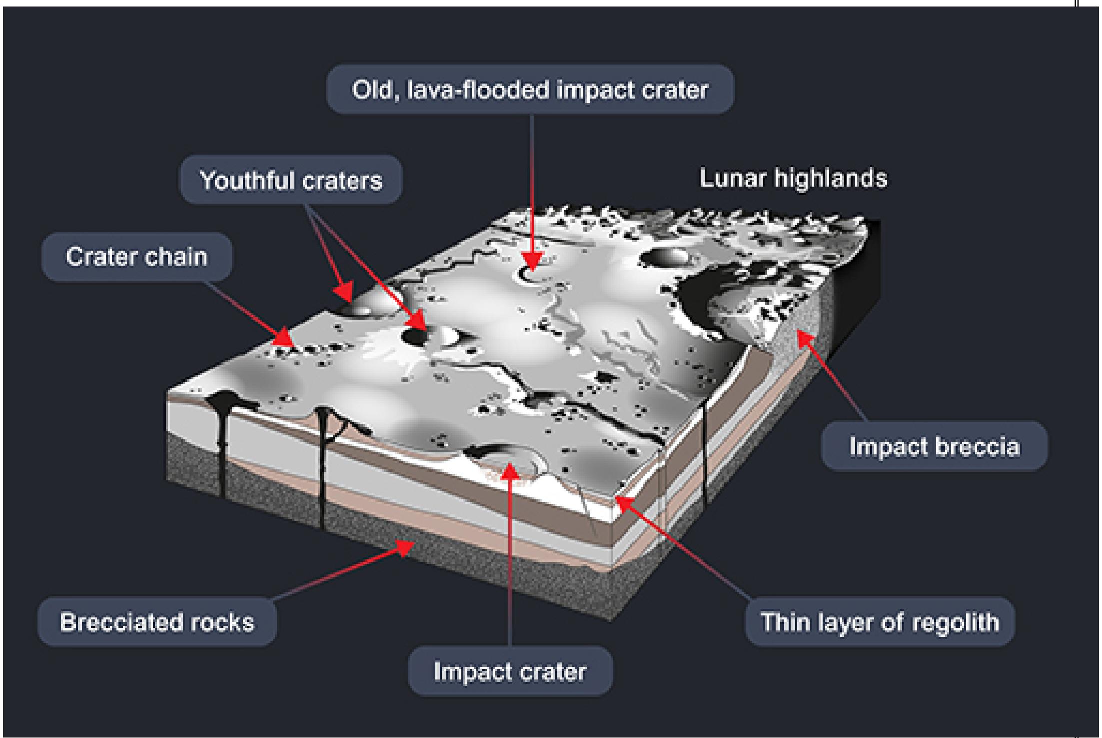

Figure 13

2 Why study Moon rocks?

The Moon rocks are stored at NASA, apart from fragments loaned to scientists for study. However the virtual microscope makes it possible to study Moon rocks up close and discover for yourself what they can teach us about the Moon.

Figure 14 Harrison Schmidt, the only fully qualified geologist to visit the Moon, sampling a large boulder during the Apollo 17 mission.

Studying rocks can tell us a great deal about the conditions under which they formed. Scientists can determine whether Moon rocks formed in a volcano, during a meteorite impact or are an accumulation of billions of years of dust falling onto the Moon's surface.

To understand how Moon rocks are formed, scientists sometimes have to look at features on a very small scale. The smallest features of Moon rocks, the minerals and glass fragments, contain information that isn't preserved on Earth – information about the early history of our Moon, the Earth and the Solar System.

The first clue for a geologist is the form the rock takes – in other words, is it crystalline or is it glass? Materials that form the surface of the Moon occur in two states: crystalline and amorphous. In crystalline solids, the atoms are located in regular repeating structures, although occasional imperfections may occur. Amorphous solids have no well-defined structure at the atomic level. The crystalline state is represented by minerals crystallised from lavas at the surface and by those that are re-crystallised as they are heated or buried. In glass, which can have a variety of chemical compositions, the amorphous state can be preserved when magma erupts as lava and doesn't completely crystallise, or when a meteorite impact causes sudden melting of the surface rocks.

The majority of minerals in Moon rocks are also found on Earth and can be recognised under the microscope. The most common mineral varieties include olivine, pyroxene, plagioclase feldspars and metal oxides such as ilmenite. Glass is also a common component of Moon rocks returned by the Apollo astronauts. As you look at Moon rocks, remember that although the processes you're observing may have happened billions of years ago, they occurred then just as they do today: an erupting volcano may last for days or weeks, while a meteorite impact happens in an instant.

2.1 Moon rocks – a scientist's view

Larry Taylor reflects on types of rocks on the Moon and the contrast between the lunar highlands and the maria. Note that he talks about another rock type, breccia. You'll learn more about breccias later this week.

Video content is not available in this format.

2.2 Minerals under the microscope

The first step to understanding rocks on the surface of the Moon is recognising the different minerals and the mineral textures of those rocks. We know how these minerals form on Earth from our study of volcanoes, so we can extrapolate to understand how the rocks on the Moon were formed.

We can determine mineral structure and composition using a microscope to study thin sections of rock only 30 micrometres (0.03 mm) thick, which are almost transparent (1 micrometre is one-millionth of 1 metre). In thin sections, the crystals show a range of colours and textures, which allows them to be identified and categorised.

Rocks are examined under the microscope using polarised light, in other words light vibrating exclusively in one direction, as seen when you look through Polaroid sunglasses. (Polaroid is the name for a plastic used to polarise light.) The rocks can be observed using one polarising filter, or two. A microscope with two polarising filters, at right angles, blocks out all the light until a thin section of rock is introduced between the two polarisers. This changes the polarisation of the light hitting the second polariser and now some light gets through. The colours of the light are called birefringence colours and are diagnostic of the minerals. Some minerals and glass do not alter the polarisation of the light and remain black between crossed polars. Finally there are some minerals – mostly oxides and sulfides or metals such as iron and titanium – that appear black under any kind of light. Such minerals are called opaque since no light passes through them even in thin sections, but in such cases reflected light can reveal structural information.

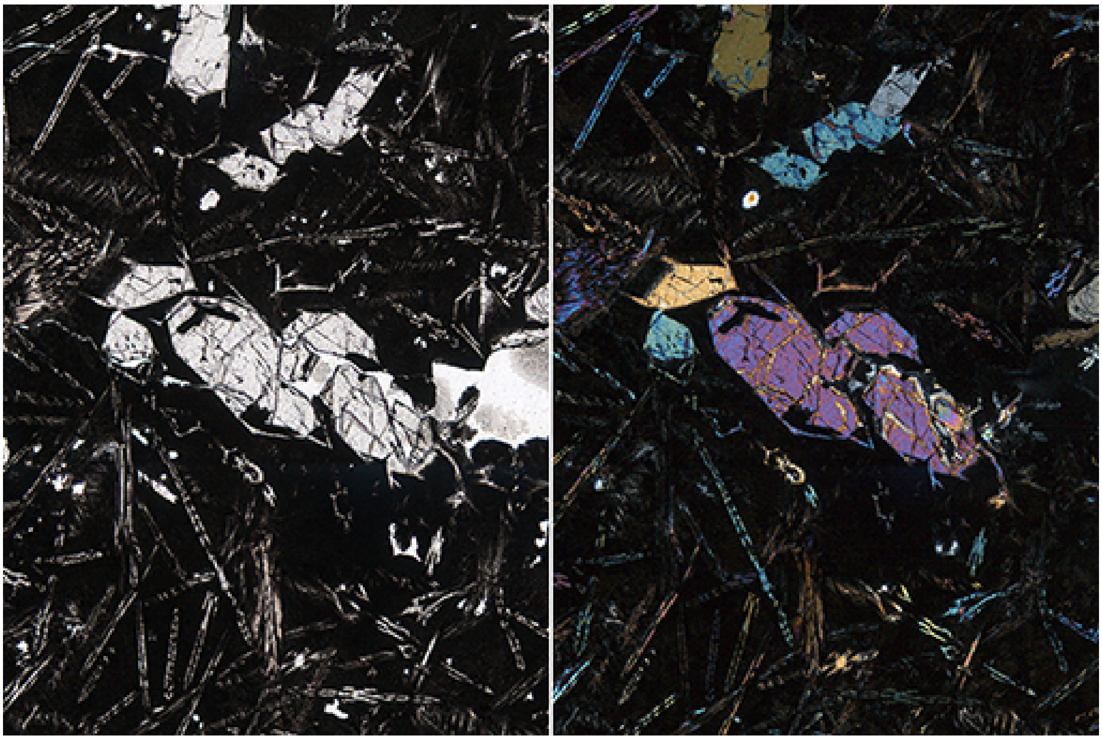

Figure 15 Thin section of a Moon rock seen in different lighting conditions.

Figure 15 was taken of one thin section of lunar mare basalt. The field of view is about 3 mm across. What can be seen is a piece of glass with minerals embedded in it. On the left you can see a range of different minerals and glass in plane-polarised light; on the right, the same view is shown with the thin section between crossed polars. Note some of the minerals are coloured in plane-polarised light and between crossed polars, whereas the glass is black in both views. This feature, combined with colours and variations as the sample is rotated, allows geologists to identify, characterise and discriminate minerals under the microscope.

See also: More on minerals and polarised light The use of the polarising microscope in petrography (the description of rocks). By identifying minerals and examining their interrelationships, petrographic evidence can be used to identify rocks and deduce how they formed.

2.3 Moon rocks under the microscope

The video introduces the study of polished thin slices of rock – known as thin sections – under the microscope, how samples are prepared and what geologists look for when they study thin sections. It also introduces the features of the virtual microscope including panning and zooming, measurements and the rotation feature. Finally, the minerals that you will see next, when you have your first chance to use the virtual microscope, are described in more detail.

Video content is not available in this format.

2.4 Your first moon rock – a mare basalt

You can explore the Moon rocks now, using the virtual microscope tool.

First, look at sample 14053 (open this link in a new tab or window so you have the two pages to work with), which is an aluminium-rich basalt. This sample was recovered in 1971 by the Apollo 14 astronauts Alan Shepard and Edgar Mitchell. It is a 3.92 billion-year-old piece of a lunar mare basalt that was found perched on the side of a boulder. This specimen is flat with one side freshly broken and the other side rounded and pitted by microcraters. Breccia material was found attached to the flat side, indicating that this basalt was probably a clast in the larger boulder (breccia). (Clast is the geologist's term for a fragment of one rock found embedded in another.) There are three main types of minerals in this rock: pyroxenes, plagioclase feldspars and opaques (probably iron oxides and sulfides). When you look at it under the microscope, you should try to identify the minerals in plane-polarised light (in fact you should be able to distinguish these three even in the view here):

- pyroxene (no particular shape, pinkish-grey colour with a rough-looking cracked surface)
- plagioclase feldspars (generally long thin crystals, clear or white and with very little visible internal structure)
- ilmenite (opaque).

Are there any other features of this rock that distinguish it from its equivalent on Earth? Compare this rock with a basalt that erupted on Earth.

There are several basalts on the Virtual Microscope Website, including the basalt that forms the Giant's Causeway in Northern Ireland.

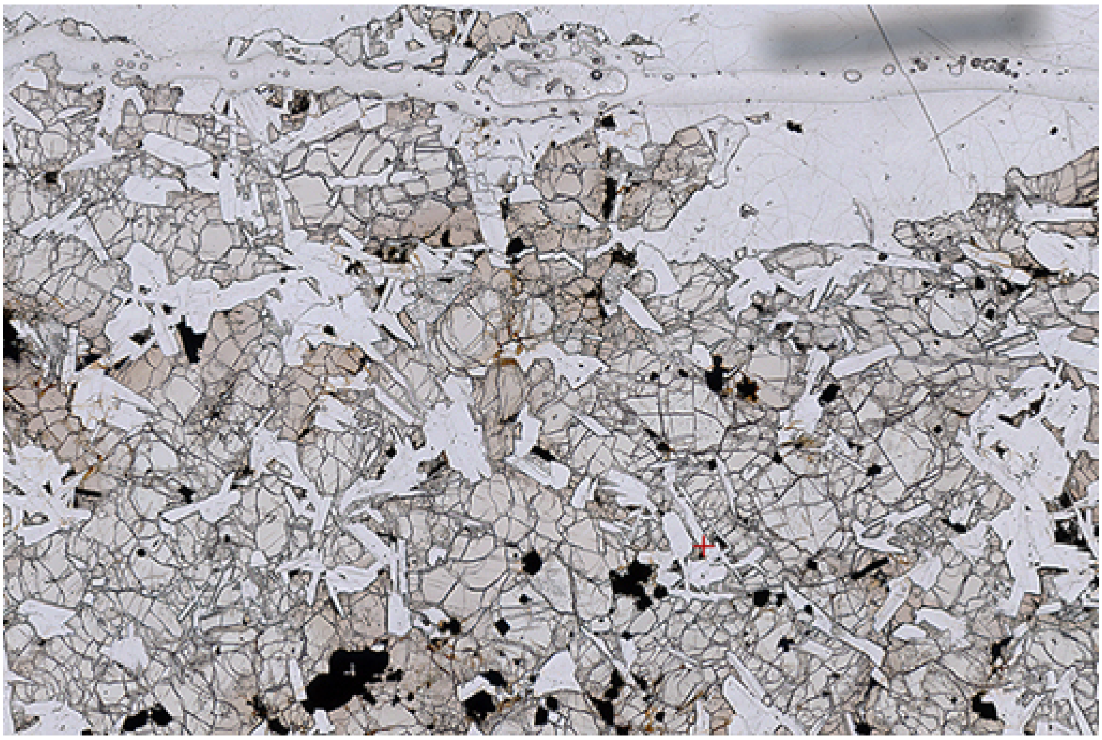

Figure 16 Mare basalt

2.5 Highland rock

Sample 78235 (open this link in a new tab or window so you have the two pages to work with) was collected from a boulder found on top of the regolith during the Apollo 17 mission. Its age has been determined as 4.3 billion years and it thus formed part of the early crust of the Moon. The sample is a light-coloured, coarse-grained plutonic rock, veined and partially coated with a dark-brown glass, which is a result of melting during an impact shock. (A plutonic rock is one that solidified from molten magma deep below the surface.) Micrometeorite impact pits on both the top and bottom of the sample indicate that the boulder had been turned over on the lunar surface.

In this rock the crystals are much larger than those in the mare basalt and they are also deformed, cracked and broken up. The larger crystal size is the result of the rock crystallising more slowly deep beneath the surface. The rock is very old, pre-dating the Late Heavy Bombardment when the surface of the Moon was very heavily cratered and any rocks at or beneath the surface were crushed and deformed. There are several features of this rock that indicate it has been deformed, but perhaps the most striking is the black vein of glass that splits the rock in two. This vein is known as a shock vein and was formed in the bottom of a crater during the explosion of an asteroid or the impact of a comet. You may recall from an earlier week that a comet is an icy body that can travel at tremendous speed and so make a very big crater.

Try to identify the pyroxene and plagioclase feldspar; it's more difficult this time because they are so deformed, but in the view here the plagioclase is clear and the pyroxene is darker with a cracked surface.

The vein filled a crack in the rock which also formed during the asteroid or comet impact. What else can you determine about the event based on the thin section?

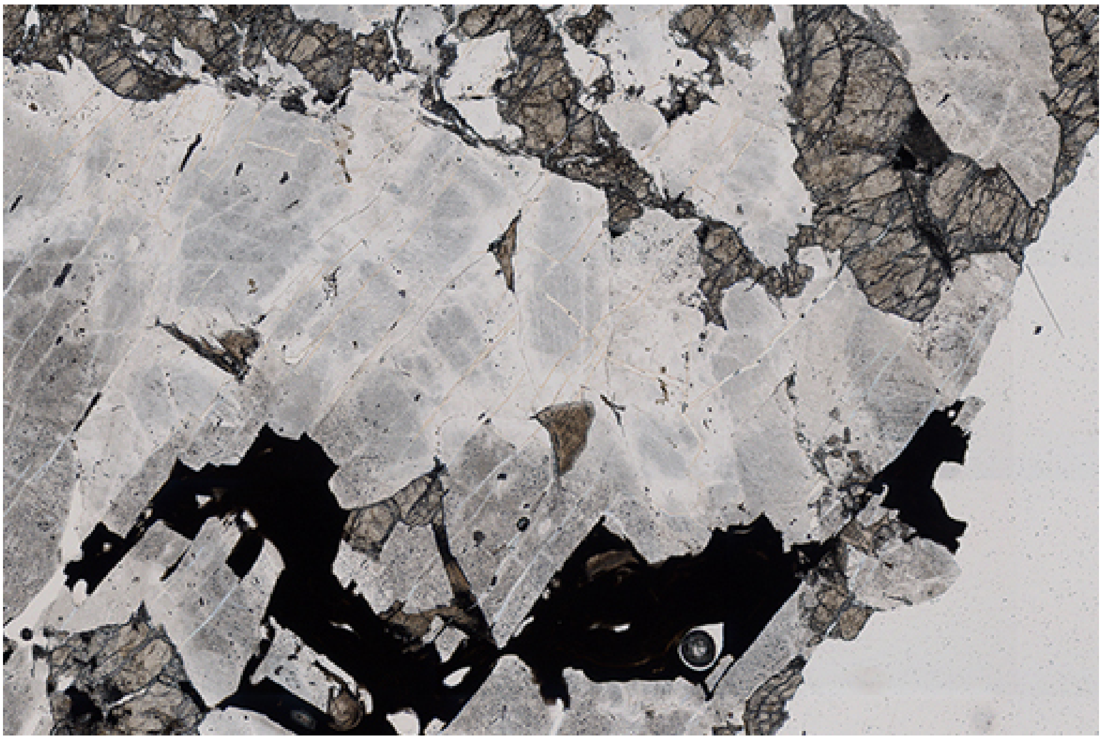

Figure 17 Highland rock

2.6 Lunar regolith sample

The next samples of the Moon are very different from the rocks you've just looked at: they are samples of regolith – lunar 'soil'. The regolith on the Moon contained a great discovery and surprise for the Apollo 17 crew and the space science community.

Look at sample 70181 (open this link in a new tab or window so you have the two pages to work with). This is lunar regolith that was collected near the lunar module during the Apollo 17 mission. Regolith is produced from the fine-grained debris formed in both large and small impacts. It contains mineral, glass and rock fragments and also agglutinates (clusters of dust welded together to form larger particles) formed by melting due to continual bombardment of the Moon's surface by micrometeorites.

Here you can see fragments of different minerals. This is unlike an Earth soil as there is no organic material or water, just very clean mineral fragments. Can you recognise the minerals you have been looking at in previous slides?

There is one additional feature you haven't seen before. Can you find any small orange spheres? What do you think they are?

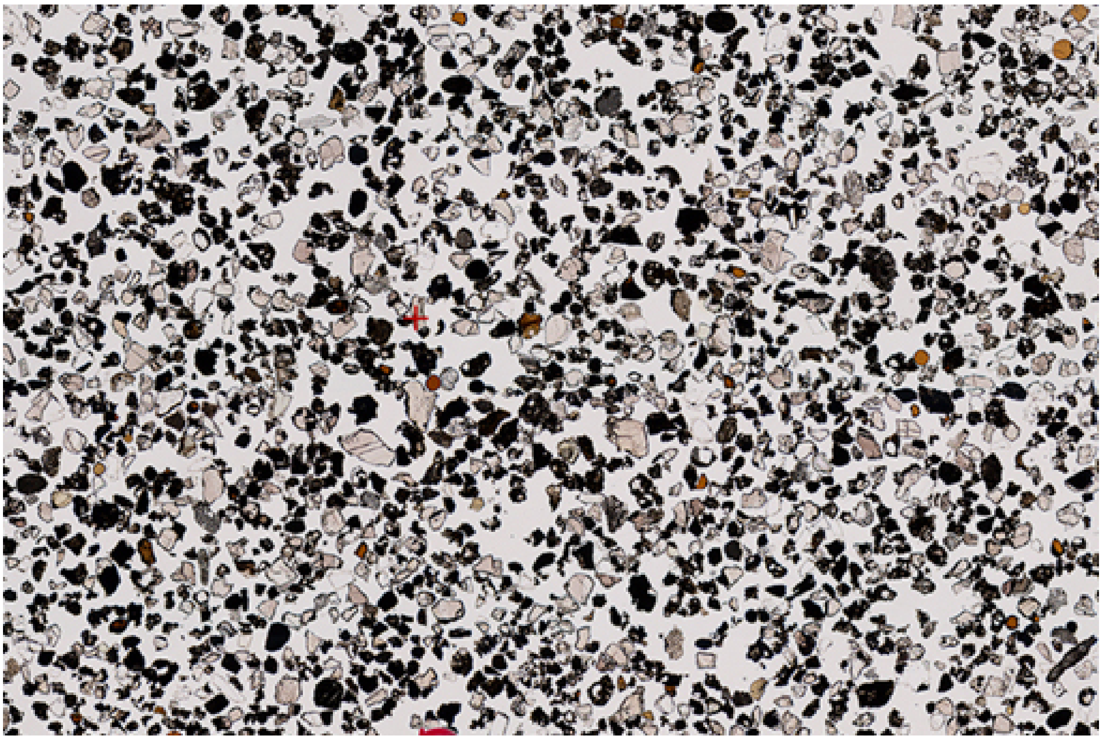

Figure 18 Lunar regolith sample

2.7 Lunar regolith – a second sample

Your second look at lunar regolith is an orange-coloured sample that caused much excitement when it was found by Harrison Schmitt. The famous sample 74220 (open this link in a new tab or window so you have the two pages to work with) is an unusual regolith sample that was discovered at Shorty Crater during the Apollo 17 mission to the Moon. The orange spheres are splatter from a volcanic eruption on the Moon and have the same age as the lunar mare basalts: 3.6 billion years.

Most of the sample consists of bright orange glass spheres, although a proportion of the glass has devitrified (i.e. become crystalline) and is now black where fine olivine needles and ilmenite feathers have grown. In chemical composition, the black former glass is identical to the orange glass.

So how did the orange regolith form on the Moon?

Take a moment to watch this video of an eruption on Earth, taken from the BBC webisite. Imagine what the area close to the volcano will look like once the eruption has finished and the lava has cooled. The ground will be covered in material with a range of sizes from solidified lumps of lava down to dust particles. This is what the astronauts gathered and recovered from the area around the small volcanic cone. The main difference is that the volcanism is still happening on Earth and over a few years the particles react with water from the atmosphere to form clay. The lunar orange regolith is over 3 billion years old but is perfectly preserved nevertheless.

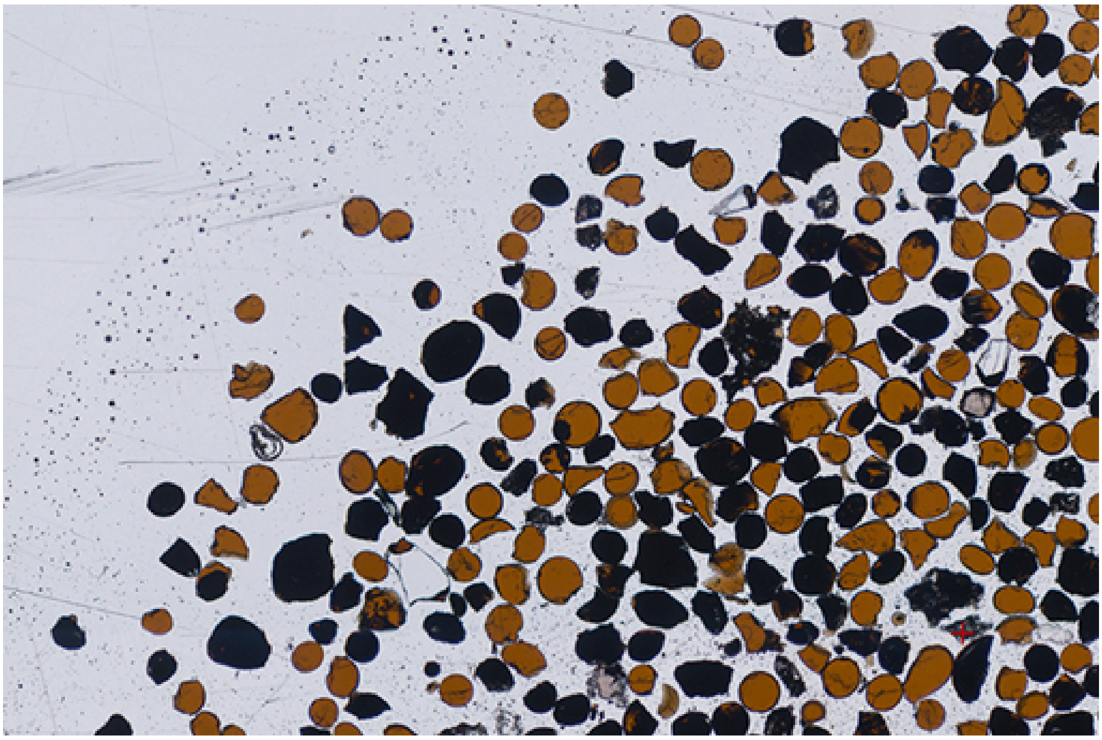

Figure 19 Lunar regolith – a second sample

3 Unravelling the Moon’s history

How much do we know of the history of the Moon? Scientists have used both cratering density and direct dating of Moon rocks to measure the ages of events on the Moon including periods of heavy meteorite bombardment, and volcanism.

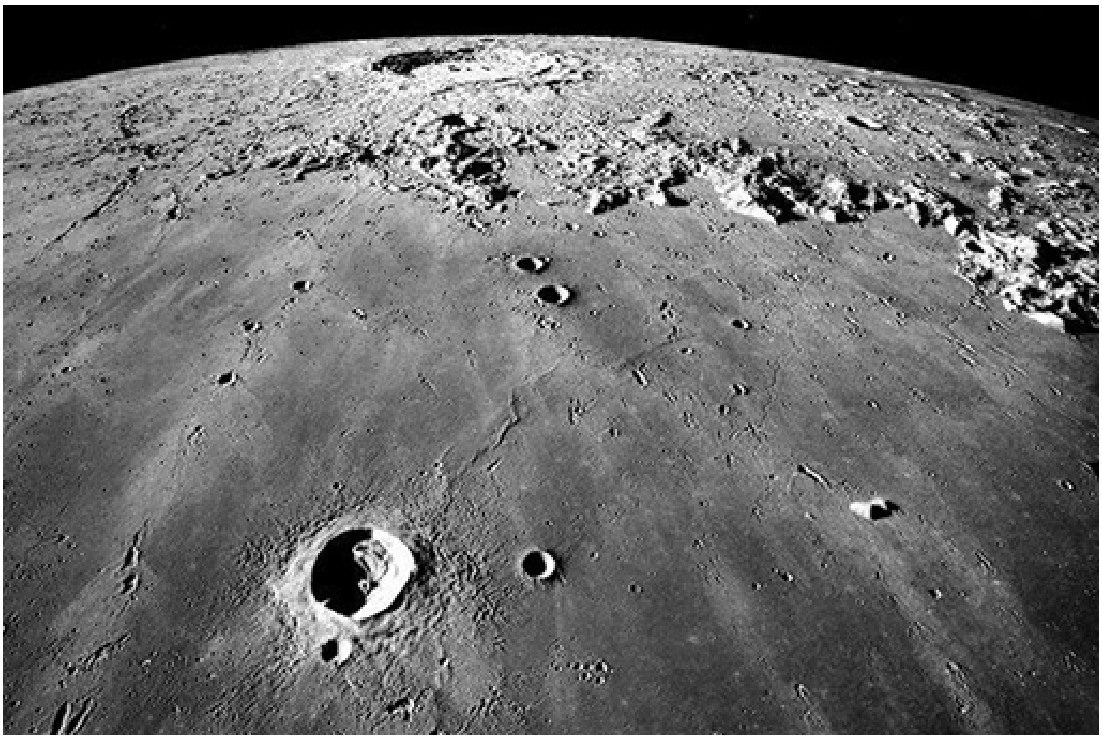

Figure 20 An image taken by the Apollo 17 astronauts showing the Mare Imbrium in the foreground and the Copernicus crater in the distance.

The Moon rocks you have studied can teach us a lot about the formation of the Moon and about the Earth itself. However, studying the rocks under a microscope can’t tell us how old the Moon is, nor the age of features on the Moon’s surface. Scientists have used two techniques to determine the age of the Moon’s surface:

- The first dating technique uses the radioactive decay of elements to find the age of individual rocks and even grains within rocks.
- The second dating technique uses impact craters on the Moon’s surface. Older areas of the Moon are more heavily cratered, while younger areas such as the lunar maria are less heavily cratered.

3.1 Radiometric dating of Moon rocks – some background

Before discussing the dating of samples using radioactive decay, it’s worth recapping a bit of background science. If you’re familiar with these concepts you can skip quickly through this step and the next.

Radioactive decay is the process whereby an atom decays to form a different element. One of the most commonly used methods for dating rocks on both the Moon and the Earth is the decay of an isotope of potassium (K) to produce an isotope of argon (Ar). It's not like nuclear fission where the whole atom breaks up releasing lots of energy, but it is a natural process going on all around us and even in your body. Naturally occurring potassium has two stable isotopes and one unstable isotope and in this case, scientists make use of the unstable one that has been slowly decaying through time.

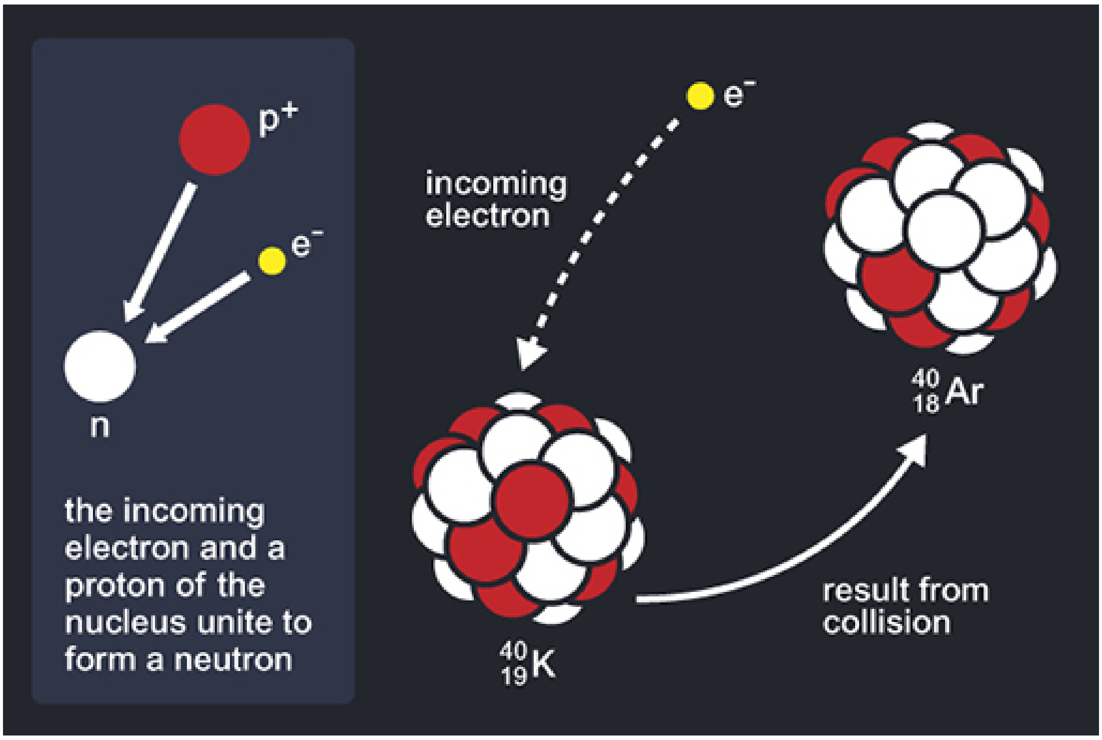

Figure 21 Cartoon of nuclei for potassium-40 and argon-40. The red spheres are protons and the white spheres are neutrons.

So, what is an isotope? Atoms are made of a cloud of electrons (negatively charged particles) surrounding a nucleus of protons (positively charged particles) and neutrons (neutral particles). Each element is defined by its atomic number, the number of protons in the nucleus (Z). To keep an atom electrically neutral overall, the number of electrons is the same as the number of protons. However, the number of neutrons (N) can vary in the atoms of a single element, resulting in atoms of different masses for the same element. The atomic mass (A) is defined by the number of particles in the nucleus:

$A = Z + N$.

Thus, isotopes of an element have the same value for Z but different values for A. In the case of potassium-40, you have Z = 19, N =21 and so A= 40. From now on, we won't show the Z values.

3.2 Get a half-life!

An unstable isotope decays over time at a rate that is characteristic of the particular isotope and is proportional to the number of surviving atoms. The result is that the number of atoms falls exponentially or undergoes exponential decay. A key feature of exponential decay is this: whatever number of atoms you start with, the time taken for half of them to decay will always be the same. This time is called the 'half-life' of the particular isotope.

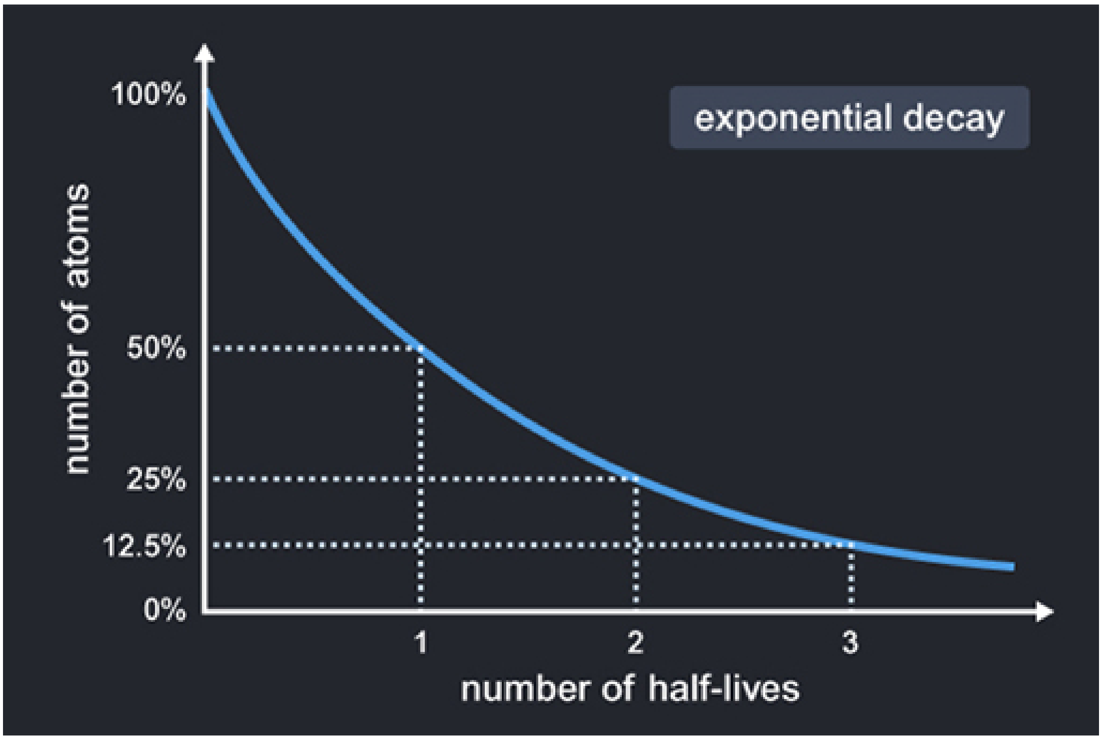

Figure 22 A plot of the number of remaining atoms against the number of half-lives. 50% of atoms remain after one half-life, 25% after two half-lives and so on ...

Exponential decay allows scientists to use the amount of surviving isotope to measure the ages of rock and minerals. The most commonly used dating technique for Moon rocks uses an unstable isotope of potassium (^{40}K or potassium-40) that decays to a stable isotope of argon (^{40}Ar or argon-40). The decay rate is very slow, even on the long timescales of the history of the Moon. Half the potassium-40 atoms decay in 1250 million years and this time span is called the half-life of potassium-40. So there have been about 3.6 half-lives of potassium-40 since the formation of the Moon. That means there is only about 8% of the original potassium isotope remaining, as you can see on the graph. This technique is known as K–Ar dating.

The other key difference between the elements potassium and argon is that argon is volatile and escapes when rocks are melted or very hot, but potassium is not volatile and so tends to be retained. So, for example, the atoms of argon escape from lavas when a volcano erupts, so when things cool down afterwards, the ratio of potassium to argon is higher than before. When the rocks like those from the lunar maria cool, they begin to retain argon and the amount of argon increases as potassium in the rock continues to decay. Thus the K–Ar decay clock is reset by an eruption. Another example is an event such as a large asteroid impact on the Moon's surface causing melting of the surface rocks; this also preserves the age of the impact. By resetting the decay clock, scientists measure the amounts of both the potassium and argon isotopes in rocks using sophisticated measurement techniques and thus estimate the age of geologically important events in the far distant past.

The K–Ar dating technique was applied to Moon rocks when they were returned to Earth by the Apollo missions and is the reason why we know so much about the Moon's history. We know that the Late Heavy Bombardment caused massive cratering of the Moon's surface between 4.1 and 3.8 billion years ago because many of the lunar highland rocks were heated and melted then. We also know that most of the lunar maria erupted between around 3.8 and 3.6 billion years ago because they cooled and began to retain argon in that period.

3.3 Radiometric dating of complex Moon breccias

In the case of the Moon, there are two major sources of rocks for dating.

Most samples studied by scientists have been returned by the Apollo or Luna missions. The second source is lunar meteorites, samples of the Moon's surface that were ejected by large impacts, captured by the Earth's gravity and, having survived passage through the Earth's atmosphere,ended up on the Earth's surface. While less abundant, they are very important to our understanding of the Moon's formation. Indeed, samples collected by space missions consist essentially of surface samples taken from the regolith at the surface of the Moon. By contrast, lunar meteorites have sampled deeper material. In addition, samples returned by missions are taken from locations that are tightly clustered, in places where it was easy to land, which can induce a bias. The high number of impacts made by meteorites means that these samples are far more random and can originate from anywhere on the Moon.

For meteorites and for some returned samples, the sampled area(s) can be larger than just the place from which the sample originated. The numerous impacts have ejected material with sufficient energy to travel up to a few hundred kilometres away from the impact point. Thus, it is possible to find different types of rock from different locations in a single sample. These samples containing different units are called polymict breccias.

Sample 61295 is a typical regolith breccia collected during the Apollo 16 mission to the Moon. The sample was chipped off a large boulder, 2 metres in diameter, on the rim of Plum Crater. The rock is a friable, light-coloured matrix breccia with both light and dark clasts (embedded fragments). The outer surface of the sample is rounded and has many micrometeorite pits. You can find this rock and other lunar breccias on the Virtual Microscope website.

Figure 23 Fragmental feldspar-rich lunar breccia 61295 illustrating the polymict nature of lunar breccias

The many clasts in the Yamato 983885 meteorite have been dated and yield ages around 4 billion years, which is older than any whole rock yet found at the Earth’s surface and older than the majority of the lunar mare volcanic eruptions. Thus scientists can determine that the surface of the Moon over 4 billion years ago consisted of some areas of impacted and cratered surface and also some less affected areas that were covered in basalt lava flows similar to the currently exposed lunar maria.

Figure 24 Yamato 983885. Cube is 1 cm^3.

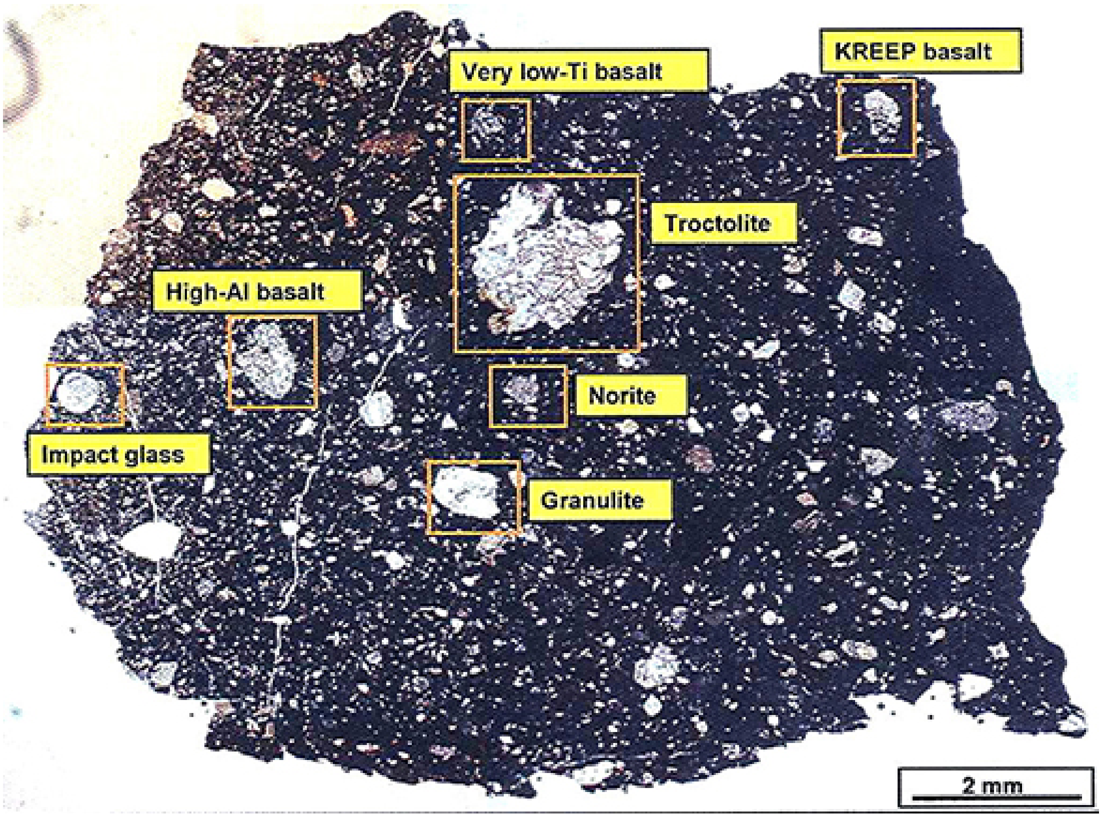

Figure 25 Image of thin section 59-2, illustrating the diversity of small-clast lithologies present in Yamato 983885.

3.4 Remote sensing – crater counting

Watch this Japanese simulated flyby of Mare Moscoviense. Pay specific attention to the difference between the brighter and darker areas in terms of the number and density of craters.

While the meteorites and returned samples give us invaluable information about lunar formation and the age of the Moon, most of its surface is unsampled and there is no way to get more rocks until future missions return samples. Still, we can learn a lot from these areas using the high-resolution images that have been returned of the Moon’s surface taken during missions such as the Lunar Reconnaissance Orbiter Camera (LROC). Indeed, the use of spacecraft to image the Moon produced a large quantity of remote-sensing data (images of the surface) that can be used to investigate the properties and characteristics of the unsampled areas.

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(Please note this video has no audio.)

3.5 Crater counting in detail

Since the return of lunar samples, estimation of age has become a much more exact science. Dates for the lunar maria and highland areas have been used to calibrate the relationship between crater sizes and the number of craters in a given area of the Moon’s surface. The Moon’s surface has been heavily cratered and, unlike on the Earth, lunar craters are preserved. We even know there is a good record of the Late Heavy Bombardment, which pre-dates any remaining rocks at the Earth’s surface. The Earth certainly went through a similar rain of asteroids and comets around 4 billion years ago but the subsequent re-surfacing of the Earth by plate tectonics, weathering and erosion has erased most impacts, even the largest ones.

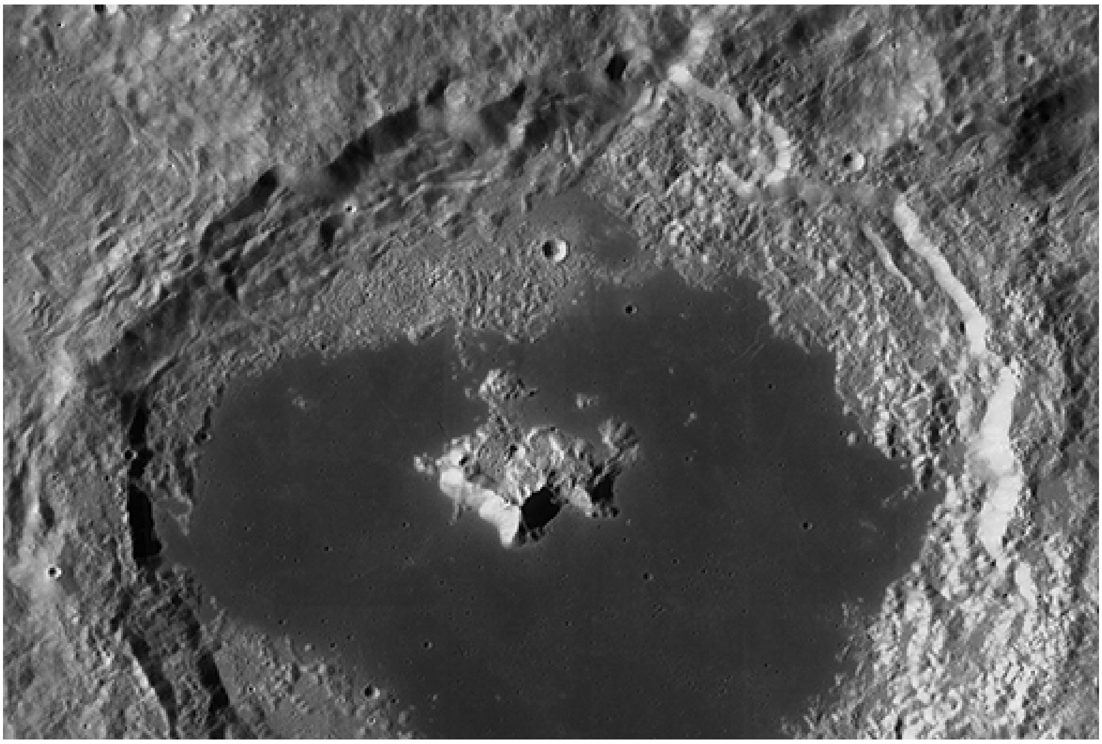

Figure 26 Image of the Tsiolkovskiy crater. Look carefully at the boundary between the dark mare and the rugged highlands. The area shown is about 200 km across.

The counting of craters on different surfaces can give an idea of the sequence in which different terrains formed. While it doesn't straightforwardly give an age in years, this method is very precise for working out the order in which events happened on the Moon and other celestial bodies. When you expanded the image did you notice how few craters there were in the mare compared to the highlands? There are two main factors to be taken into account: the density (i.e. number per unit area) and the size of the craters. Within a given terrain there is a strongly reproducible relationship between the density of craters and their size. There are fewer large craters and more small craters as the size–frequency distribution plot below shows. Using this, scientists have managed to characterise the age of different terrains on the Moon's surface and use the same calibration to determine the age of surfaces on other bodies such as Mars. While the calibration is different, the same effect is the reason why the surface of Europa, for example, has few craters and the asteroids (which have no re-surfacing) are heavily cratered.

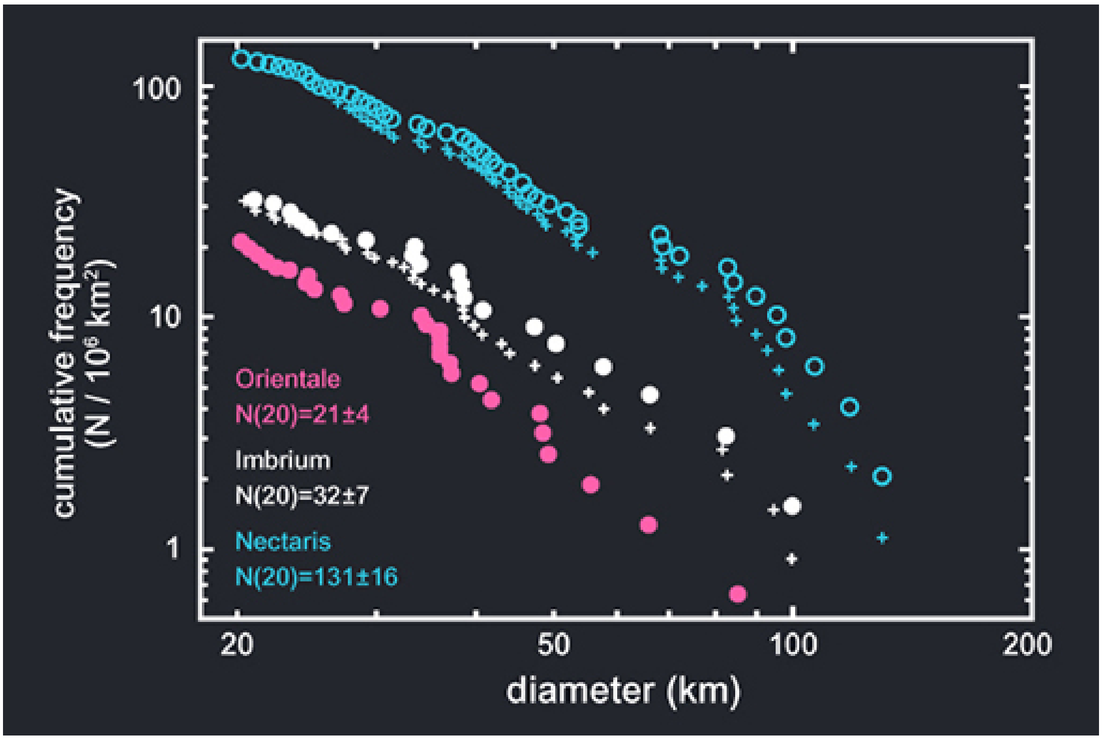

Figure 27 Size–frequency distribution plot for three important lunar terrains: Mare Orientale, Mare Imbrium and Mare Nectaris.

At this stage you may be wondering if a geological map of the Moon has been made yet. The answer is that it has. The United States Geological Survey has prepared a map of the Moon's near-side.

See also: LROC interactive map of the Moon's surface. If you would like to explore the Tsiolkovskiy crater (or any of the other craters on the Moon) in greater detail, you can use this LROC interactive map.

3.6 History of the Moon

When combined with isotopically dated samples from known areas, the Apollo landing sites for instance, it has been possible to estimate an absolute age for an area from crater counting using the kind of size–frequency distribution that you saw in the previous step. This way, it is possible to estimate ages for areas for which samples are unavailable and a full history of the Moon can be inferred.

The history starts with the giant impact, the most commonly accepted current hypothesis for lunar origin. As you have seen, after accretion, the Moon was in a state called a magma ocean, which means that a significant portion of the Moon's rock was molten.

Dating of these two lithologies in the samples gives a highland crust formation that would have started 4.56 Ga ago (where 1 Ga is 1 billion years). The youngest basalts associated with the main crust-forming events have an age of around 3.8 Ga.

Lunar mare volcanism took place after the formation of the highland crust. The volcanic eruption filled basins in the crust where it was made thinner; filling impact basins for instance. The oldest mare basalt dated isotopically is 4.23 Ga old while the youngest is 2.7 Ga old. On the basis of remote-sensing data stratigraphy and crater density, a younger age of 1.5 Ga has been suggested for the eruption of mare basalts in Oceanus Procellarum.

Thus mare volcanism overlapped with the end of crust formation and may have continued up to 1.5 Ga ago, which marked the end of volcanic activity on the Moon but not the end of its story.

The ages of polymict breccias, which are related to impacts on the Moon, cluster noticeably around 3.9 Ga. This means that prior to this time or at this time only, the impact rate was far higher than it is today. Such a clustering of ages is also observed on other planets or asteroids in the Solar System, most notably on Mars and the asteroid Vesta. This event, the Late Heavy Bombardment, was spread across the Solar System and not just localised on the Moon. The cratering rate decreased rapidly after this bombardment, by an order of 10 between 3.9 and 3.1 Ga ago. Impactors have continued to shape the surface of the Moon in more recent times, forming younger craters. Among the notable younger craters are Copernicus (1.0 Ga) and Tycho (0.3 Ga).

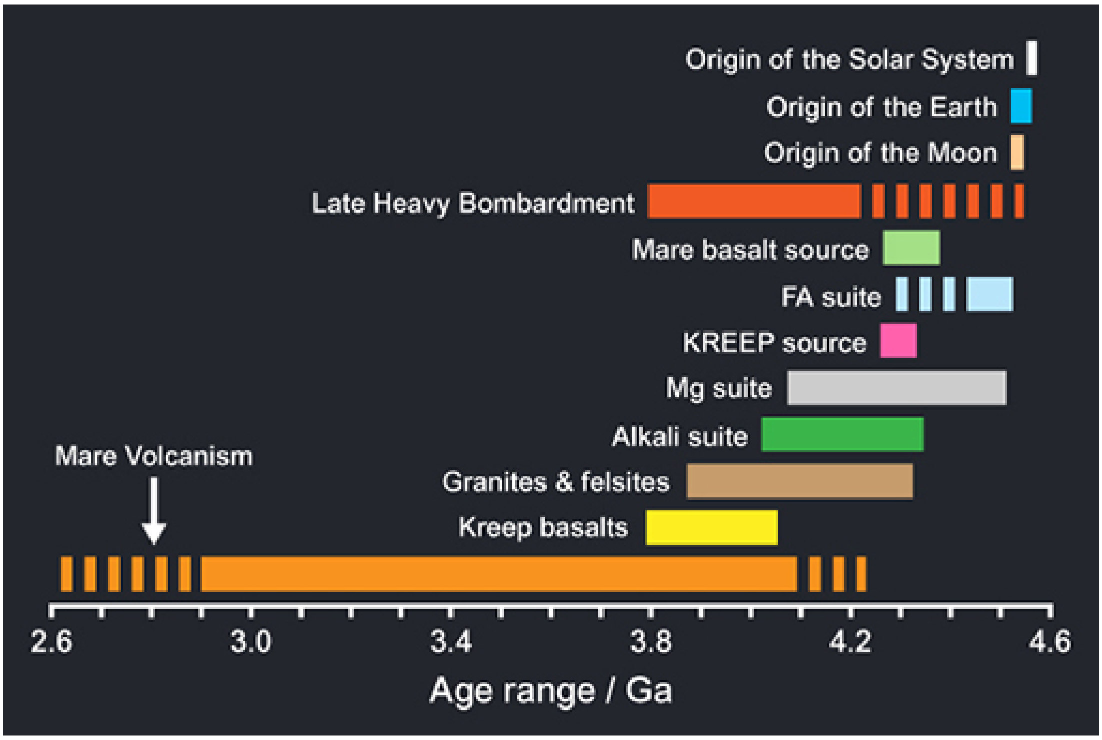

Figure 28 Summary of the chronology of the formation of the lunar crust. Ga (Giga-annum) is 1 billion years.

4 This week's quiz

This quiz allows you to test and apply your knowledge of the material in Week 5.

Complete the Week 5 quiz now.

Open the quiz in a new window or tab then come back here when you're done.

5 Summary

This week you have explored the Apollo 11 and Apollo 17 missions to theMoon and what dust and rock samples tell us about its surface and structure. Next week we discuss how science advances by continuously testing hypotheses.

You should now be able to:

- understand the significance of the Apollo 11 and Apollo 17 missions to the Moon, and what was investigated there
- consider what Moon dust and rocks brought back to the Earth tell us about the Moon.

You can now go to Week 6: Water on the Moon.

Week 6: Water on the Moon

Introduction

Scientists had long debated the presence of water, but the Apollo missions appeared to settle the matter – the Moon rocks were dry. In the few cases where water was detected, it appeared to be terrestrial contamination.

Jess introduces Week 6 and the debate around water on the Moon.

And here’s a note from Jess on her research:

> My research fits into the hot debate ‘dry versus wet Moon’ as I’m working on determining the water content of a specific lunar mineral: apatite. This calcium phosphate mineral is important because it can lock up water in its crystal structure. Incidentally, apatite is the most commonly occurring hydrous lunar mineral and occurs in almost every rock type we have from the Moon. Knowing how much water is contained in a range of lunar rocks permits us to assess the water budget of the lunar interior including in some cases rocks that date back to just after the Moon was formed (c. 4.5 billion years ago).
>
> In addition to quantifying the amount of water in lunar apatite my colleagues and I are measuring the hydrogen isotopic composition of the water. This is a very powerful tool since different Solar System objects have characteristic hydrogen isotopic signatures, allowing us to infer the origin of lunar-interior water. Our current understanding suggests that there is a strong link to some examples of a class of meteorites called carbonaceous chondrites and hints to a common origin for water within the Earth and the Moon.

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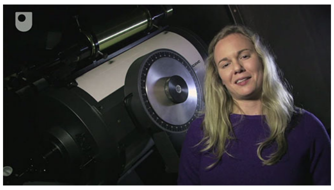

By the end of this week, you will be able to:

- understand the debate around lunar water and the two kinds of Moon water
- explore examples of how science advances by continuously testing hypotheses.

1 Early theories about water on the Moon

When astronauts first visited the Moon in 1969, there were very few certainties about the presence of water, but no lack of hypotheses. When Apollo 11 landed and samples of the Moon's surface were first collected, the initial analysis did not detect any water and indeed as you saw in Week 5, the samples appeared almost completely unaltered with little to no water interaction evident.

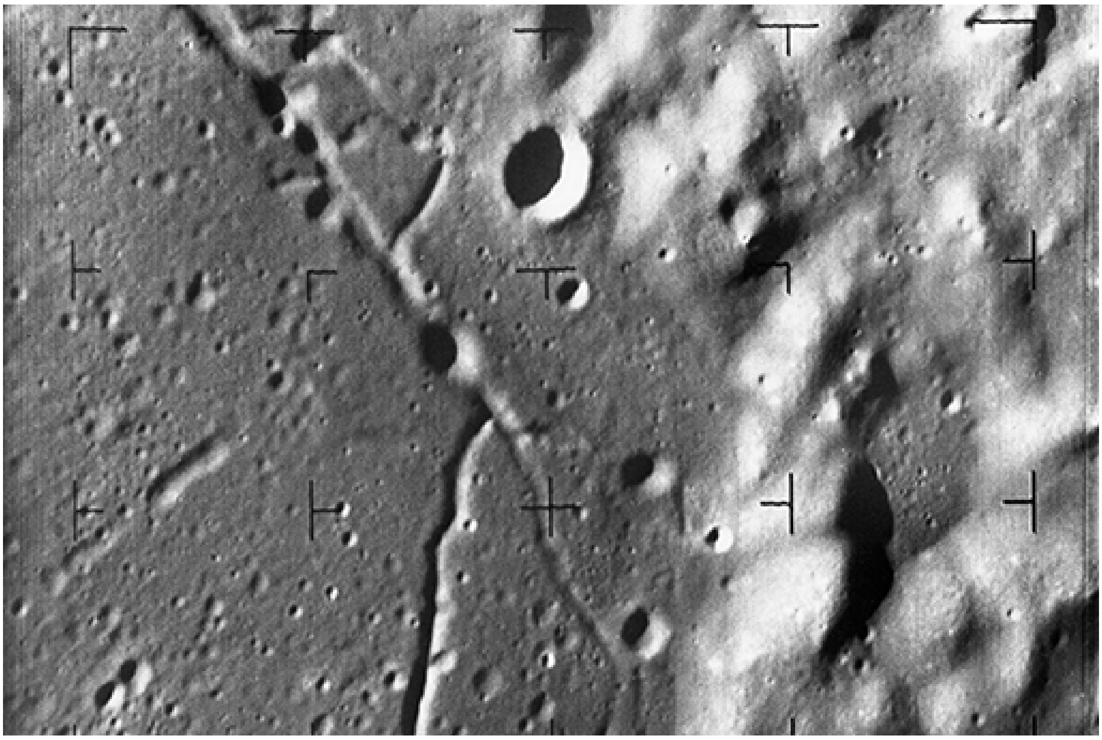

Figure 1 An image of part of Alphonsus crater on the Moon taken in 1965 by the Ranger 9 mission, showing channels.

The idea that water has been present on the Moon has been debated for centuries. This includes many strange theories such as one proposed by Danish astronomer Peter Andreas Hansen in 1856. Hansen believed that the Moon's centre of mass (its gravitational centre) is offset from its geographical centre, which could allow a large atmosphere to exist on the far side of the Moon, under which oceans and rivers could exist. The prevailing opinion by the time astronauts visited, however, was that the very low atmospheric pressure would not allow liquid water to exist anywhere on the surface. In the mid-20th century, the idea of water existing on the surface was taken up by Nobel Prize winner Harold Urey. Based on the Ranger 9 images, there appeared to be channels created by flowing liquid. Urey was eventually proven wrong by the Apollo 15 mission when one of the channels, Hadley Rille, was visited by astronauts Dave Scott and Jim Irwin and it was evident that the channel was created by lava, not water. However, Urey's arguments were a key driver for NASA to explore the Moon and they helped greatly in the space programme. As you'll see in this week, although Urey was mistaken about Hadley Rille, he wasn't completely wrong.

The lack of water on the Moon was further corroborated when it was established that the regolith returned from the Moon resulted from lava break-up by billions of year of meteorite impacts rather than from water-related processes. At the time no water could be detected inside any minerals in the samples brought back by the Apollo missions; in particular, there was a lack of the most common hydrated mineral found in basaltic rocks on Earth, amphibole.

1.1 Dry rocks

When samples were first brought back from the Apollo 11 mission, they appeared to show pristine basalts, as fresh as the newly erupted basalts being created on the volcanic island of Hawaii. As the rocks were curated and given to scientists to analyse, the analysis appeared to corroborate the completely dry nature of the samples.

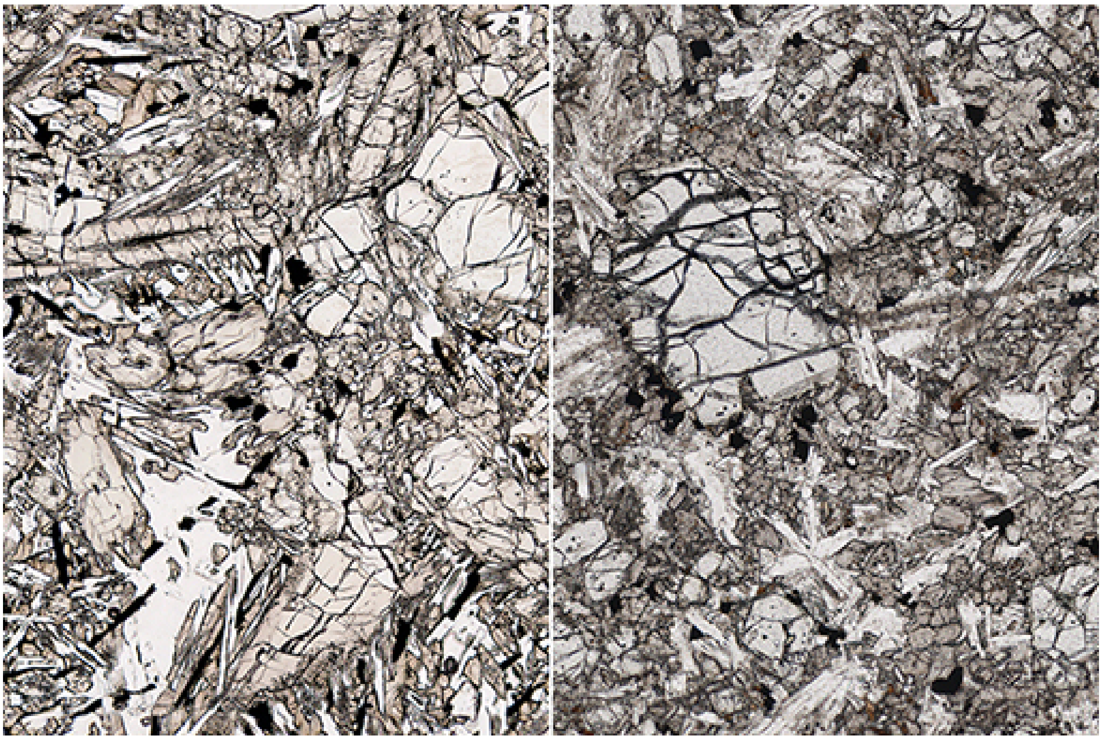

Figure 2 Left: a microscope image of a lunar basalt. Right: a microscope image of a terrestrial basalt from Scotland.

These images show a 3000 million-year-old lunar mare basalt (NASA sample 12002) (left) and a 335 million-year-old terrestrial basalt from Scotland (right).). Although the terrestrial basalt is one tenth of the age of the lunar basalt it has patches of rust throughout, following fractures and cavities. The mare basalt collected by Apollo 12 astronauts is completely clean, despite being over 3 billion years old. It has not been subjected to interaction with water.

The Full analysis of lunar and terrestrial basalt PDF gives you a table of data that shows the composition of two basalt samples, analysed using sophisticated X-ray fluorescence spectrometry in laboratories on Earth. The totals lie close to 100%, although not exactly, because there are small errors in the analysis of each element, shown as its oxide. Both the analyses totals shown here are sufficiently close to 100 to be considered ‘good’ analyses.

Note that the analysis of the picritic basalt (an eruption in India with a similar composition to the Mare basalts) does contain a small amount of water and this is not all related to later weathering by Indian rain. Fresh Earth basalts contain water in small amounts, not just from interaction with the atmosphere and oceans, but they also contain water from the magma source where the magma was generated and can often contain some hydrous minerals such as biotite or amphibole. The Earth's mantle contains low concentrations of many volatiles (substances that are easily vaporised) including H_2O, CO_2, CH_4, SO_2, and halogens such as Cl_2.

1.2 What happened to this lunar basalt?

Look at sample 10029, which was collected by Apollo 11 astronauts. It is a 3.9 billion-year-old lunar basalt containing pyroxene, plagioclase feldspar and metal oxides. Try to locate the rusty spots within the thin section. Can you recognise the different minerals present in the sample? How does this differ from the lunar basalt you saw in Week 5?

1.3 Patchy evidence

Here you can see patches of what appear to be rust staining surrounding some of the black patches. There are three minerals in this field of view, the pinkish-grey mineral is pyroxene, the clear mineral is plagioclase, and the opaque areas are the metal oxides and sulfides (appearing black in plane-polarised light because no light passes through the thin section).

Figure 3 A microscope image of Apollo sample 10029, a mare basalt, taken in plane polarised light.

These apparently rusty patches surrounding some of the opaques are a mineral called akaganeite, formed from the hydration of some iron sulfides. It frequently occurs in samples exposed to humid conditions or small amounts of water. This discovery revitalised the argument over the hydration of the Moon.

However, the discovery was met with great scepticism as the dry moon theory was linked to the hypothesis that the Moon formed when a large planetesimal impacted into the Earth, driving off all volatile elements and leaving behind a dry moon. The apparent rust in this sample was at odds with this hypothesis and so other explanations were sought.

If you've enjoyed using the Virtual Microscope and want to know more, read An introduction to minerals and rocks under the microscope.

See also: Open University minerals under the microscope. This is the Open University's virtual microscope, with more info on identifying minerals and their characteristic features.

1.4 How does science advance, and how do we know when it happens?

All this week you'll see how the story of water on the Moon is a debate between scientists that has so far lasted over 30 years.

What has the debate been about? Some lines of evidence have appeared to indicate a completely dry Moon, but other evidence has indicated the presence of water.

What do you think motivates scientists to persist in this kind of debate? What are the features that distinguish it? How do scientists' earlier theories and preconceptions direct or distort research? Is it advantageous to have preconceptions – to work hard to prove a point – or is this constricting? If it is disadvantageous, how can this approach be overcome? And finally, how would you recognise a debate that had finished?

Figure 4 De revolutionibus orbium coelestium (On the Revolutions of the Heavenly Spheres), by Copernicus, 1543. His proposition that planets go round the Sun rather than round the Earth was a revolutionary idea that took several hundred years to be accepted.

1.5 A little dust goes a long way

Do you remember the video in Week 5 of the
two astronauts discovering the Genesis Rock in 1971?

In the video, one of them mentions what they are putting the sample into. The sample goes into a plastic bag, which unfortunately allowed oxygen from the lunar module and some water vapour from the South Pacific and Houston (taken in after their arrival back on Earth) to interact with the mineral troilite (iron sulfide). The seal of the bag was compromised, as many were, by the dust kicked up by the astronauts as they moved around on the Moon's surface. This dust turned out to be a greater nuisance than anticipated because each dust particle was susceptible to becoming electrically charged by friction with other dust particles. You'll see the same effect if you rub a dry plastic bag and pass it close to any fine-grained material like flour. Some of the dust stuck to the seal of the sample bag and made it incomplete. It is now thought that the rust formed once the rock returned to Earth, and so was not proof of water on the Moon.

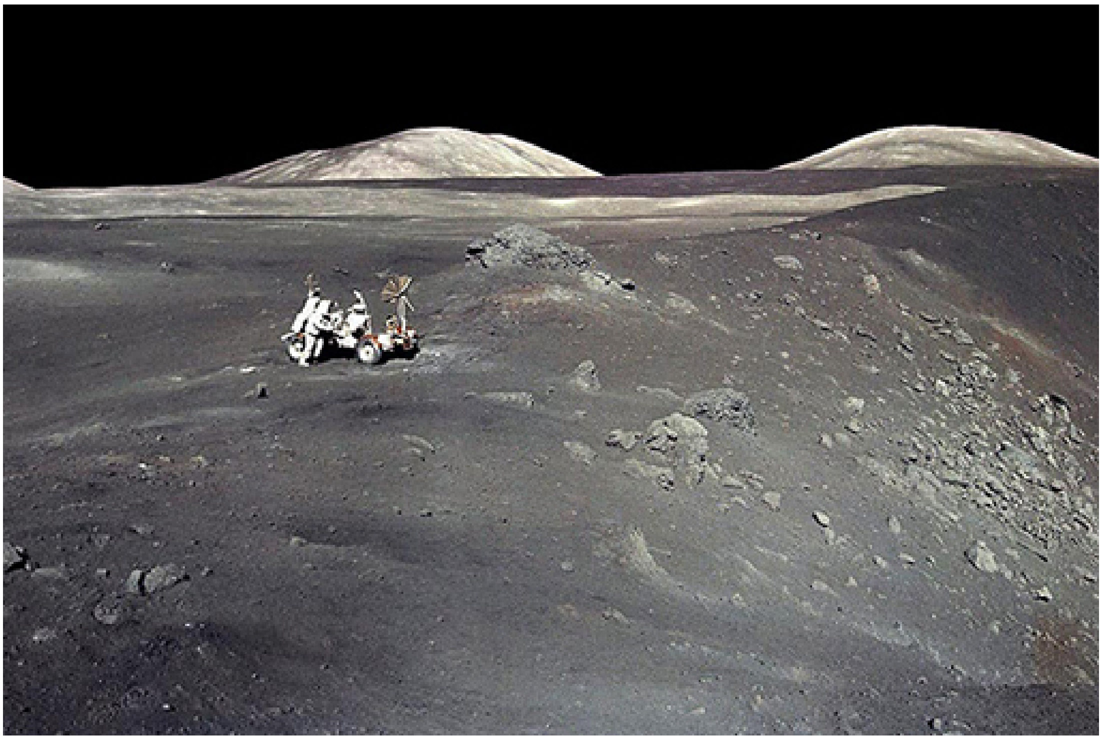

Figure 5 An image of the Apollo 17 astronauts and the moon buggy on the edge of Shorty Crater in 1972.

1.6 A paradigm shift?

The idea of a bone-dry Moon persisted for decades as the few measurements that supported the presence of water were dismissed as terrestrial contamination. That was the situation until the 1990s, when a new generation of orbiting spacecraft started gathering data.

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See also: David Rothery talks to Everett Gibson. In July 2014 David Rothery recorded a bonus video with Everett Gibson about lunar samples.

2 Odd craters

After the Apollo missions the debate over water on the Moon continued. Satellites orbiting the Moon in the last few years have discovered tiny amounts of water in ice within craters at the poles and locked up in rare minerals.

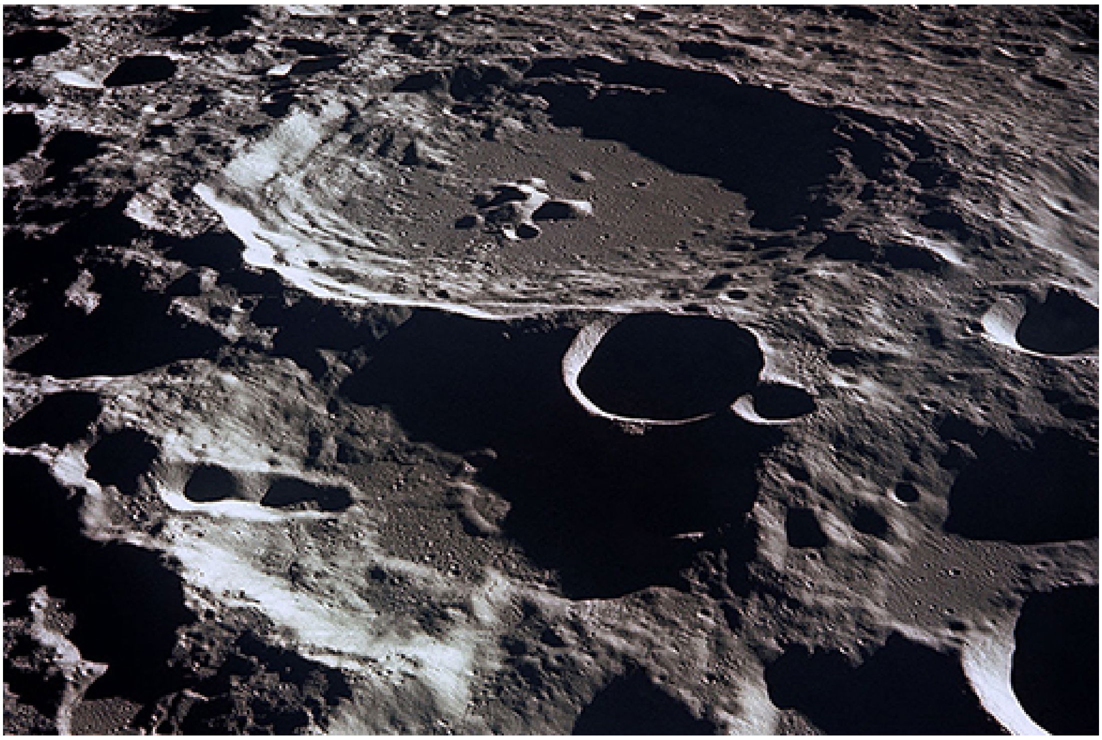

Figure 6 Odd craters

In the previous video, 'A paradigm shift?', you heard how the long-held idea that the Moon was a completely dry body has been turned on its head thanks to several recent discoveries. Now you start to find out more about these ground-breaking discoveries, and why finding water on the Moon is so important for both scientific understanding of the Moon, and further exploration of the Solar System.

To date, two distinct types of lunar water have been found: water on the surface of the Moon and water locked up inside minerals formed in the Moon's interior. This part of the course focuses on the water found on the lunar surface, how it was discovered, and how it might have formed. First, learn about water locked deep in Moon rocks.

2.1 Looking for water from lunar orbit

After a hiatus in lunar exploration of two decades from the last Apollo mission in 1972, in 1994 NASA's Clementine spacecraft was sent into orbit around the Moon with a mission to map the chemical and mineral composition of the lunar surface.

Using its on-board instruments, a mid-mission decision was made to conduct what was called the Bistatic Radar Experiment. For this experiment, the spacecraft used its radio transmitter to bounce radio waves off the surface of the Moon, bombarding the surface near the north and south lunar poles. The reflected radio waves were picked up by a powerful Deep Space Network (DSN) radio antenna back on Earth.

By looking at the scattering patterns of the radio waves, scientists were able to tell what sort of material the signals were being reflected off. This led them to an exciting conclusion, which was published in 1996; it seemed that the floors of some of the craters near the Moon's poles were coated in water-ice. Because the Moon's axial tilt is so slight, there are some deep craters near to the lunar poles that never see sunlight, and so are extremely cold. In fact they are cold enough for any water inside them to remain stable as ice over millions or even billions of years.

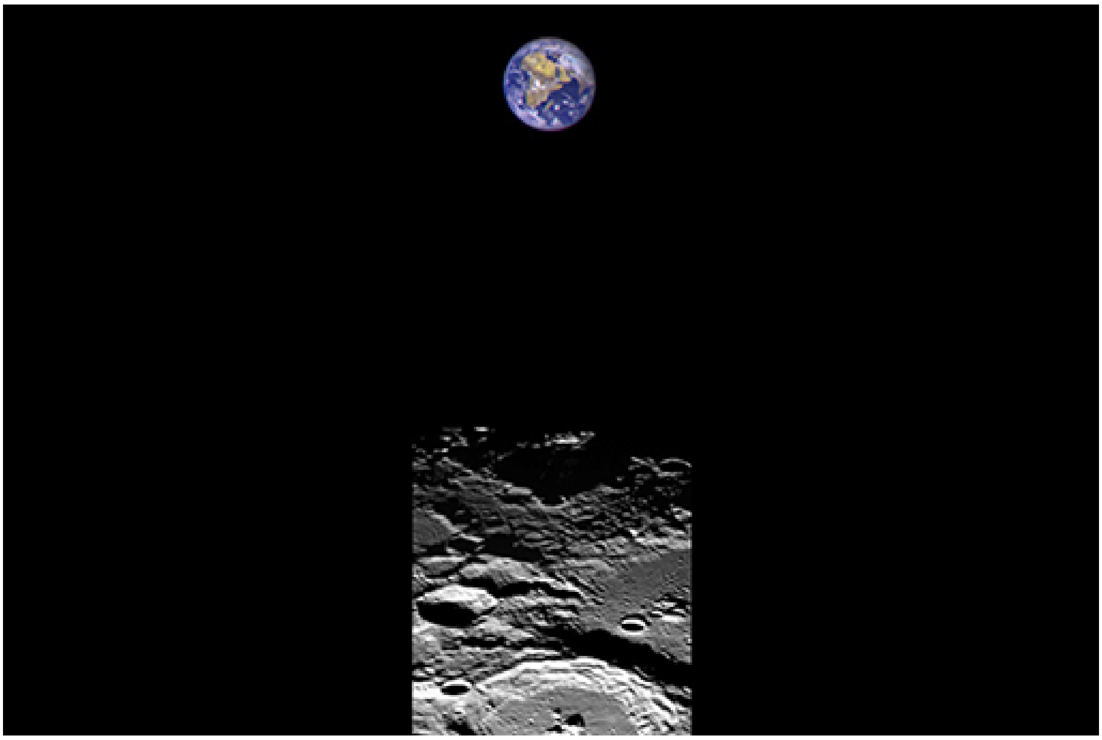

Figure 7 Image taken by Clementine of the Moon's surface with the Earth rising behind. Note the contrast in colour between the grey lunar surface, where water is difficult to find, and Earth's abundant blue oceans.

2.2 Ice in polar craters on the Moon

This image of craters at the lunar south pole contains some deep craters that are completely black – they were always in shadow. In the case of holes on Earth close to the poles the atmosphere scatters light, so some light (and heat) always penetrates, but this can't happen on the airless Moon. These craters are places on the Moon where water-ice could remain for immense spans of time.

Although the news of the radar reflections was considered very important at the time, being the first observation of anything resembling water on the Moon, there was controversy surrounding the findings. Using the Arecibo telescope in Puerto Rico, other teams of scientists were able to demonstrate that similar reflected radio signals were possible from non-shadowed regions of the Moon, where water-ice would certainly not survive during the lunar day. This suggested that the 'water-ice' seen by Clementine was just a feature of the surface roughness of the crater floors investigated.

Two steps forward, one step back. The scientific method consists of establishing a hypothesis and testing it repeatedly so scepticism is 'normal' and healthy for any new discovery. Clementine had re-awakened interest in finding water on the Moon, and had possibly found the first traces of evidence to support the idea. But it couldn't provide conclusive proof for the presence of water on the Moon, and so the uncertainty and searching continued.

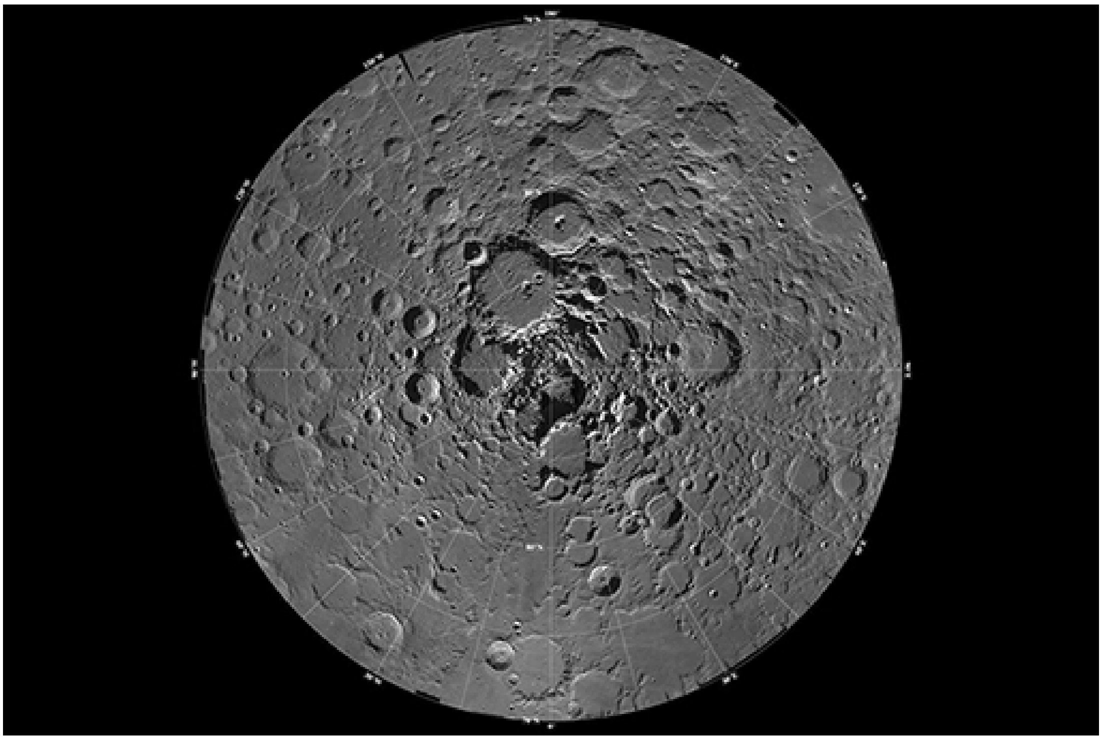

Figure 8 Image taken of polar craters by the Clementine mission in 1998.

2.3 More missions – detail and resolution

The next important milestone in the search for water on the surface of the Moon was the launch of NASA's Lunar Prospector spacecraft in 1998, designed to provide definitive answers that would either confirm or deny Clementine's findings once and for all.

This time, rather than use the same radar techniques as the Clementine mission, Lunar Prospector used an instrument called a neutron spectrometer to search for hydrogen on the lunar surface. Since water (H_2O) is made up of two hydrogen atoms to every one oxygen atom, any water-ice on the lunar surface would be expected to show up as an area rich in hydrogen.

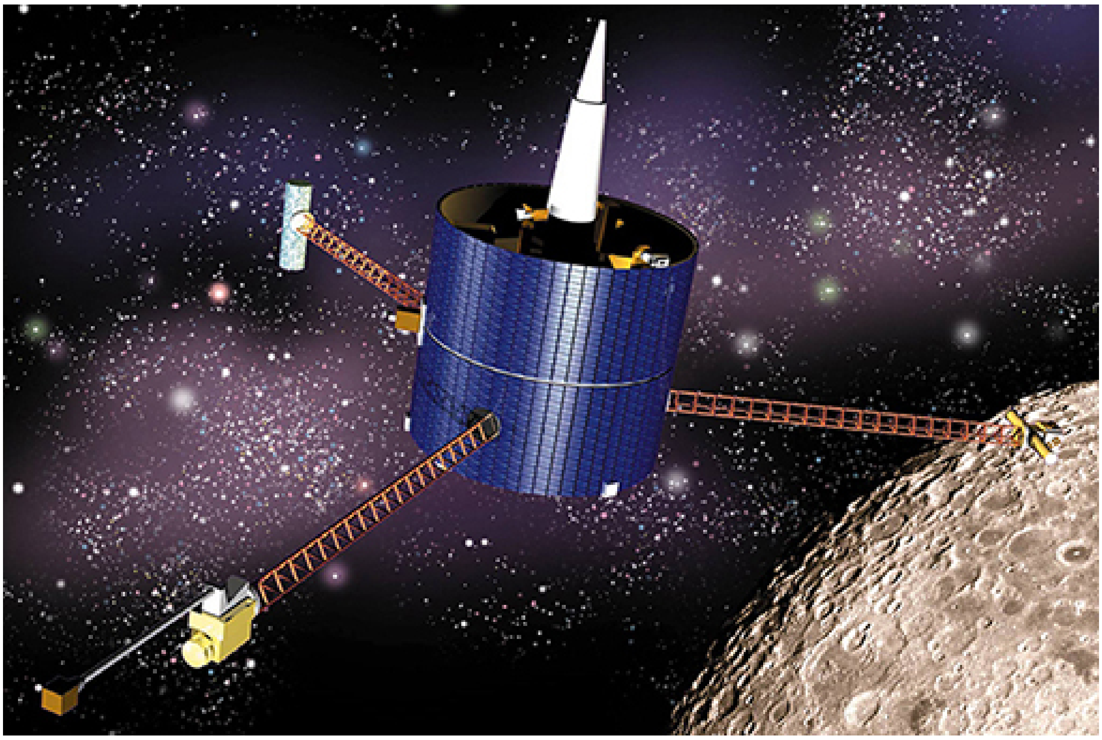

Figure 9 An artist's impression of the lunar prospector spacecraft launched in 1998, and deliberately crashed into a crater near the lunar south pole in July 1999.

2.4 Results from the Lunar Prospector mission

As with Clementine, initial findings were very encouraging; the greatest concentrations of hydrogen were seen in craters near the lunar poles, and these were taken to be in the form of water-ice, equivalent to almost 300 million metric tonnes in mass.

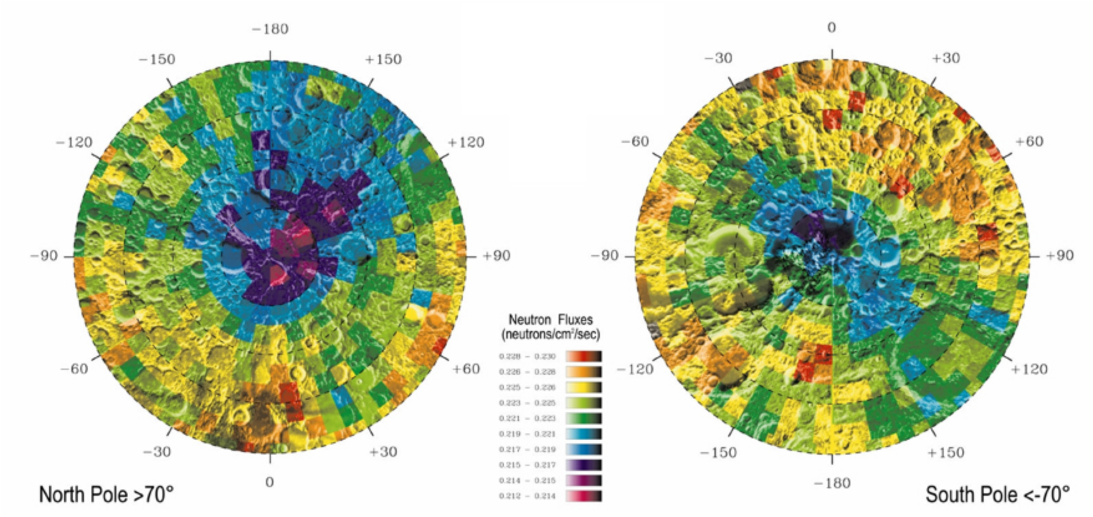

Figure 10 Neutron spectrometer results from the Lunar Prospector mission.

Figure 10 shows the neutron spectrometer results from the Lunar Prospector mission. Where fewer neutrons are measured, this indicates the presence of greater concentrations of hydrogen in that area. Areas shaded blue and purple are places where the spacecraft observed the lowest neutron counts and thus have high hydrogen abundances.

The final stage of the mission involved crashing Lunar Prospector into the Moon, in order to generate a plume of ejected material. It was hoped that any water present in this plume kicked up by the spacecraft would be detected by instruments in observatories back on Earth. However, although the crash into a polar crater went according to plan, no plume was observed at all, let alone any water-ice within it.

So, although these measurements of hydrogen matched the locations for the potential water found by Clementine, nobody had yet directly observed genuine H_2O on the surface of the Moon.

2.5 The SELENE mission

In 2007, the Japanese space agency, JAXA, launched their SELENE spacecraft, which came to be known by its nickname of ‘Kaguya’, after the lunar princess in an ancient Japanese folk story, ‘The Tale of the Bamboo Cutter’.

Kaguya orbited the Moon for 20 months, sending back stunning images of the lunar surface taken by its high-resolution cameras. These included the first ever optical images of the interior of Shackleton, a permanently shadowed crater near the lunar south pole, which was a prime candidate location for lunar water-ice to be found.

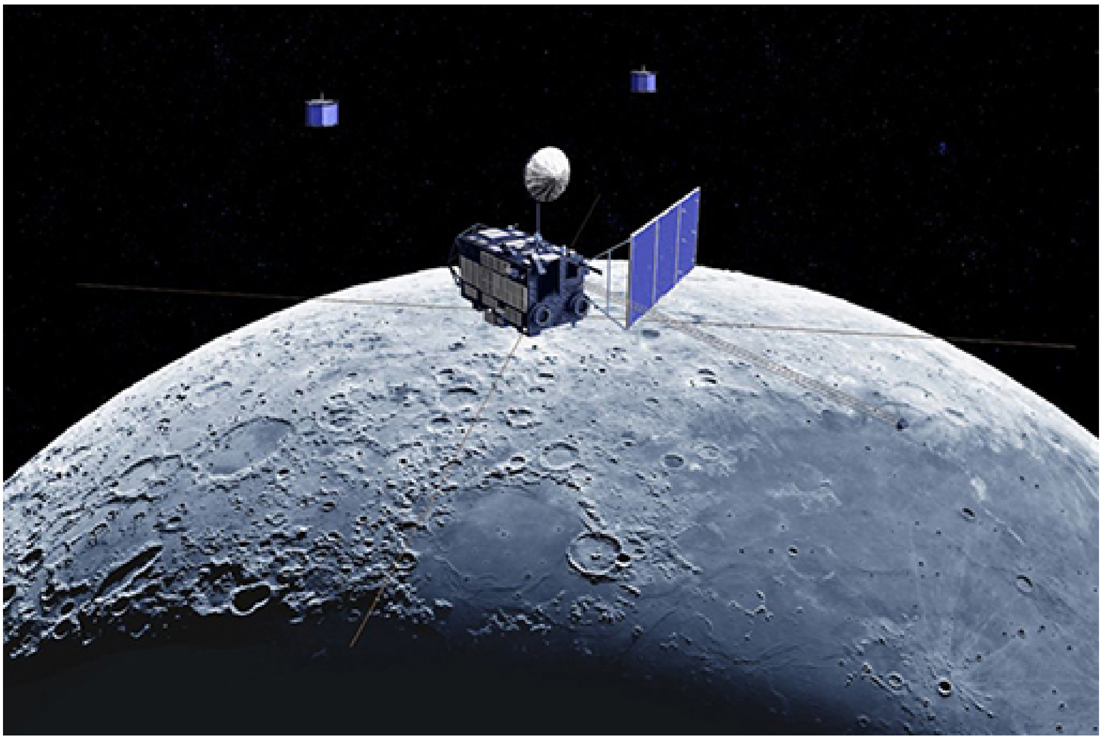

Figure 11 An artist’s impression of the SELENE spacecraft launched in 2007 and successfully completed an extended mission, crashing into the lunar surface in June 2009.

2.6 Results from SELENE

Frustratingly, however, Kaguya failed to see any evidence for water-ice exposed in the bottom of Shackleton crater, and these findings only generated further debate about the likelihood of finding any water on the Moon. (The two images above show the same region. On the left is a normal exposure. On the right the data have been processed to bring out the previously invisible detail inside the shadows, which are illuminated faintly by the sunlight reflected diffusely into them from the sunlit areas.)

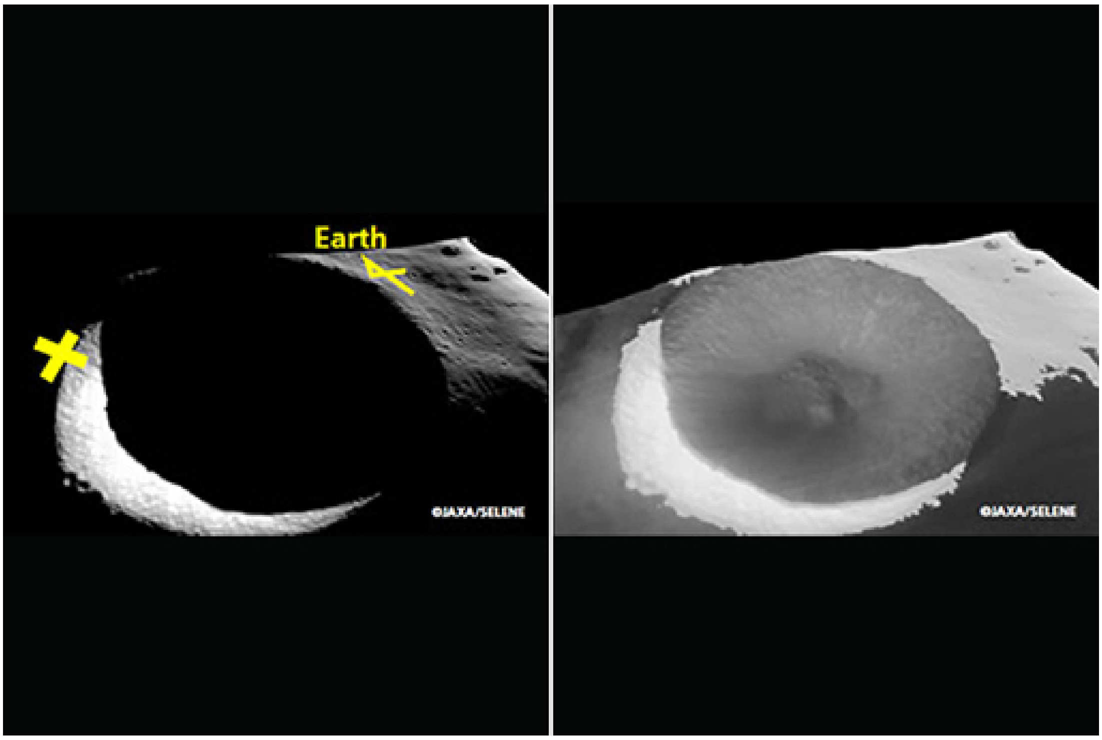

Figure 12 High resolution optical images of the Shackleton crater at the lunar south pole showing mounds imaged in the crater but no significant buildup of ice despite the temperatures permanently below -170°C. X marks the lunar South Pole. The arrow shows the direction of Earth.

2.7 The Chandrayaan-1 mission

India's 2008 Chandrayaan-1 orbiting spacecraft carried with it a NASA instrument called the Moon Mineralogy Mapper or M^3 (known as M-cubed). By observing the different absorption and reflection patterns of the Sun's near-infrared radiation hitting the lunar surface, this instrument was designed to build up a detailed map of the minerals that make up the rocks on the Moon's surface, and how these mineral compositions vary across the whole surface.

In 2009, it was announced that using this same technology, M^3 and Chandrayaan-1 had made the first measurements of H_2O and OH (hydroxyl), proving that the previously observed hydrogen was definitely in the form of water-ice. And interestingly, although by far the greatest concentrations of H_2O and OH that M^3 measured were at the lunar poles, smaller abundances were seen surrounding fresh or newly formed craters closer to the Moon's equator, suggesting that trace amounts of OH and H_2O may be present in other parts of the lunar surface, and are then concentrated and trapped in the coldest craters at the poles.

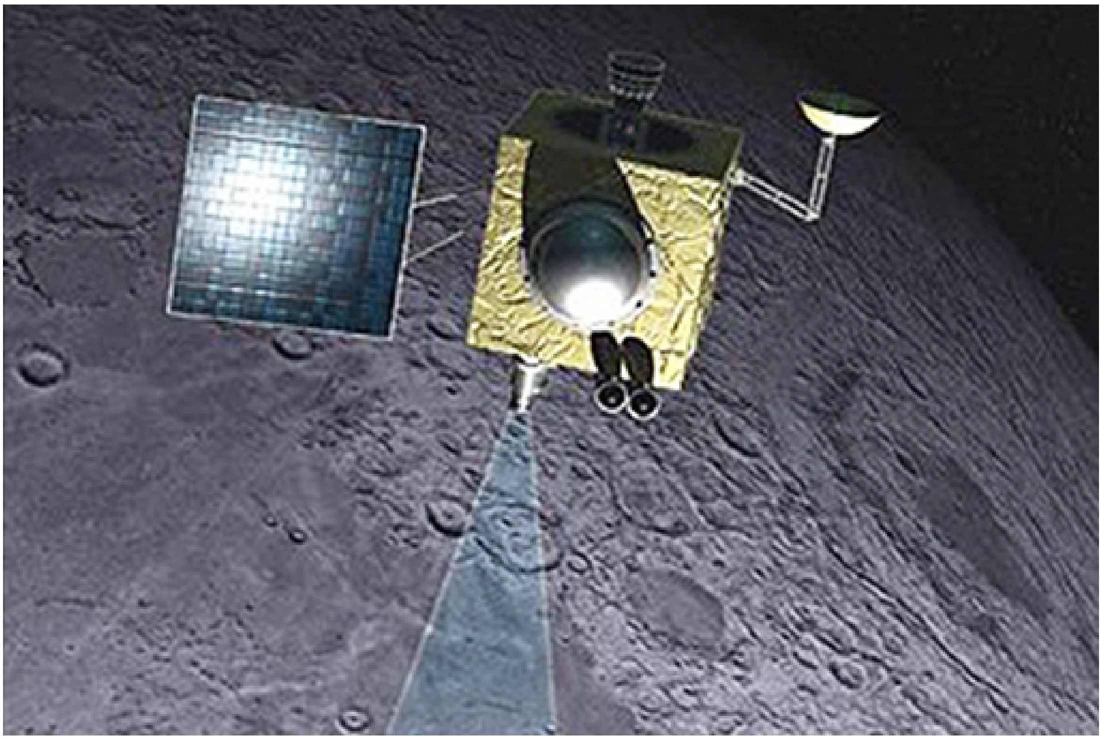

Figure 13 An artist's impression of the Chandrayaan-1 spacecraft in orbit around the Moon.

2.8 Results from Chandrayaan-1 and LCROSS

The hypothesis that Chandrayaan-1 and its Moon Mineralogy Mapper instrument had detected water was still debated but their findings were confirmed by NASA's Deep Impact spacecraft (later in 2009) which observed hydrogen all over the lunar surface.

Most recently, in the summer of 2009, NASA launched its Lunar Reconnaissance Orbiter (LRO) spacecraft, at the same time as its Lunar Crater Observation and Sensing Satellite (LCROSS) mission.

LCROSS consisted of two components: a shepherding spacecraft and a Centaur rocket stage. The Centaur rocket section was deliberately crashed into the lunar south pole crater Cabeus. The shepherding spacecraft was able to fly overhead immediately after the crater impact and record the composition of the debris plume kicked up from the surface by the force of the impact.

In November 2009, the LCROSS mission scientists were able to announce that they had made the first direct observations of water-ice particles on the Moon in this ejecta plume, and later calculated that Cabeus crater contains between 3 and 9% (the LCROSS team determined the content of the plume created was 5.6 ± 2.9%) water by mass, much more than previously thought. In addition to the water observations, hydrocarbons of low molecular mass were also measured in the plume, suggesting that perhaps other volatile compounds can exist near the surface of the Moon too.

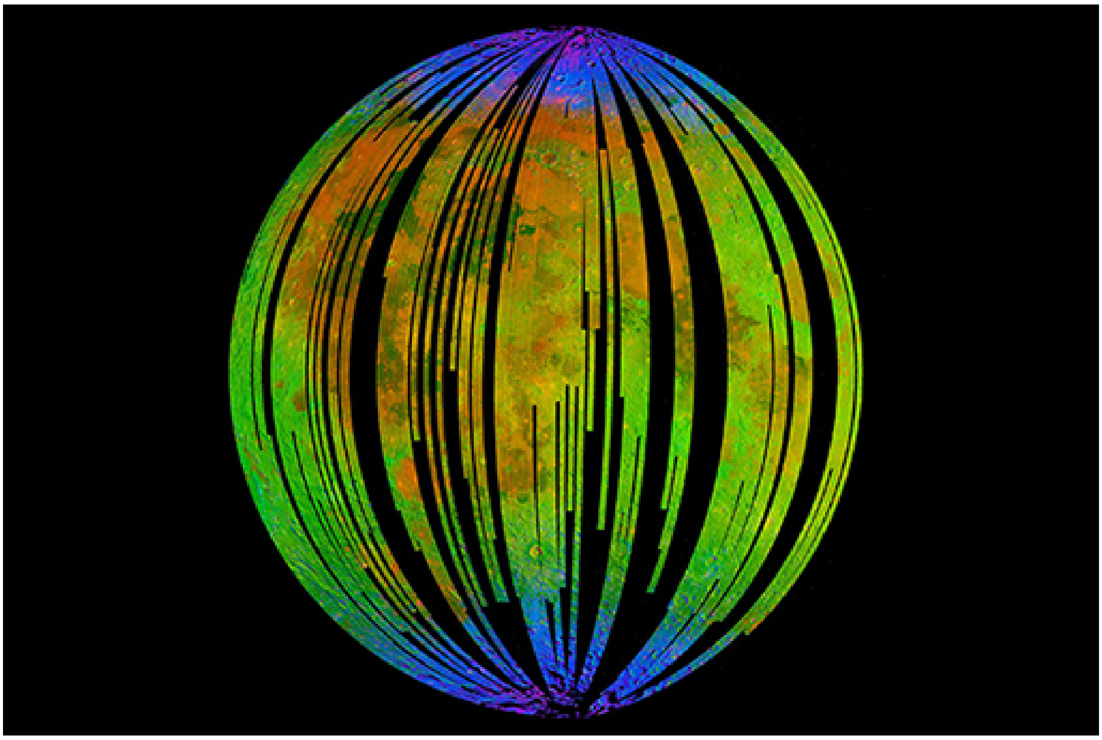

Figure 14 In this composite map of the Moon Mineralogy Mapper's findings, water and hydroxyl are coloured blue and purple, and orange is the mineral pyroxene, which contains no water.

2.9 Where does water on the Moon's surface come from?

There are two main candidates for the origins of water on the surface of the Moon: water carried to the Moon from elsewhere and water formed in situ on the Moon's surface.

First, with no atmosphere to protect it, the Moon is regularly bombarded by comets and asteroids, both of which contain water from elsewhere in the Solar System. As you saw earlier in the course, many of the outer Solar System moons contain large amounts of water and ice.

During a comet impact, its water molecules evaporate, and some are blasted away from the surface back out into space, but some are trapped back down onto the lunar surface and are adsorbed onto mineral surfaces or into cold 'traps', in permanently shadowed craters. Some craters on the Moon hold the record for having the coldest recorded temperatures in the Solar System, down to 20 kelvin (-253 °C). Because the Moon experiences very little reworking of surface material (unlike the Earth), water delivered to the Moon in this way can build up slowly via thousands of impacts, over millions of years, to form the icy deposits observed in polar craters.

The other possibility involves the production of water or hydroxyl (OH) on the lunar surface due to the interaction of charged particles from the Sun (the solar wind, which you met in Week 4) with material on the Moon's surface. The solar wind bathes illuminated parts of the Moon's surface with charged particles, mostly protons, which are hydrogen ions (H^+) for the purposes of chemistry. When these protons come into contact with oxygen atoms inside the structures of minerals that make up the rocks and soil on the lunar surface, they form a chemical bond together and make hydroxide ions (OH^-). These OH^- ions are adsorbed onto the surface of lunar rock or soil minerals, and so are trapped there. If enough protons are delivered to the immediate area, or if another hydroxide group forms nearby, an extra proton may be added to the OH^-, forming H_2O (water).

This newly formed water molecule then experiences a series of successive episodes of evaporation and condensation. Heat from the Sun causes the water to evaporate (remember the Moon's surface heats and cools far more than the surface of the Earth because it has no atmosphere) and when it is free from being trapped to a mineral surface, it will 'bounce' around. If it hits a warm surface it will rebound, but if it hits a cold surface it will tend to stick. It will evaporate again when the surface warms up, but if the surface is permanently cold, it will stay there. Over time, water molecules can 'hop' across the lunar surface, from the warmer sunlit regions where they form, to the cold permanently shadowed polar craters where they accumulate as water-ice and are measured in greater abundance.

However, both of these processes – the delivery of water from elsewhere in the Solar System and its generation in situ – may be important for making lunar surface water, and they form the focus of a lot of on-going research; so keep your eyes open for new revelations as our understanding of the Moon's water evolves.

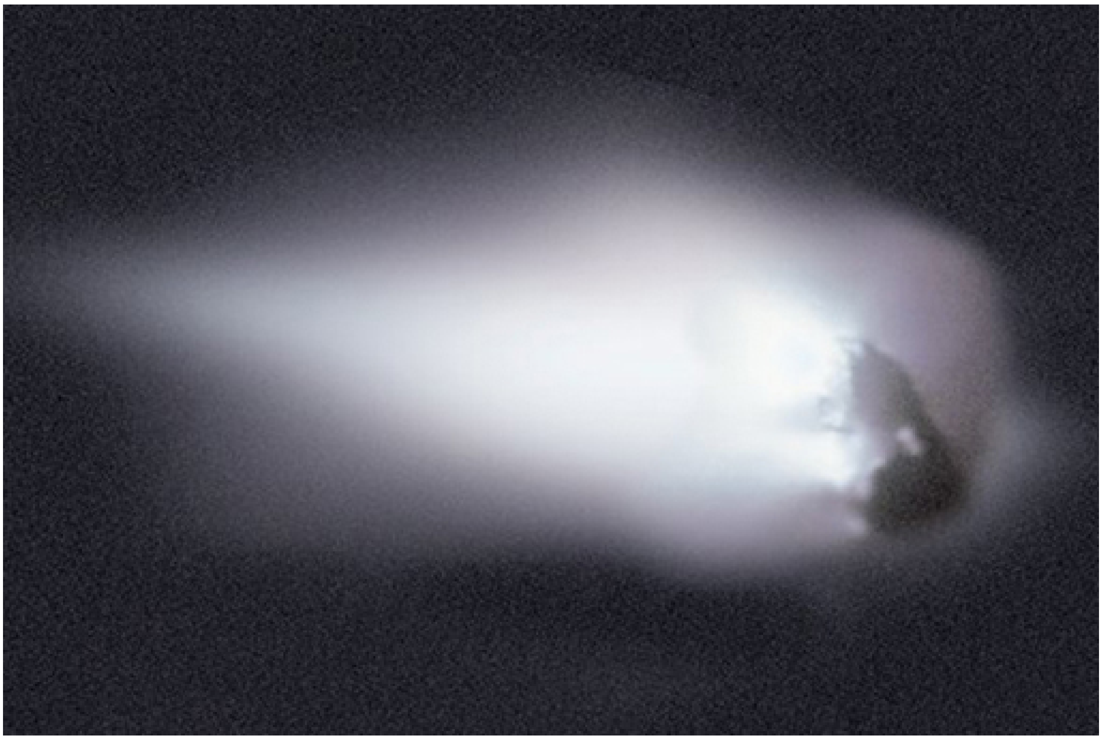

Figure 15 Image of the nucleus of comet Halley taken during the Giotto mission in 1986. Comets are thought to be the main source of water now found in craters at the lunar poles – but there may be other sources.

2.10 How much water?

Thanks to all of the spacecraft observations that you've studied this week, scientists are now able to state with certainty that there is indeed water-ice present on the surface of the Moon. But one key issue that remains unresolved is exactly how much lunar water there is. LCROSS measured 5.6% water in the plume generated by the Centaur impact into the floor of the Cabeus crater, but is that representative of all other polar craters, or is it exceptional in terms of its relatively high water content?

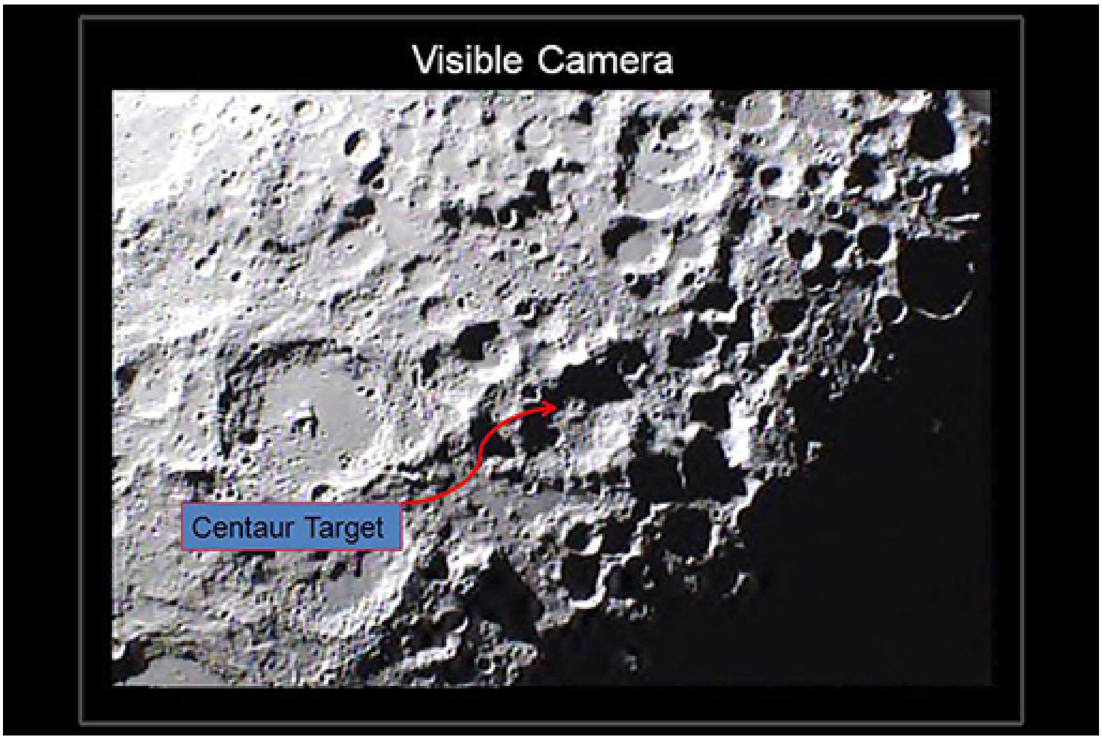

Figure 16 Image of the Cabeus crater showing where the LCROSS mission crashed the Centaur rocket section.

Given what is now known about the extent of the locations water is found in, and the mechanisms that are suggested for forming water on the Moon's surface, how much water do you think there is on the Moon? How many swimming pool equivalents? And given the resources, how might you set about testing to see if you are right?

One thing is clear from the successes of the last few decades: finding water on the Moon is a big task, and needs people to work together to build up knowledge, so get sharing!

3 Water from a stone

The discovery of water was significant to more than a few academics. Water is key to human life and as a potential fuel. The presence does open new opportunities for habitation and long-distance space travel.

Figure 17 Water from a stone

Water is widely recognised as being important in many geological processes that take place on Earth. In particular, it has been shown to greatly affect the physical properties of magmas in the crust and erupting from volcanoes, the stability of melts, and processes that occur during eruptions. In contrast, it is widely accepted that lunar magmas did not contain sufficient water to influence such properties. This has influenced our understanding of the structure and evolution of the Moon. But geologists have also found evidence for a 'wetter' moon than we first imagined.

In 2008 a group of scientists at Brown University (in Rhode Island, USA) led by Alberto Saal, measured volatile elements including water in lunar volcanic glass beads, using an instrument called an ion microprobe. This instrument is capable of analysing very small areas of samples and detecting the water that is present at levels of just 0.005%. Saal and his colleagues found that the glass beads contained measurable quantities of water, and also sulfur, fluorine and chlorine. Importantly, they were able to make several measurements in each glass bead and detected higher concentrations in the centre of the beads, and decreasing amounts towards the outer surface. This type of pattern is known on Earth and suggests that water molecules were present in the droplets of liquid magma when it erupted from the volcano on the Moon, but they were leaking out into the vacuum of space as the glass cooled. The reason the water is still there 3 billion years later is that the glass cooled so quickly that not all of it could escape during the eruption. Using measurements of water movement in similar-composition glasses on Earth, Saal and his colleagues calculated that the lunar magmas contained at least 260 parts per million (0.026%) of water. This is around one-tenth of the percentage found in lavas erupted on Earth, but new instruments, such as the ion microprobe, being used by geologists are now capable of detecting this level routinely.

3.1 Water in lunar minerals

While the first evidence for small amounts of water in lunar rocks came from analyses of volcanic glass beads, there are also signs of water in the minerals of crystallised Moon rocks, because some minerals that have been found in Moon rocks are capable of holding small amounts of water as structurally bound hydroxide (OH^-) ions. The most suitable mineral candidates are apatite (phosphate of calcium) and amphibole because both minerals contain OH^- (derived from water) as an essential structural constituent. While amphibole is extremely rare in lunar rocks, apatite is more common.

Figure 18 Large apatite crystals from Quebec in Canada. There crystals are several centimetres long, apatites in lunar rocks are commonly less than a tenth of a millimeter across.

Apatite contains structurally bound water (H_2O) in much higher concentrations than the glass, as much as 0.7%. The amounts of water in apatite are much higher than in the glass, so scientists are able to make different kinds of measurements and explore the reasons why the water is there and where it came from. This is a very exciting area of lunar science, and recently Open University researchers have measured the hydrogen isotope ratios, specifically the deuterium : hydrogen ratio in apatites. (Deuterium is hydrogen with an extra neutron, written ^2H. Ordinary hydrogen, when viewed as an isotope, is written ^1H.) They have discovered that Moon apatites have very similar ^2H : ^1H ratios to their terrestrial counterparts. This is significant because the ratio is different from that in samples from other Solar System bodies, such as meteorites.

This is an area of science that is currently changing very rapidly as new discoveries are made, but if confirmed, these findings may indicate that the water in lunar rocks came from the early Earth. The most likely scenario is that this occurred during the giant impact Moon-forming event. The new discoveries appear to be tying the Earth and Moon together even more strongly, making it a truly unique pairing in the Solar System. This doesn't mean the Earth's oceans are leaking water to the Moon; remember that this event happened just a few million years after the Earth formed, and the unaltered lunar rocks in which these measurements have been made are older than any rock at the Earth's surface.

See also: The search for water on the Moon A video by Open University lunar scientist Mahesh Anand (2m21s).

3.2 Uses for water on the Moon

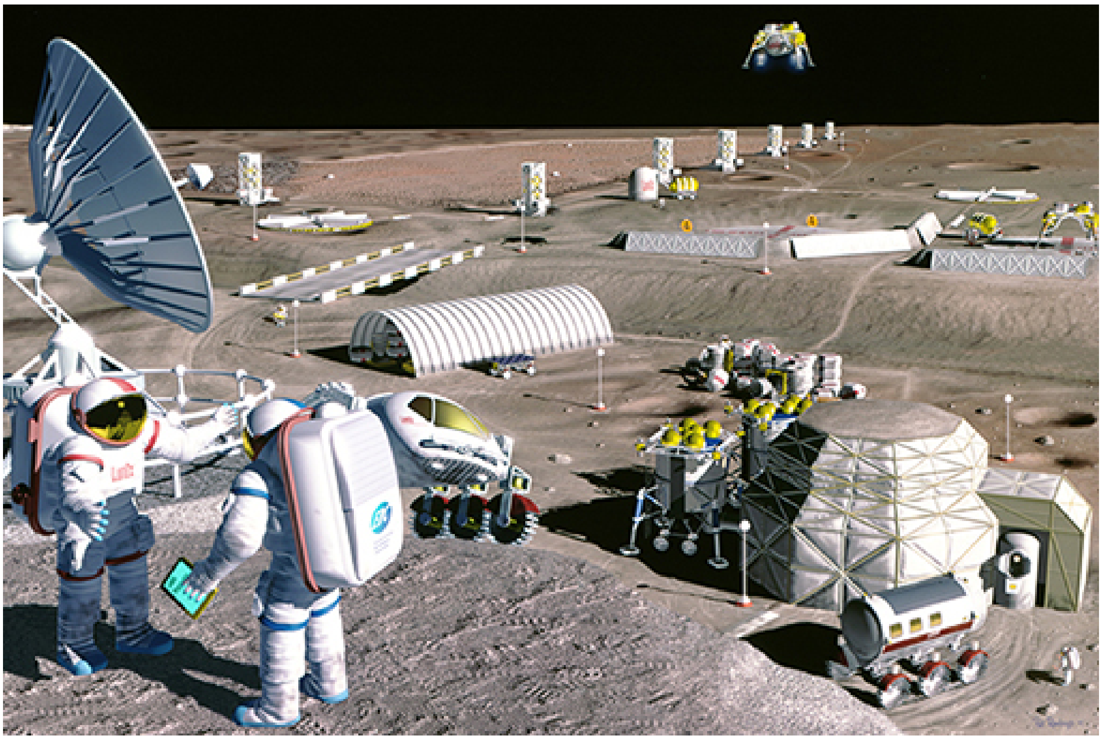

Figure 19 Uses for water on the Moon

Throughout this week, you've heard about how the Moon was thought to be dry, and then how it was discovered that there was water on the Moon. Why is this important? What can be done with this water? What can this tell us about water on other moons? These are interesting topics to consider.

3.3 The future of lunar exploration

Paul Spudis says in the video that the exploration of our Solar System is not just important for science, but potentially for the future of our species and that the Moon has an important part to play in both of these. Do you agree?

The resources available on the Moon's surface include metals from the lunar soil, solar energy to provide power, and water from permanently shadowed regions of craters near the poles. All this could enable infrastructure to be built, allowing humans to create a lunar base. A satellite system is the first thing needed to be placed in orbit around the target body, and this has been done for both the Moon and Mars. This allows communication with landers and surface roving vehicles. Technology will play a big role in these quests.

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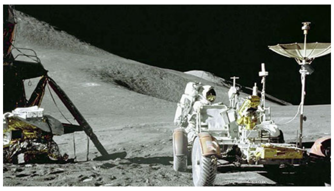

See also: The Value of the Moon If you want more from Paul Spudis on this subject, here is a 50 minute talk by him recorded in October 2016.

3.4 The economics of it

When the Apollo Moon rocks were analysed, they were discovered to lack the water content that would be expected based on analyses of similar rocks on Earth. Even the recently discovered water in glass and minerals is at too low a concentration to make its exploitation viable. However, the discovery of water on the Moon surface has brought up new questions for humankind, with some of the most interesting and controversial being related to how we can utilise this resource.

The heavier a vehicle being launched into space, the more it will cost to launch it. If certain items could be removed from the launch vehicle or just reduced, money could be saved. If the water on the Moon is drinkable, less water may need to be taken on a lunar mission, which would save significant amounts of money and extend the time astronauts could remain on the Moon.

Even more important than water for humans is the gas oxygen. Without oxygen, no human can last more than a few minutes. In the past, oxygen tanks have been supplied for space walks. The water on the Moon could undergo a process (explained in the next step) to extract the oxygen from it, thereby putting less of a constraint on the amount of time that could be spent on the Moon. Rather than relying on oxygen being transported, it could be generated on the Moon.

Rocket fuel is a very expensive commodity and it gets used up very quickly, so finding an alternative fuel is important if we want to develop better methods of flying to and from the Moon. Using electricity (which can be generated from sunlight using photovoltaic cells like those on Earth), rocket fuel can be created using water and some simple pieces of equipment. The technique is called electrolysis and it uses simple chemistry to separate the water into hydrogen and oxygen gas, as you'll see in the next step.

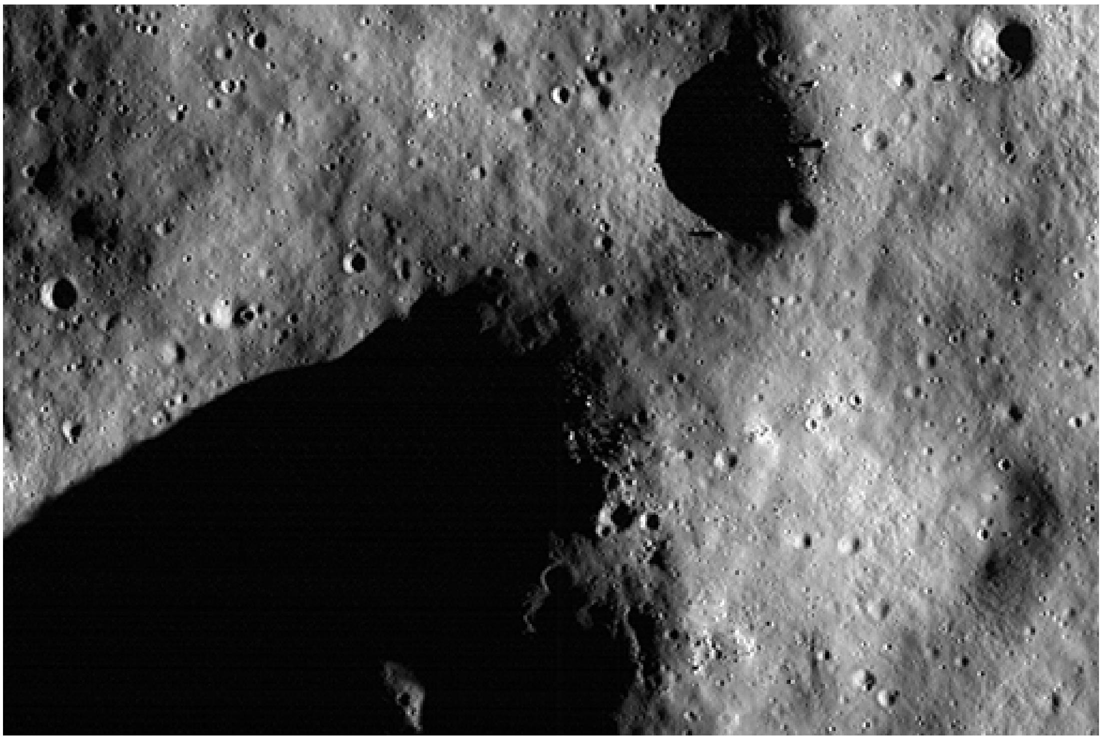

Figure 20 A heavily cratered area of the lunar surface. Some of the craters preserve ice in permanently shadowed crater floors.

3.5 Making rocket fuel

Water as we know it on Earth consists of hydrogen and oxygen atoms bonded together (H–O–H). To separate these elements requires an electric current and two electrodes, called a cathode and an anode. These electrodes have opposite charges: the cathode is negative, the anode positive. When the water is placed in a container with the electrodes and the electric current is switched on, there is an enhanced tendency for the water molecules to dissociate into hydrogen ions (H^+) and hydroxide ions (OH^-). (Water molecules have some tendency to dissociate even without help from us!) The hydrogen ions are then attracted to the cathode and the hydroxide ions are attracted to the anode. The hydrogen and oxygen can then be stored away in separate containers in their elemental form until they are needed.

Now you have seen that an input of energy in the form of electricity was needed to split water into hydrogen and oxygen. It should not be a huge surprise then to discover that if the two elements are brought back together, the result will be a release of energy with the production of water. In fact, the release of energy is so explosive that these elements can be used as rocket fuel. Liquid hydrogen and liquid oxygen were used to propel the second and third stages of the Saturn V rocket that sent Apollo to the Moon. The first stage of Saturn V used a special type of kerosene and liquid oxygen. Why the difference? You may have already guessed part of the answer: cost. The amount of fuel required to launch a spacecraft from the surface of an object, be it the Moon or Earth, is quite high. The bigger the object, the more fuel required to escape its surface, which is one of the reasons combustion of pure hydrogen and oxygen obtained by electrolysis of water hasn't been used on Earth for rocket launches. Another important reason why this hasn't been used on Earth is because of the high cost of the electricity to create the fuel. This might be less of a problem on the Moon though.

Figure 21 Apollo 15 launched on the 26th of July 1971.

The lunar poles are subject to over 80% sunlight in certain regions. The areas with water are also in the lunar polar regions. If the sunlight can be harvested using solar panels, enough energy could be produced to use electrolysis to make rocket fuel from the water. And, as you know, the Moon has less gravity than the Earth, so less fuel is required to escape the lunar surface. If we were able to get to the Moon and set up the equipment, it might be possible to return to Earth using rocket fuel made from lunar water (assuming there is enough water available).

If you still have time now you have almost finished this week's work, you will probably enjoy ESA's marvellous 8-minute video Destination: Moon that goes through the history and possible future of lunar explanation, ending with the manufacture of rocket fuel from lunar water.

But before you move onto the next section you may find it interesting to watch the following video, which is a recording of a live video presentation in which answers to some of the questions raised earlier in this course are given.

View at: youtube:Kda_GCws1pc

See also: NASA - SELENE data suggests no perpetual sunlight on lunar poles

4 This week's quiz

This quiz allows you to test and apply your knowledge of the material in Week 6.

Complete the Week 6 quiz now.

Open the quiz in a new window or tab then come back here when you're done.

5 Summary

This week focused on the debate around water on the Moon. Next week you will be looking at other moons and the latest technologies used to explore our Solar System's moons.

You should now be able to:

- understand the debate around lunar water and the two kinds of Moon water
- explore examples of how science advances by continuously testing hypotheses.

You can now go to Week 7: Exploring moons.

Week 7: Exploring moons

Introduction

Find out about the missions that gave us our first close-up views of distant moons: Voyagers 1 and 2, Galileo and Cassini-Huygens. Learn why probes are crashed into giant planets rather than risk crashing into a moon.

Here Jess reflects on the past three weeks and then introduces the missions that have taught us most about other moons. Windsurfing on Titan anyone?

Please note that when Jess refers to Titan as 'the only moon in the Solar System with an atmosphere' she should have said that it is the only one with a '*dense* atmosphere'.

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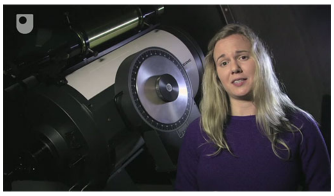

By the end of this week, you will have an understanding of:

- the missions that have explored moons in the outer Solar System
- the surface and atmosphere of Titan
- some medium-sized icy moons.

1 Finding new moons

This week is all about exploration. How do we know about all these moons that you've been looking at? Well, apart from our own rather obvious Moon, it all began with telescopes of course. You may remember about Galileo discovering the four large moons of Jupiter in 1610. By 1700 five satellites of Saturn were known. Within six years of his discovery of Uranus in 1781, Sir William Herschel had found two of its moons. Triton, the largest moon of Neptune, was discovered less than three weeks after the planet itself was first seen in 1846. As time went by, smaller and fainter moons were discovered, either by peering or by taking long-exposure photographs through telescopes. Phobos and Deimos, the two small moons of Mars, were discovered visually using a 66 cm telescope in 1877. By 1950 the tally of outer-planet satellites was: Jupiter eleven; Saturn nine; Uranus five; and Neptune two.

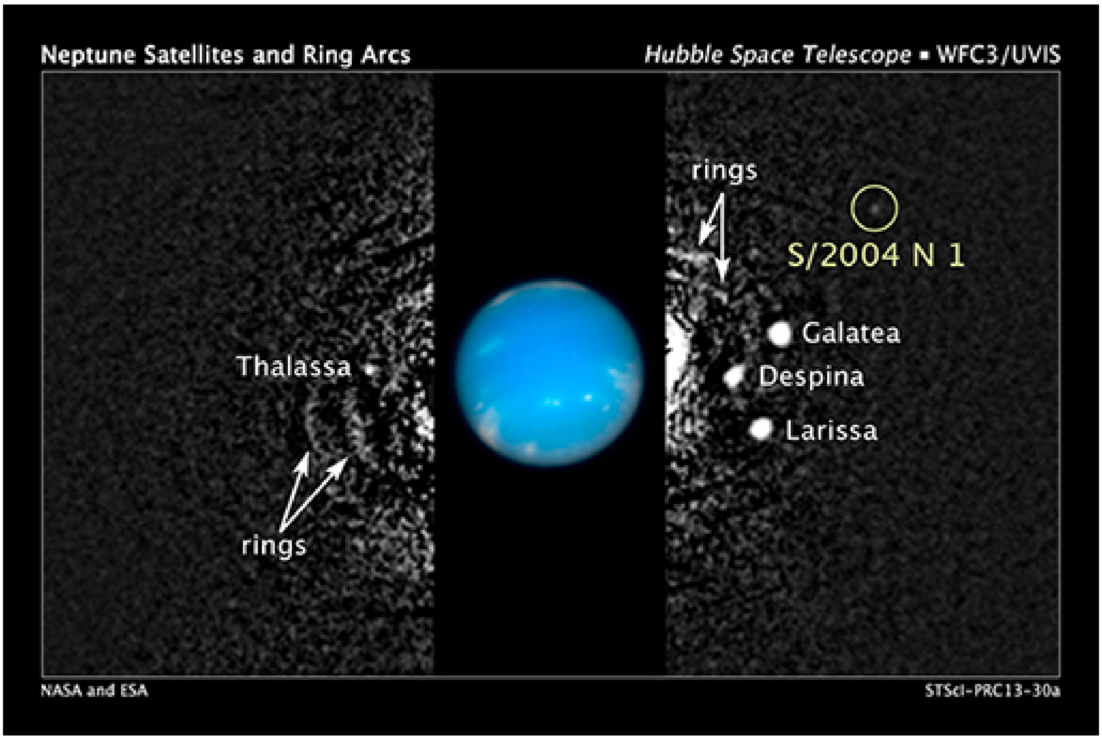

Figure 1 A new moon of Neptune, provisionally designated S/2004 N 1, as seen by the Hubble Space Telescope in 2009.

Discoveries continue to be made using telescopes, such as the fourteenth known moon of Neptune (S/2004 N 1), only 20 km across, announced in July 2013 while this course was being prepared and shown in the figure above. (It was first noticed in July 2013 on Hubble Space Telescope images made in 2009, but subsequently found on Hubble Space Telescope images dating back to 2004, hence the 2004 designation in its provisional name).

However, many first sightings have also been made by visiting spacecraft, and without the close-up detailed images that these probes have beamed back to us, we would not have much to excite you – unless you really like orbits! That's not quite fair, because by analysing the sunlight reflected from the moons that are large enough to give a clear signal (a technique called spectroscopy) you can tell what the surface is made of. Between the 1950s and 1970s it became clear that many moons at Jupiter and beyond have surfaces dominated by water-ice. Exceptions include Titan, whose spectrum is dominated by methane (which we now know to be in its atmosphere), and Io, where there is no ice but plenty of sulfur. But knowing their surface composition is not nearly enough to tell us what they are really like.

This week, you will discover what spacecraft can tell us about moons a long way from home. The week begins with the history of outer Solar System exploration, which basically means the four great projects so far: the two Voyagers, Galileo and Cassini–Huygens.

1.1 The Grand Tour

In the 1960s and 1970s, NASA was the only space agency with the capability to send a probe to the outer Solar System. Proposals were made to take advantage of a rare alignment of the planets to allow a single mission to fly past Jupiter, then onwards in turn to Saturn, Uranus and Neptune and maybe even onwards to Pluto. This was dubbed the ‘Grand Tour’. It wasn’t so much the shortness of the route from planet to planet that was important; it was that a spacecraft could take advantage of the first planet’s gravity to swing its trajectory onwards towards the next target, and so on, in a so-called ‘gravitational slingshot’ manoeuvre – known more prosaically as a ‘gravity-assist manoeuvre’. You may recall that it was just such a manoeuvre round the Moon that was critical in getting Apollo 13 home safely.

At that time, the prime goals for exploration were the planets themselves. Few people expected their moons to be anything like as fascinating as we have now discovered them to be. In preparation for this proposed Grand Tour, NASA launched two trial probes: Pioneer 10 in 1972 and Pioneer 11 in 1973. Pioneer 10 flew past Jupiter in 1974. Pioneer 11 flew past Jupiter in 1975 and past Saturn in 1979. By today’s standards, these were very simple probes, lacking anything that we would count as an on-board computer, and able to store only a very limited number of commands transmitted from Earth. The images they beamed back were of poor quality (and few were of the moons). However, they did prove that a space probe can survive passage through the Asteroid Belt, which lies between Mars and Jupiter. These probes also showed the strength of the magnetic fields and radiation belts close to Jupiter and Saturn that future missions would need to withstand.

Neither of the Pioneers passed close to any more-distant planets, but being the first probes from Earth whose trajectories would ultimately take them beyond the Solar System and into interstellar space, each carried an engraved gold-coated plaque bearing symbolic greetings from Earth and other graphics intended to allow the point of origin to be traced by any beings who might one day salvage the craft.

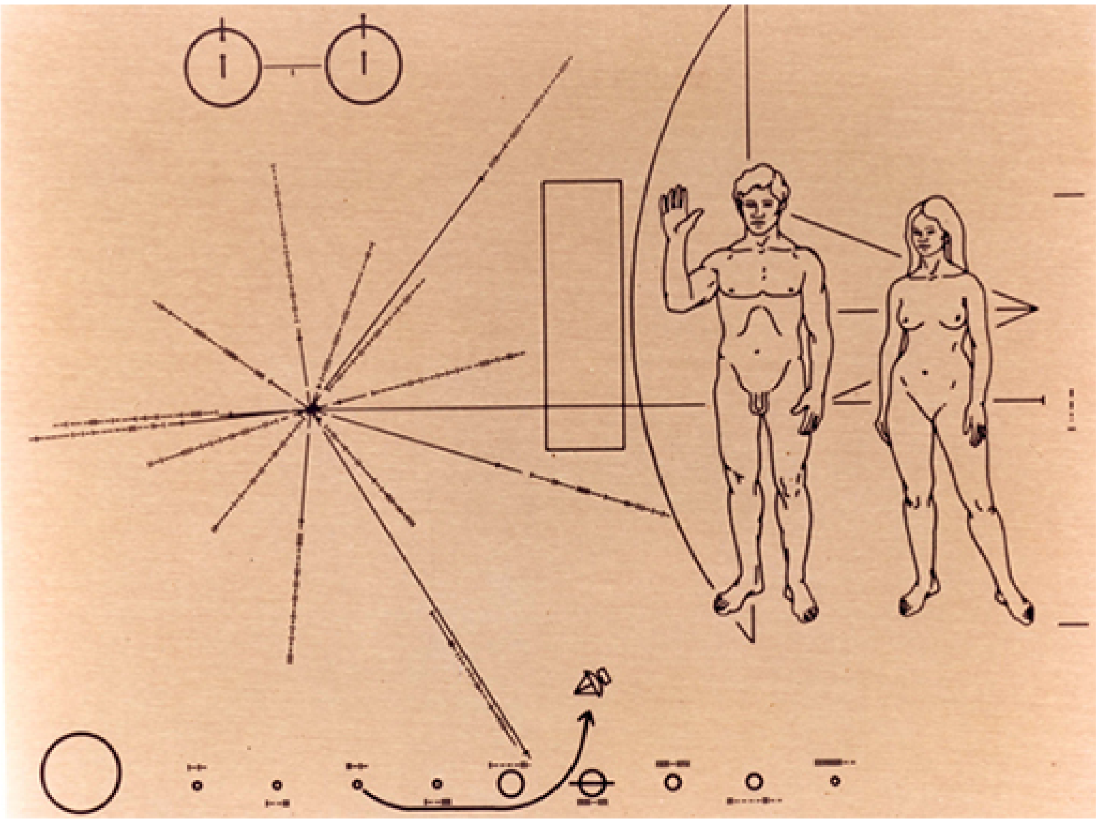

Figure 2 The plaque carried by Pioneers 10 and 11. Actual size 23 cm by 16 cm.

1.2 Voyager

Even while NASA was launching its two Pioneers, the budget for its ‘Grand Tour’ mission was being cut. Fortunately NASA was able to salvage a more modest programme called Mariner Jupiter–Saturn, soon to be renamed Voyager. These two probes were launched in 1977, flying past Jupiter in 1979 with their arrivals timed to fly as close to as many moons as possible either on the way in or on the way out. Voyager 1 reached Saturn in December 1980 and was then diverted to pass behind Titan so that its atmosphere could be studied by beaming a radio signal through it towards Earth. This encounter flung Voyager 1 onwards at an angle of 35° above the plane of the Solar System. It is now the most distant human artefact, about 130 times further from the Sun than the Earth at the start of 2015, but it is still in touch thanks to its radioactive power source, sending back data on the local particle density and magnetic field strength.

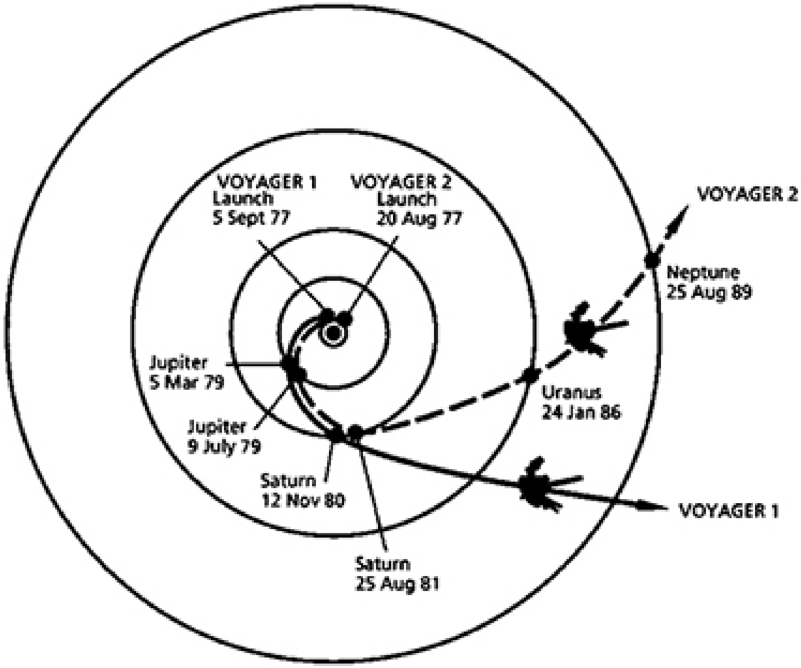

Figure 3 A historic NASA graphic showing the trajectories of Voyager 1 and Voyager 2, the positions of Earth at launch and the positions of Jupiter, Saturn, Uranus and Neptune during each fly-by.

Voyager 2 reached Saturn in August 1981, and because it was still functioning very well, permission was granted to keep the project alive and continue onwards to Uranus (1986) and Neptune (1989). Although the cameras had not been designed to function in the low light levels encountered so far from the Sun and the antenna was not designed to transmit large volumes of data over such a great range, software fixes were transmitted to its on-board computer that circumvented most problems.

There was no way to direct Voyager 2 onwards to Pluto (at the time the most distant known target), which will remain largely mysterious until the New Horizons mission flies past in July 2015.

Headline moon discoveries by the two Voyager probes include:

- discovery of erupting volcanoes on Io (a moon of Jupiter)
- three new moons of Jupiter
- dense atmosphere of Titan (the largest of Saturn's moons)
- seven new moons of Saturn
- geological variety on Miranda and Ariel (two of Uranus' moons)
- ten new moons of Uranus
- nitrogen-ice polar cap on Triton (the largest of Neptune's moons)
- six new moons of Neptune.

1.3 Voyager – inspiring generations

This video may perhaps make you realise what an amazing achievement the Voyager project has been. Some of the speakers are scientists who were involved in the project since its inception; others are those influenced by Voyager since childhood.

Video content is not available in this format.

1.4 Voyager – last picture show

This classic NASA video from 1989 shows all four planetary flybys of Voyager 2, but dwells longest on Neptune, its rings and its moon Triton. It's a blend of animation and actual images. Hopefully by now you'll recognise many of the moons featured. The '3-D' views of moon surfaces are not real; they're simulations based on the actual images.

There's music and some background sound on this video but no commentary. The strange wire-like lines you see at times are representations of magnetic fields and radiation belts.

If you want to keep track of the Voyager mission, you can do so by visiting the Voyager Interstellar Mission website.

Video content is not available in this format.

1.5 The Galileo mission

Having flown past the giant planets and their satellites, the next logical step was to go into orbit about one of these planets, to allow a longer look (to observe changes) and more complete imaging (planetary flybys don't allow you to see both sides of a moon in detail). Getting into orbit is more difficult than merely flying past, because you need to use rocket fuel to slow down and change your direction of travel. To maximise the number of instruments carried you need to save on fuel. With this in mind, mission planners these days usually arrange for their probe to fly past other planets on the way to their destination, to speed it on its way and to help it arrive at its destination from a direction that makes capture into orbit relatively inexpensive in terms of fuel.

Such was the plan for Galileo, the first probe to orbit Jupiter. It was meant to be sent into space by the Space Shuttle Atlantis in 1986 but the loss of the Space Shuttle Challenger earlier in the year delayed the launch until 1989.

Galileo's gravity-assist trajectory took it past Venus in 1990, then twice past the Earth before flinging it outwards towards Jupiter. On the way, it made flybys of the first two asteroids to be seen at close quarters: Gaspra in 1991 and 243 Ida in 1993. Everyone was surprised when, several months later, a tiny moon of Ida, now named Dactyl, was spotted on images of Ida that had been awaiting processing. This was the first moon of an asteroid to be discovered, and the only one that has yet been seen at close quarters, though as you saw in 'The moons of asteroids' video back in Week 3, several others are now known either from optical telescopes or from radar observations.

Galileo achieved orbit about Jupiter in 1995, and also sent a probe by parachute into Jupiter's atmosphere. The orbital tour was a complex affair, with numerous adjustments to give as many close flybys of the large moons as possible. Just before manoeuvring fuel ran out, it was deliberately crashed into Jupiter in September 2003.

The amount of data, especially images, beamed back to Earth by Galileo was less than planned, because unfortunately its main parabolic antenna failed to deploy, with the result that all communications had to be via its small low-gain antenna. However, resourceful planning, use of data compression techniques, and the deployment of multiple antennas on Earth to listen for the weak signals from Galileo allowed most of the science goals to be achieved.

Headline moon discoveries by the Galileo mission include:

- Dactyl, the first known moon of an asteroid
- volcanic activity on Io tracked for several years
- images of Europa detailed enough to show the complexities of its surface, and magnetic field observations suggesting a salty ocean below its ice surface
- similar magnetic data suggesting salty oceans at greater depth below the surfaces of Ganymede and Callisto.

Galileo did not discover any new moons of Jupiter, but between 1999 and 2003, while Galileo was still active, ground-based observers used sensitive telescopes to locate no fewer than 34 previously unknown outer irregular moons of this gas giant.

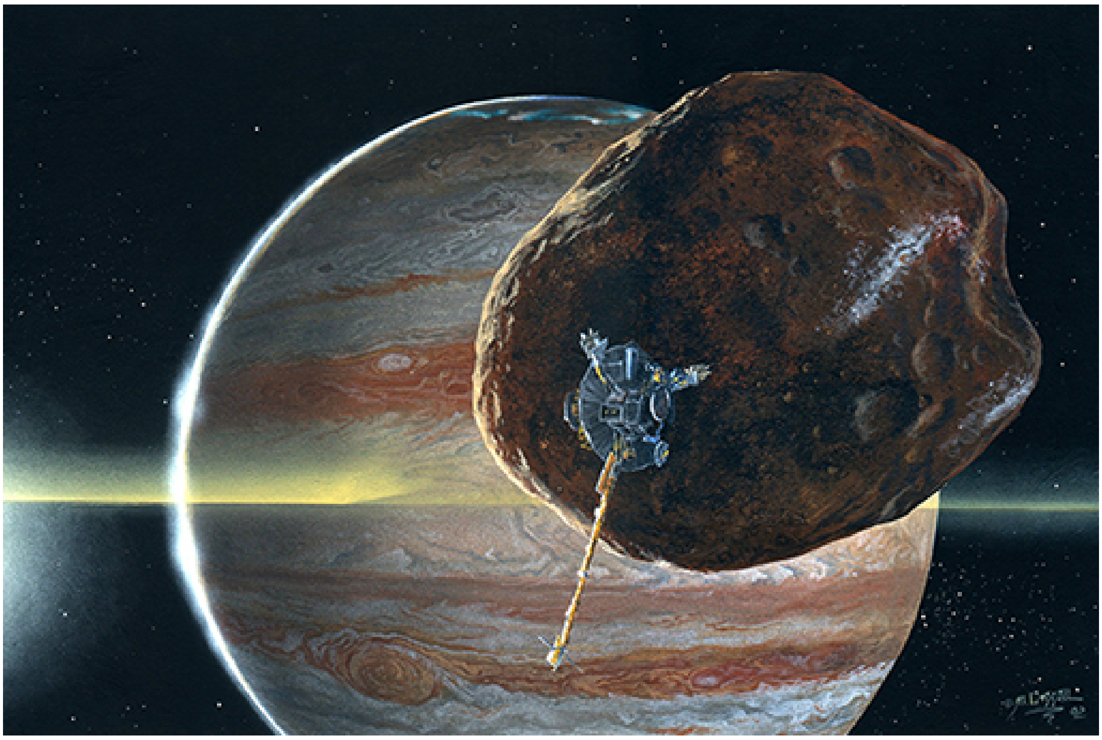

Figure 4 Artist's impression of Galileo passing near Amalthea, Jupiter's largest inner moonlet, which it flew by in November 2002.

Next, have a go at answering a question about why Galileo was crashed into Jupiter.

Activity 1 Why was Galileo deliberately crashed into Jupiter?

Allow approximately 15 minutes.

Why do you think the Galileo mission was ended by a deliberate crash into Jupiter?

○ So that its instruments could sample Jupiter's cloud composition before contact was lost.

Incorrect. That was the function of Galileo's Jupiter entry probe in 1995. The orbiter did not carry suitable instruments, but, more importantly, it would not be able to send a signal to Earth while it was plunging into Jupiter's clouds (the orbiter had acted as a relay for the entry probe's signal in 1995). Try again.

○ Because to leave it in orbit about Jupiter would make it a hazard to future spacecraft.

Incorrect. This was not a major consideration. Its presence as a derelict orbiter would not add much to future hazards, given the likely large number of similar-sized rocks and lumps of ice also orbiting Jupiter. Try again.

○ To remove any possibility of it one day crashing into Europa.

Correct. Given that Europa is potentially habitable, especially in the ocean below its surface ice, the mission controllers wanted to safeguard Europa from the remote chance of contamination by any microbes from Earth that might have been inadvertently carried by the orbiter, if one day when no longer under control, it accidentally crashed into Europa.

1.6 Cassini–Huygens

Cassini–Huygens rates as an even more successful mission than Galileo. It was a joint project between NASA and ESA (the European Space Agency), launched in 1997 and achieving orbit about Saturn in July 2004, after flybys of Earth, Venus and Jupiter. Its landing probe, named Huygens, descended by parachute to the surface of Titan in January 2005. The orbiter Cassini plus lander Huygens had a total mass of 2500 kg, making it the largest unmanned mission to date.

Figure 5 Cassini image of Pandora, a 110 km long inner moonlet. Its orbit lies just outside Saturn's narrow F-ring, whereas Pandora's partner Prometheus has an orbit just inside the inner edge of the F-ring.

The Huygens lander transmitted data and images all the way down to the surface of Titan, and continued to do so for 90 minutes after touchdown until its batteries ran out. The Cassini orbital tour was even more complex than Galileo's tour of the Jupiter system and was extended several times, before ending in September 2017 with a plunge into Saturn's atmosphere. You should realise why that was done if you answered the question posed in the previous step – crashing it into Saturn while it is still under control means that it will never be able to accidentally contaminate a possible life-bearing moon, such as Enceladus.

Headline moon discoveries of the Cassini–Huygens mission include:

- the first images sent back from the surface of any moon other than our Moon
- discovery of methane lakes on Titan
- discovery of jets of ice crystals erupted from cracks on Enceladus
- the best views of inner moonlets ever achieved – in the case of Pandora (see image) and Prometheus, their gravitational/tidal interactions with the ring particles maintain the F-ring's narrow shape

- close-up views of Phoebe, an irregular outer moon that may be a captured icy asteroid
- disturbances at the outer edge of Saturn's 'A-ring' that may show a new (tiny) moon forming (announced in April 2014)
- unexpectedly large libration shown by Mimas suggesting either a subsurface ocean or and eloganted core (announced October 2014)
- evidence for hydrothermal vents on the floor of Enceladus's internal sea (announced March 2015)

See also:

- Birth of a new moon? The announcement of a possible new inner moonlet forming at the edge of Saturn's main ring.
- Wobbly Mimas. Revelation from Cassini observations that Mimas has an unanticipated large libration (a 'wobble'). This could be explained either by an elongated core or an underground ocean (which would be surprising for such a small moon with an ancient heavily-cratered surface).
- Hot vents on Enceladus's sea floor? Two independent lines of evidence pointing to hydrothermal (hot water) vents at the rock-water interface on the floor of Enceladus's internal sea.
- Cassini proves habitability of Enceladus. An article describing how Cassini found molecular hydrogen during its final, and closest, dive through Enceladus's plumes, demonstrating that Enceladus's internal ocean meets ALL the requirements for habitability. The only thing we don't yet know is whether or not it is actually inhabited (by microbes).

1.7 Cassini–Huygens – 15 years of exploration

This short NASA video sums up some of the achievements of the first 15 years of the Cassini–Huygens mission. It contains a blend of real images and animation.

To compare Voyager and Cassini image-based maps of several of Saturn's moons using an on-screen swipe function, visit here.

Would you like to learn what the Huygens lander and the Cassini orbiter have revealed about Titan? That's what's coming up next.

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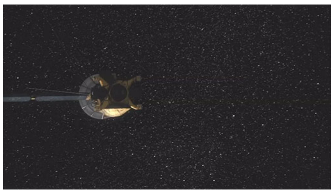


See also: The Saturn system through the eyes of Cassini. Here you can download a NASA retrospective 'book' on the Cassini mission and what it discovered in various formats.

2 Titan – a new area of exploration

Titan is the only moon on which we have landed a probe, apart from our own Moon, and it has a dense atmosphere which makes it hard to see the surface from orbit.

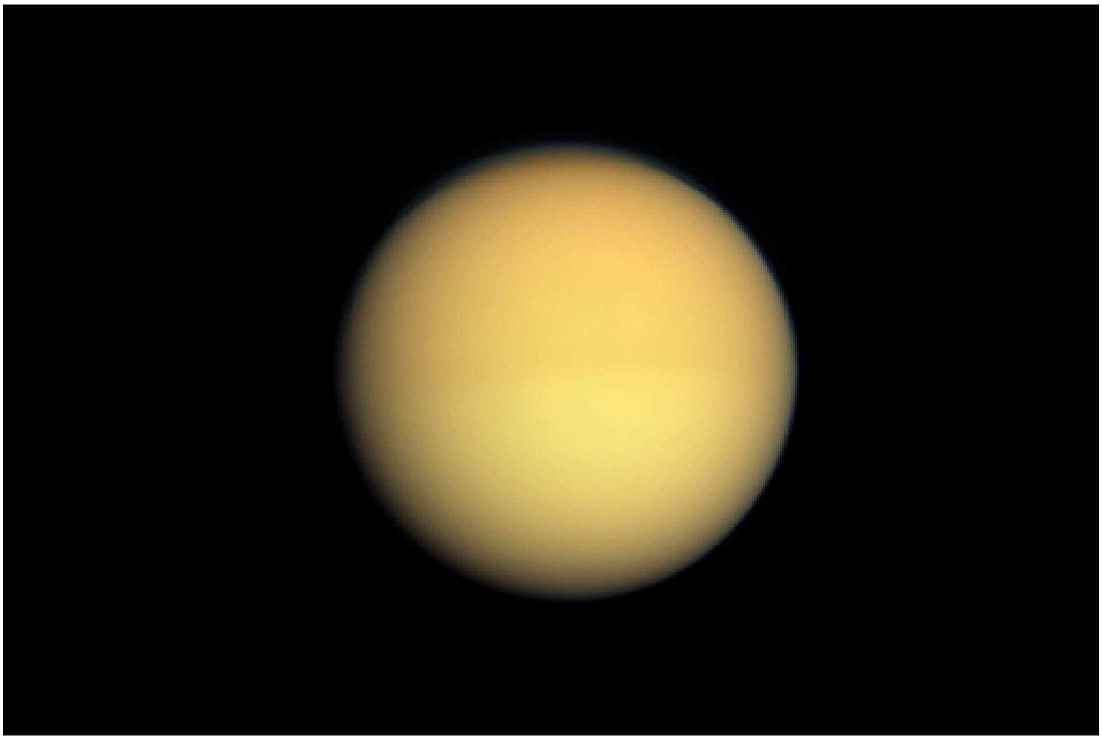


Figure 6 Titan seen in natural colour, by Cassini.

As you have seen, the Voyager mission revealed that Titan is shrouded in a dense, hazy atmosphere, obscuring its surface. The Cassini–Huygens mission had the cameras on board to reveal the surface features, and instruments to test the composition and properties of the atmosphere and surface. Here, you will explore what Cassini–Huygens discovered and what the similarities and differences are between Titan, the Earth and Neptune's largest moon, Triton.

2.1 Titan and its atmosphere

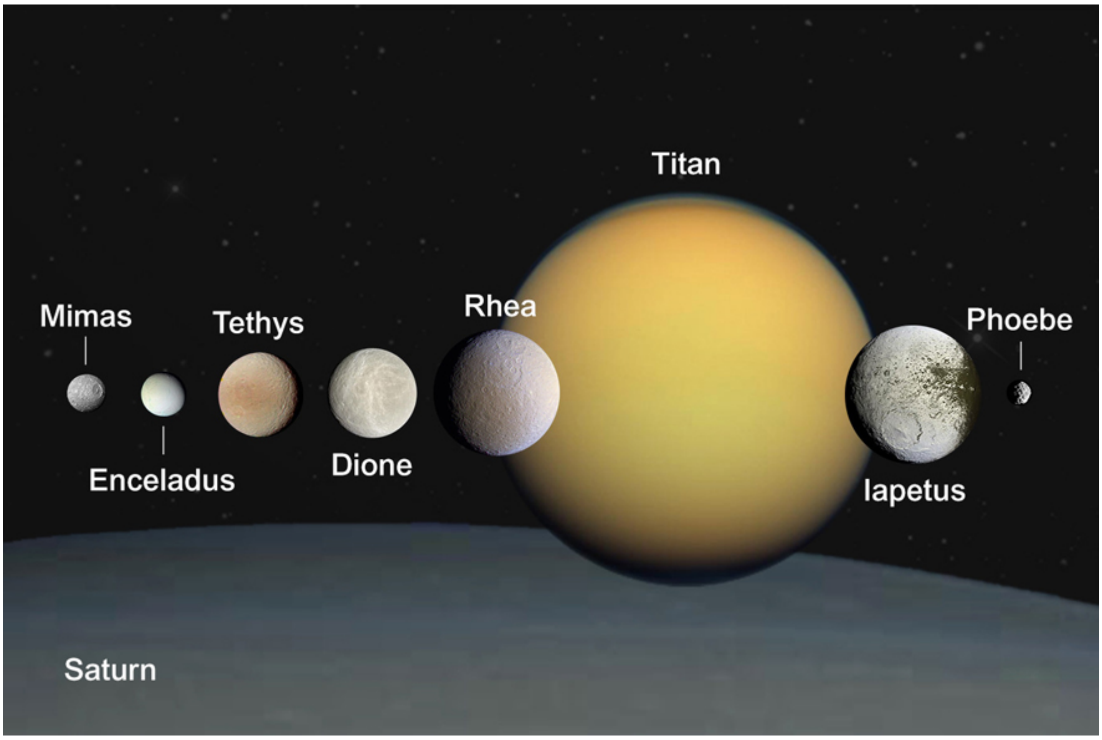


Figure 7 Saturn's largest moons to scale.

Titan is the only moon in the Solar System with a dense atmosphere. It is the largest of the 53 known moons of Saturn and the second-largest moon in the Solar System, after Jupiter's moon Ganymede. It was discovered in 1655 by the Dutch scientist Christiaan Huygens. It has a surface temperature of −178 °C.

Figure 8 Titan with Mimas in the background.

Titan has a dense atmosphere of which 97% is nitrogen. The rest is mostly methane, but solar ultraviolet radiation high in the atmosphere breaks down the methane into components that then combine to form progressively larger and more complex hydrocarbon molecules, beginning with ethane and ending up with microscopic specks of tar. These organic compounds form orange smog that hides the surface from view in visible light. The blue haze above the smoggy layer is probably composed of very tiny particles of hydrocarbons. In this view from the Cassini orbiter, the much smaller moon Mimas is visible in the background.

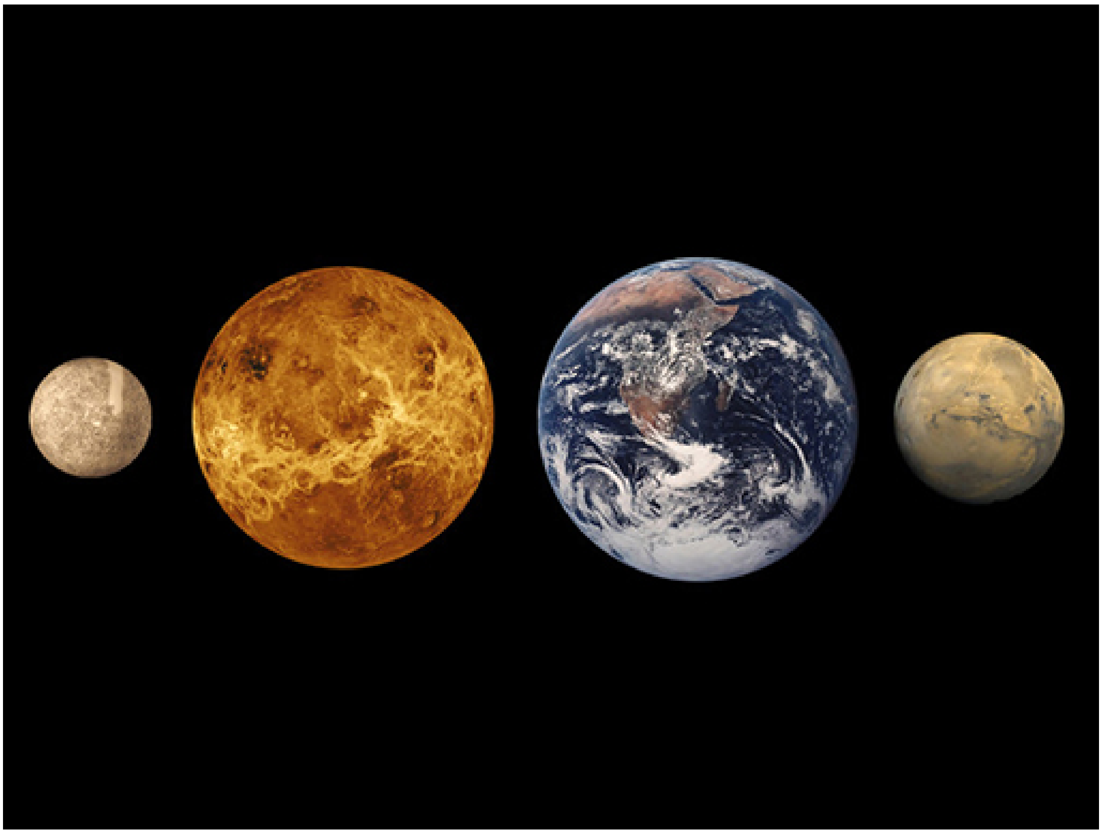


Figure 9 From left to right: Mercury, Venus, Earth and Mars to scale.

Regarding atmospheric pressure, Titan is more like Earth than either Mars or Venus. The atmospheric pressure at Titan's surface is 1.5 times that on Earth. Earth's atmospheric pressure is sometimes expressed as 1 bar or 1000 millibars. The latter unit is used on weather maps. For comparison, the pressure at the surface of Venus is nearly 100 bars, whereas the atmospheric pressure on Mars is about 0.01 bars.

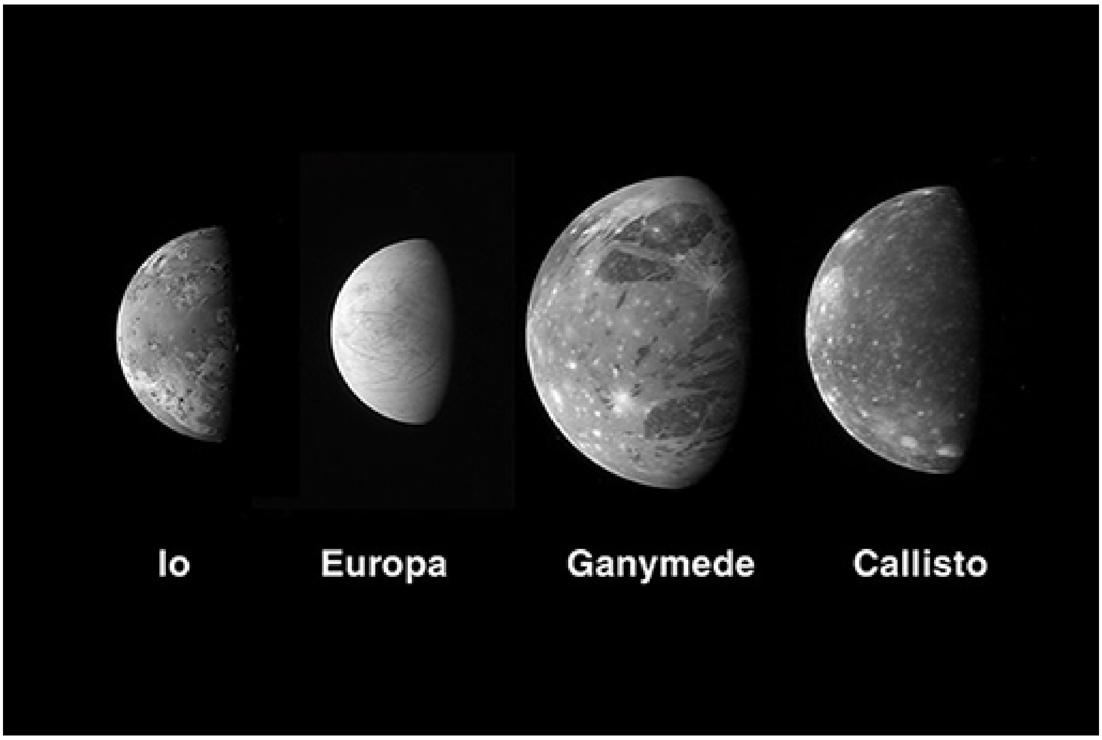


Figure 10 The Galilean moons of Jupiter to scale.

So why does Titan have an atmosphere but the Galilean moons Ganymede and Callisto do not? Ganymede is bigger than Titan and Callisto is only slightly smaller, yet they have not retained any atmosphere at all. Jupiter is 5 astronomical units (5 AU) from the Sun, whereas Saturn is at 9.5 AU. It may be that Jupiter is too close to the Sun for its moons to retain an atmosphere, but that Saturn and Titan are far enough and therefore cold enough to do so.

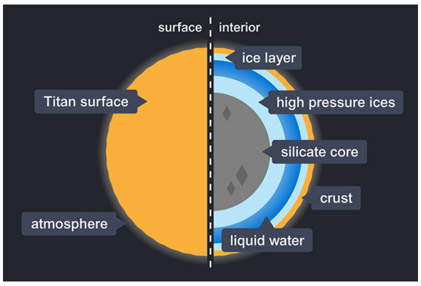


Figure 11 Titan's possible internal structure.

Sunlight would destroy all methane in Titan's atmosphere over tens of millions of years and from this, scientists infer that the methane on Titan must have been replenished many times since its formation. The volume of methane stored in surface lakes is too small a reservoir to replenish the atmosphere, so the most likely explanation is that methane trapped inside Titan since its formation is released to the surface episodically by cryovolcanic eruptions. The heating mechanism may have changed over time, but the result is the release of methane by melting of the methane-rich water-ice.

2.2 The surface of Titan

The Cassini–Huygens mission was the first (and so far the only) mission to show us what lies on Titan's surface, below its smoggy atmosphere.

Previously, scientists had speculated that condensation in the atmosphere could lead to rainfall (of methane or ethane) and that the whole surface of Titan might be covered by a global methane–ethane ocean. The Cassini orbiter can image the surface in two ways: by looking specifically at narrow ranges of near-infrared wavelengths of light that pass through the smog with only a small amount of scattering, and by transmitting a radar beam to the surface and constructing an image from the echoes (radar imaging). Radar images show more detail. Huygens was a lander carried by the Cassini–Huygens mission that descended to the ground by parachute. It got a clear view of the surface from below the smog layer, but the view was of only a tiny portion of the globe.

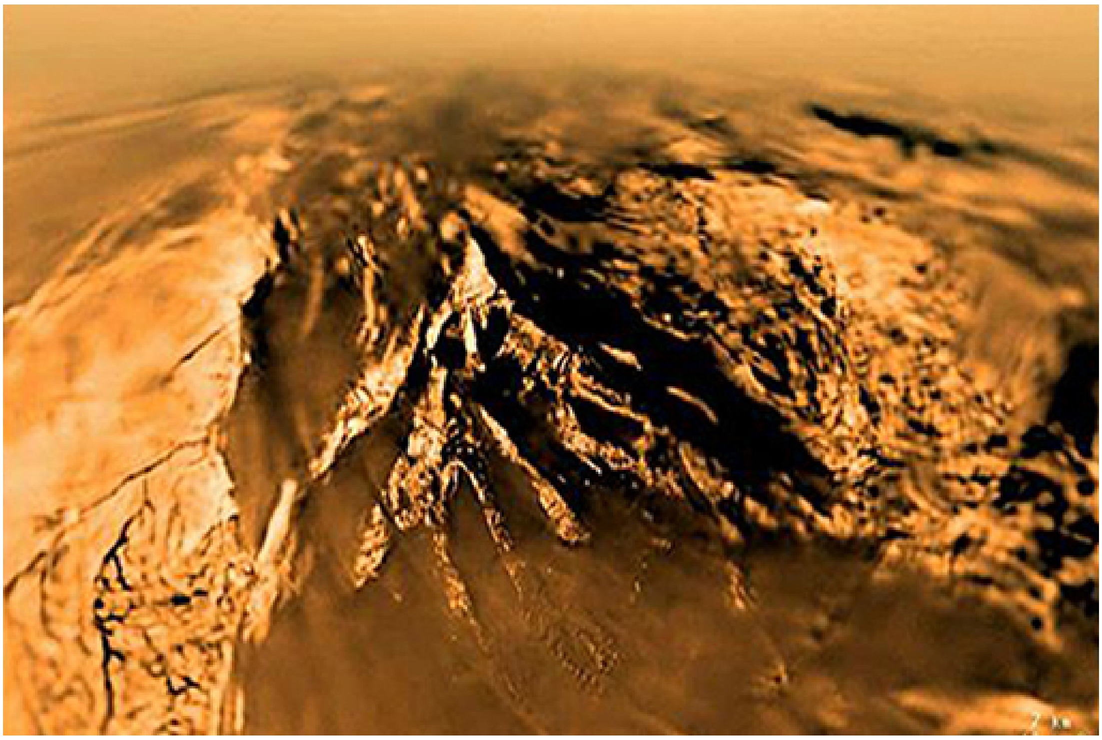


Figure 12 A view of Titan's surface, seen during the parachute descent, by the Huygens lander. The view across the foreground is about 50 km wide

2.3 Descent to Titan

This video allows you to see (and hear) the data collected by the Huygens lander during its descent. Four hours is compressed to less than five minutes.

The first part of the video shows how Titan appeared to the camera as it acquired more and more images during the probe's descent. Each image has a small field of view and dozens of images were made into mosaics of the whole scene. The view is pretty boring until Huygens passes through the smog layer.

The video includes sidebar graphics that show:

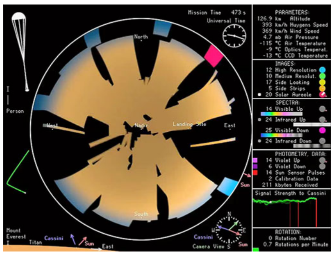
- (Lower left corner) Huygens' trajectory views from the south, with a scale bar for comparison with the height of Mount Everest; coloured arrows point to the Sun and to the Cassini orbiter.
- (Top left corner) A close-up view of the Huygens lander highlighting large and unexpected parachute movements; there is a scale bar for comparison with human height.
- (Lower right corner) A compass that shows the changing direction of view as Huygens rotates, along with the relative positions of the Sun and the Cassini orbiter.
- (Upper right corner) A clock that shows Universal Time for 14 January 2005 (Universal Time is the same as GMT). Above the clock, events are listed in mission time, which starts with the deployment of the first of the three parachutes.

Sounds from a left speaker trace Huygens' motion, with tones changing with rotational speed and the tilt of the parachute. There are also clicks that track the rotational counter and sounds for the probe's heat shield hitting Titan's atmosphere, parachute deployments, heat shield release, jettison of the camera cover and touchdown.

Sounds from a right speaker go with the Descent Imager/Spectral Radiometer activity. A continuous tone represents the strength of Huygens' signal to the Cassini orbiter, which then relayed the signal to the Earth. Various chimes denote data acquisition by Huygens' on-board instruments.

After landing, you see a colour image and a series of black-and-white images from the surface, which continue until contact is lost, but the view of a footprint on the left is an Apollo image of the surface of the Moon to show you the scale of the Titan surface view.

Video content is not available in this format.



(Please note this video has no spoken audio.)

For another way of visualizing the descent, take a look at this video that blends Cassini images with Huygens images.

2.4 Surface features revealed by Cassini–Huygens

Explore this image gallery to discover what the Cassini–Huygens mission found out about the surface of Titan on a broader scale.

Figure 13 is about the best that the Cassini orbiter's selective near-infrared imaging can do. It shows bright and dark areas on the surface. The bright areas are highlands, probably of exposed water-ice (which plays the role of solid bedrock on Titan), whereas the dark areas are low-lying regions made dark by tarry substances (hydrocarbons of high molecular mass) washed out of the atmosphere. The very brightest features are clouds of condensed methane, which occur below the global smog layer and from which methane rainfall may be expected at times.

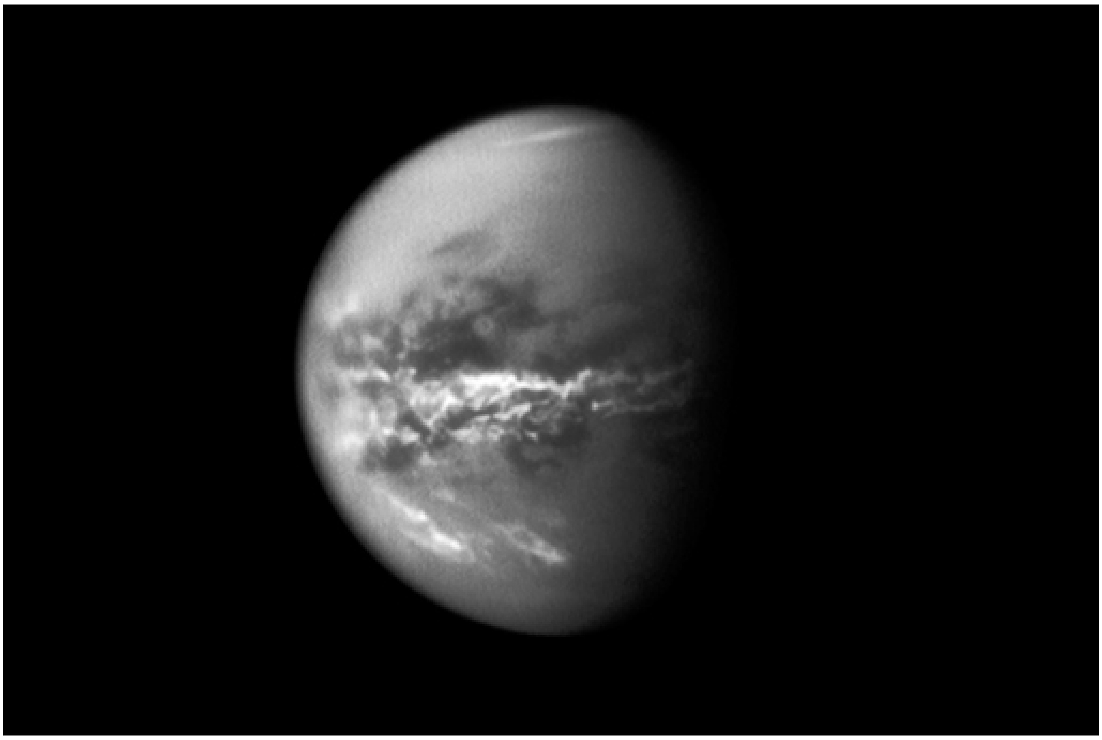


Figure 13 Titan's surface and clouds glimpsed through the haze.

Figure 14 is a near-infrared, colour view mosaic of Cassini images obtained in August 2014. It is of Titan's far north, and here the darkest areas are large lakes or seas filled by liquid methane and ethane. The bright 'bathtub-ring' shores of some of the seas are a consequence of seasonal fall in the liquid level, and are either clean ice yet to be darkened by tarry surface contaminants, or something bright deposited as the liquid evaporated. The yellow spot in the upper left is 'sun glint', the reflection of the Sun from the liquid surface. The red-tinted arrowhead-shaped feature near the centre is clouds of condensed methane.

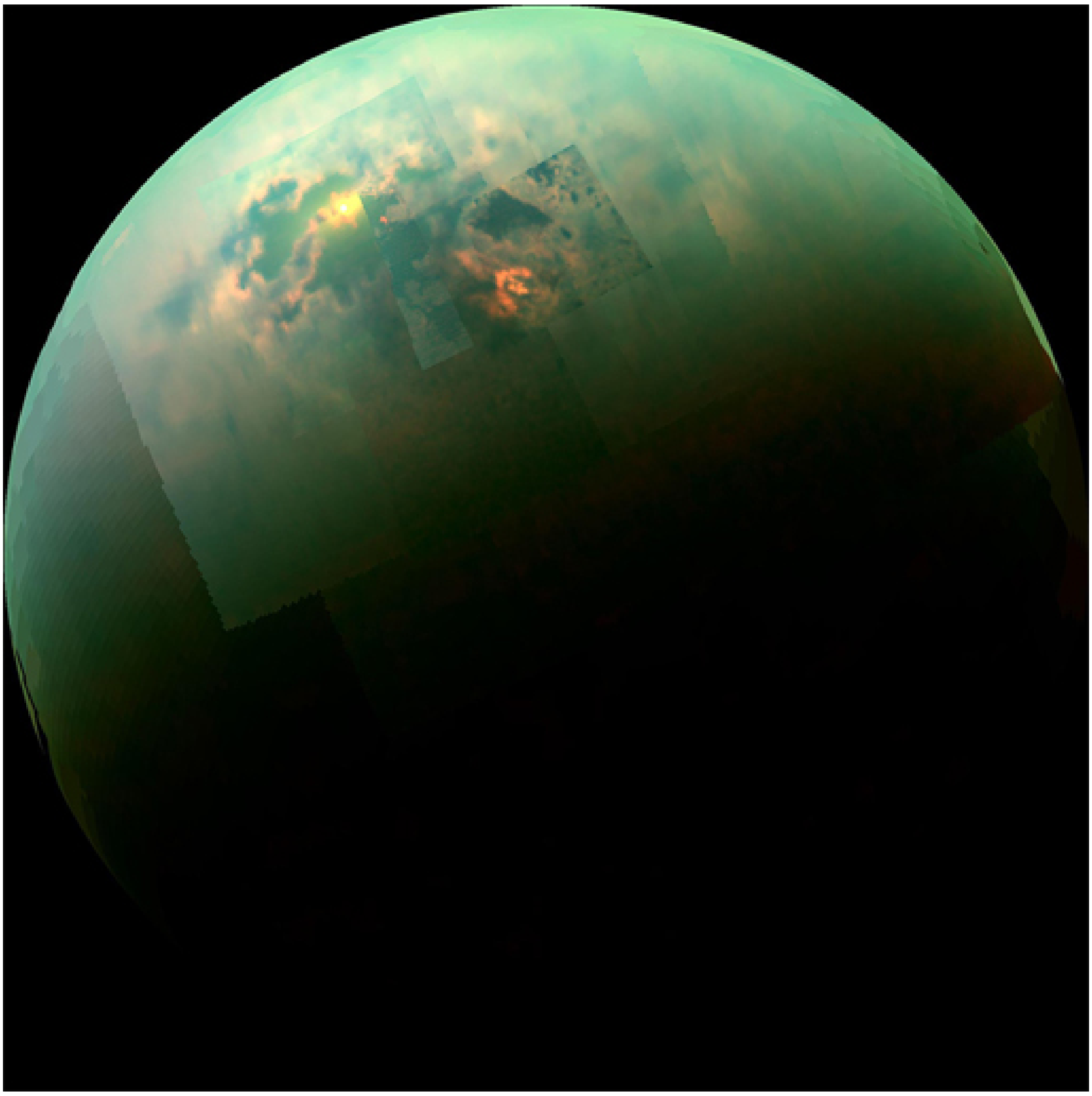


Figure 14 Sun-glint on Titan's seas, August 2014.

This radar image (Figure 15) shows an area known as Titan's Lake Country in the moon's north polar region. Part of a 125 000 km^2 lake can be seen in the bottom of the image. Drainage channels can be seen feeding into the lake. Other smaller lakes are annotated (red arrows). These lakes are full of liquid hydrocarbons (methane and ethane).

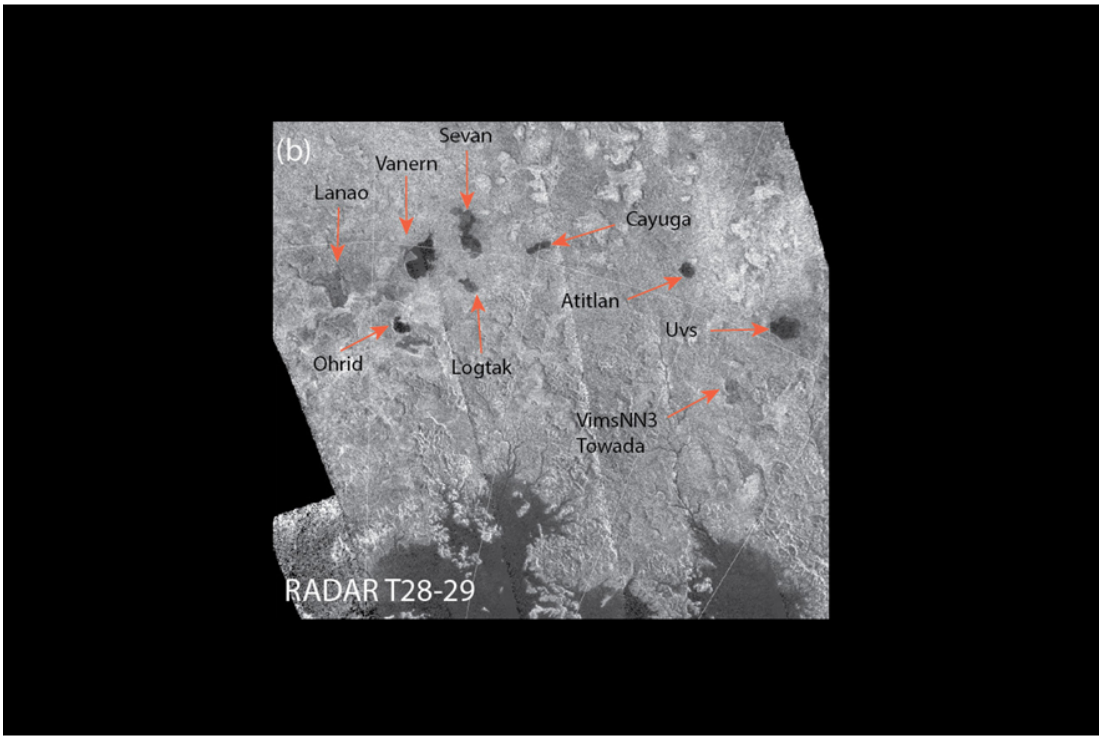


Figure 15 Lakes on Titan.

As well as lakes and drainage channels, radar has also imaged dune fields. They stretch across 10 million km^2 of Titan's surface and are constrained to tropical regions 30° north and south of the equator. They consist of organic material that accumulates from the atmosphere and is shaped into dunes by winds. Figure 16 is a 900-km long portion of an image strip. The bright patches are high ground consisting of icy bedrock. The dunes are the curved dark streaks on the low-lying tracts of the icy bedrock.

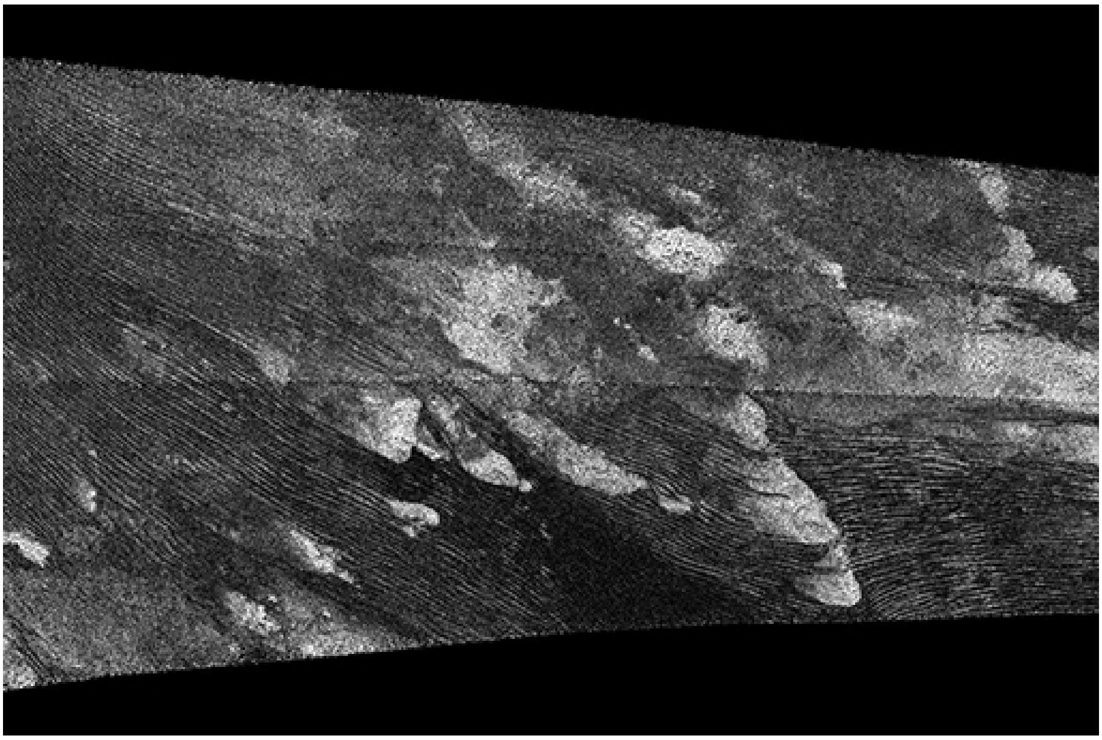


Figure 16 'Sand' dunes on Titan.

As you saw in the ‘Descent to Titan’ video, the Huygens lander was able to image the landscape during its descent and after its landing. Figure 17 is images taken at four different altitudes during Huygens’ descent. During descent the orange haziness cleared to reveal valleys, ridges and channels.

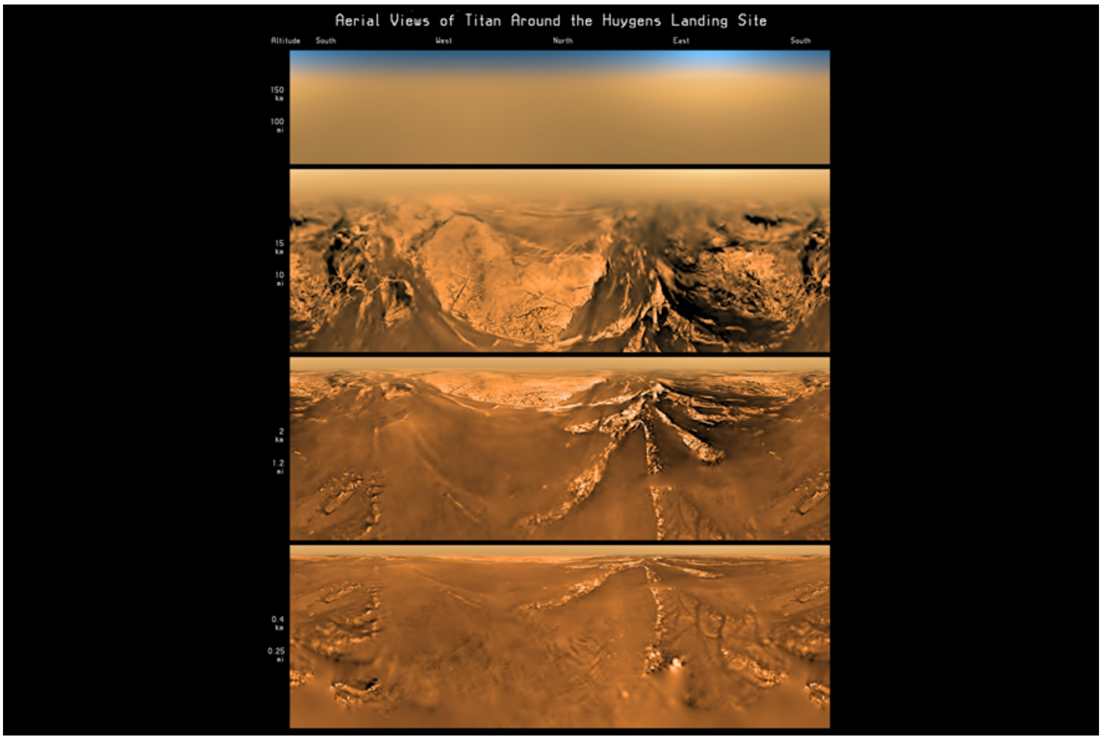


Figure 17 Huygens descent images.

Figure 18 is a mosaic of three images, showing a lighter, higher area of high ground next to a darker, lower area. The high ground has dark channels with smaller tributaries feeding into it and the main channel eventually leads to the darker area. These features are remarkably similar to drainage channels and shorelines seen on Earth. Huygens landed near Titan’s equator and the dark areas here are not occupied by liquid today (unlike the lakes near Titan’s poles) so they are currently dry. The white patches may be low banks of methane cloud.

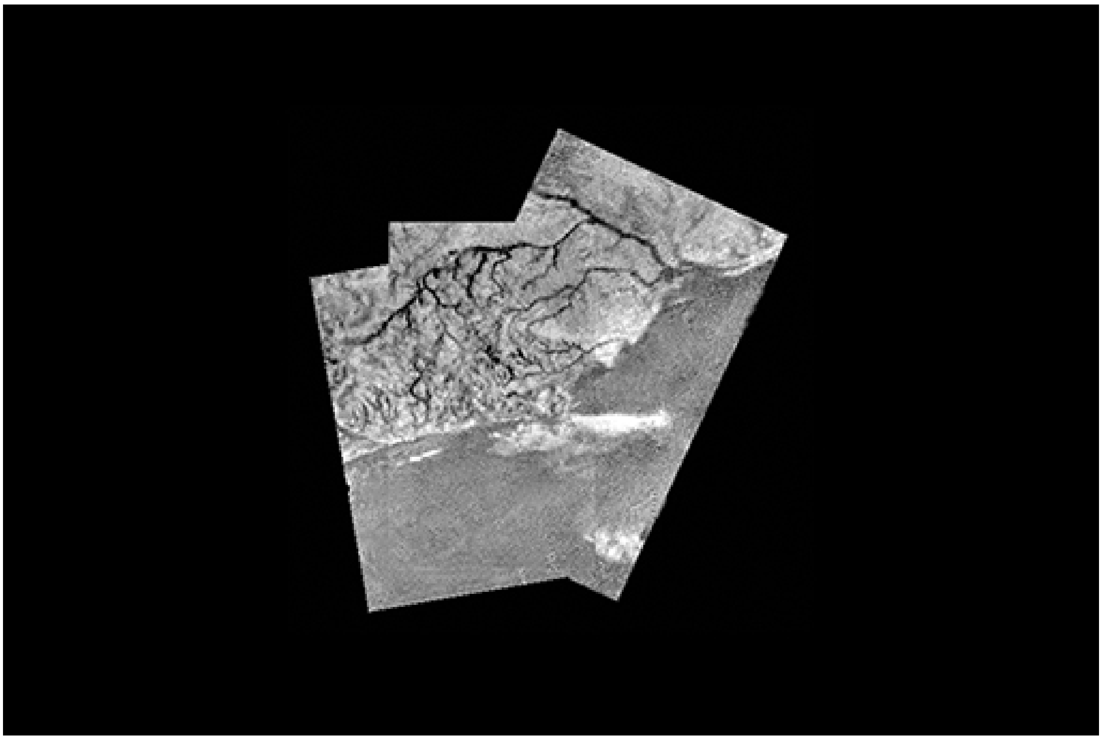


Figure 18 Huygens mosaic.

Huygens landed in what may be a dry river bed. Figure 19 is a false-colour image of the landing site, showing larger, rounded pebbles of dirty water-ice, within fine-grained sediment. The roundness of the pebbles suggests they had been transported and subjected to abrasion by liquid and that beneath some of the pebbles the finer sediment was either washed away as the liquid drained or blown away by the wind after the area had become dry. The liquid was almost certainly methane, as the surface temperature is far too cold for liquid water. The Cassini orbiter revealed lakes of liquid hydrocarbons in other locations, suggesting that Titan has a methane cycle analogous to the hydrological cycle on Earth, controlling the distribution of liquid on the surface.

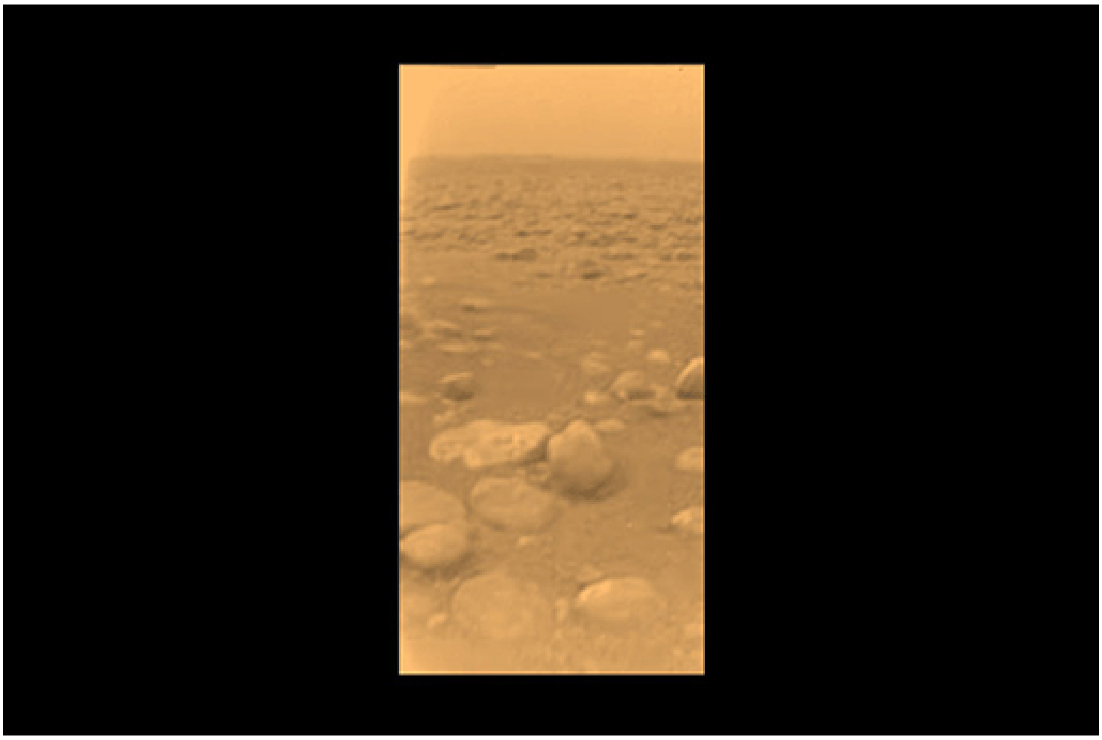


Figure 19 Huygens view from the surface.

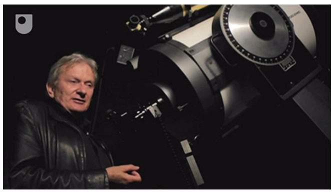
2.5 Making plans for Titan

In the video Titan is referred to as the only moon with an atmosphere. In fact, the truth is that Titan is the only moon with a dense atmosphere. Neptune's largest moon, Triton, also has an appreciable atmosphere. Triton is smaller than the Galilean moons of Jupiter, but with a surface temperature of only −235 °C it has been able to retain a thin atmosphere of 99% nitrogen plus traces of methane and carbon monoxide, with a surface pressure about one-fifty-thousandth of Earth's (0.02 millibars or about 20 microbars). This may be miniscule, but it is enough to form clouds of tiny nitrogen-ice crystals at heights of a few kilometres, analogous to Earth's cirrus clouds, which are made of tiny crystals of water-ice.

The Titan Mare Explorer (TiME) referred to near the end of the video was short-listed for development by NASA, but was dropped in favour of a Mars mission in 2012.

Use the downloadable table to compare some of the characteristics of Titan and Triton.

Video content is not available in this format.



2.6 A look at Triton

The southern terrain is pinkish and hummocky (Figure 20). North of this is a greenish terrain with a texture similar to the skin of a cantaloupe melon, where the landscape may be the product of cryovolcanic eruptions. The pinkish material is a polar cap predominantly of frozen nitrogen. The green material is thought to be mostly methane or carbon dioxide-ice, which constitutes the upper part of Triton's surface crust, with a veneer of nitrogen-frost coating the ground. Changes in atmospheric pressure have been detected on Triton as a result of the seasons, as nitrogen frost turns to vapour.

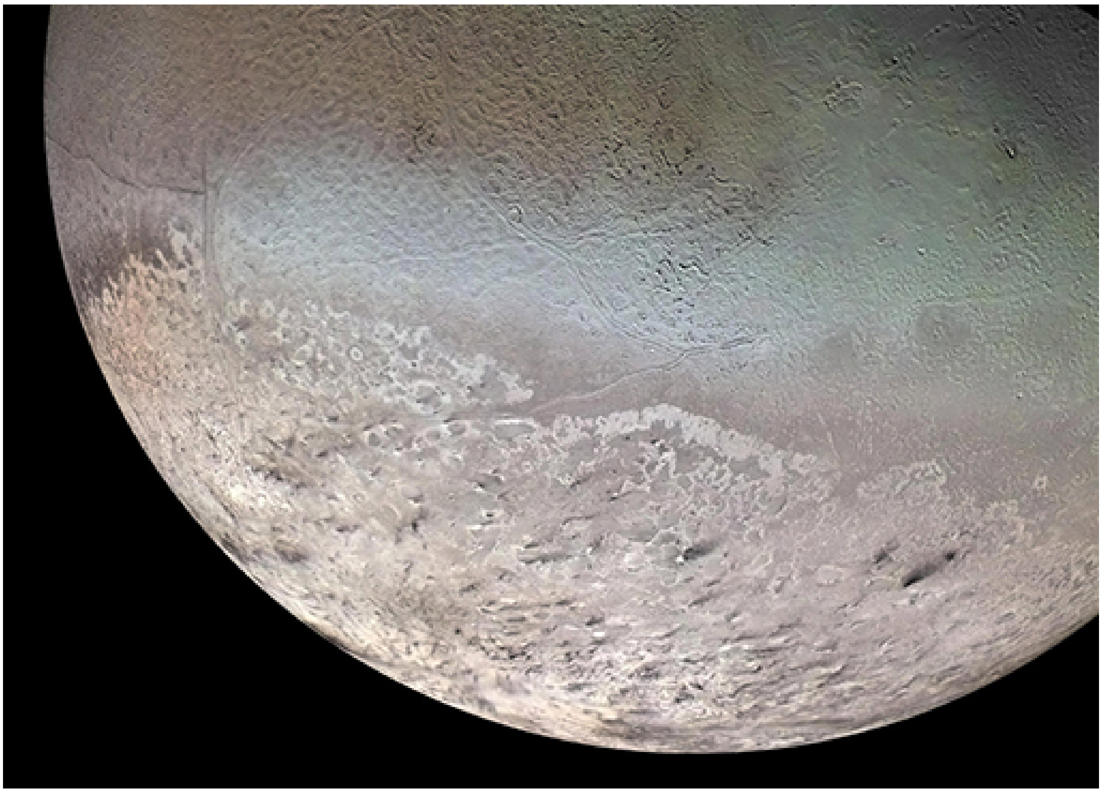


Figure 20 Voyager 2 image showing Triton's two main terrains.

The dark smears on the pinkish terrain (seen in Figure 21) are thought to be deposits from plumes from geysers that erupted from below the polar ice cap, some of them active during the Voyager 2 flyby. These may be solar-powered geysers. If that is correct, sunlight shines through the ice and warms the dark dusty substrate below. The absorbed heat vaporises the base of the nitrogen-ice, creating a pressured blister, which then bursts, ejecting nitrogen and dust.

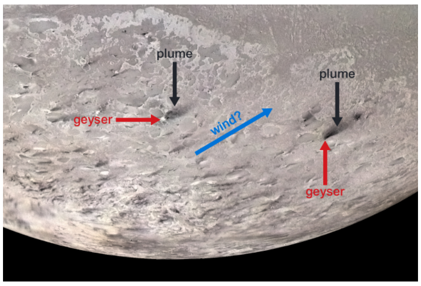


Figure 21 Plumes and wind streaks on Triton's south polar cap.

To many people's surprise, when New Horizons flew past Pluto in 2015, its landscape (part of which was imaged in more detail than Voyager had managed at Triton) bore little resemblance to Triton, despite their broadly similar bulk compositions.

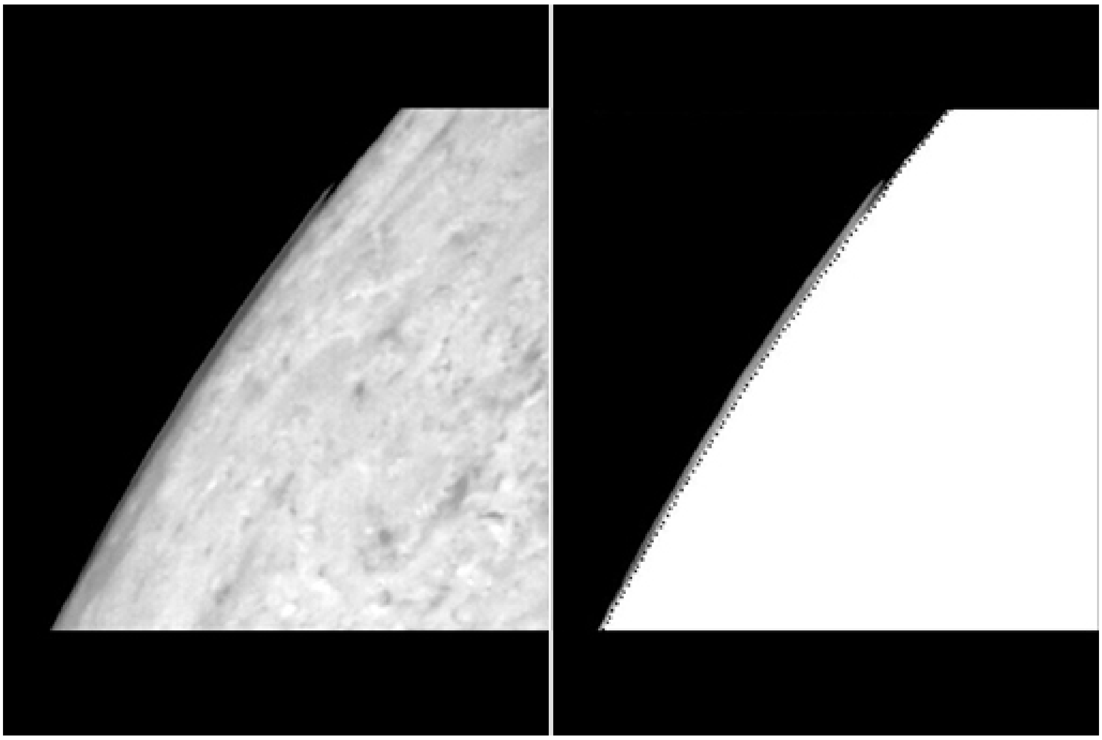


Figure 22 Voyager 2 view across the limb (edge) of Triton, showing a tenuous layer of nitrogen 'cirrus' cloud a few kilometres above the horizon. The version on the right has been processed to show the cloud layer more clearly.

3 Rhea, Miranda and Ariel

Compare Rhea, Miranda and Ariel – three varied icy moons.

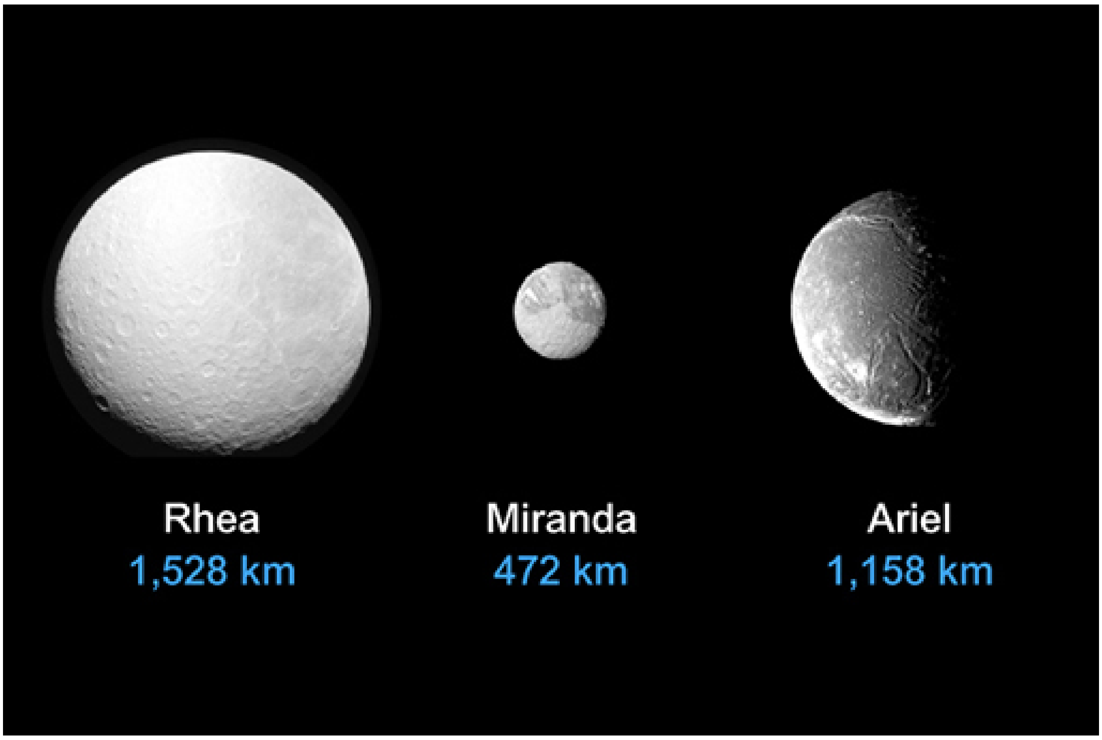


Figure 23 Voyager images showing Rhea, Miranda and Ariel at their correct relative sizes.

Earlier in the course, you learnt about the structure of moons. Most moons are composed of varying amounts of rock and ice; our Moon is atypical in being composed of rock with very little water. Most other moons have a rocky core and an icy mantle and/or crust. Now you have the chance to study three icy moons that you have not yet studied in detail: Rhea, Miranda and Ariel. Use the downloadable table for some interesting facts about these moons.

See also: David Rothery talks to Paul Byrne. In June 2014 Professor David Rothery recorded a bonus video with Paul Byrne about what excites him about beginning a new project on icy moons.

3.1 Rhea

Rhea (diameter 1527 km) is the second-largest moon of Saturn. It was first discovered by Giovanni Domenico Cassini in 1672 and was imaged by Voyager 1 in November 1980, by Voyager 2 in August 1981 and on various occasions by the Cassini spacecraft during its orbital tour of Saturn's family of moons that began in 2004.

Before the launch of the Voyager space probes, most scientists expected all moons to be heavily cratered due to multiple impacts, with no mechanism of resurfacing, such as cryovolcanism, to erase the craters. Although many of the moons proved them wrong, Rhea is a good example of what was originally expected. Rhea lacks signs of cryovolcanism and its most notable geological features are its many craters. It has more craters per square kilometre than either Dione or Tethys (two other heavily cratered moons of Saturn). It is not known why this is the case, but it could be that the other moons' closer proximity to Saturn allowed stronger tidal heating in the distant past and this gave rise to greater internal heating, allowing liquid water to reach the surface and refreeze, effectively erasing craters. However, it could also be that Rhea simply received a heavier bombardment than either Dione or Tethys.

Apart from its craters, the Voyager probes revealed wispy lines that cut across both craters and plains. The Cassini orbiter's more detailed images showed that the wispy lines are canyons, suggesting that even Rhea may have had tectonic activity in the past. Surface features like these are also present on Dione and Tethys.

Rhea has a density of 1.233×10^3 kg m^{-3} suggesting that it is composed of around three-quarters water-ice and one-quarter rock. Measurements by Cassini suggested that Rhea is composed of a homogenous mixture of ice and rock, and it has been likened to a dirty snowball.

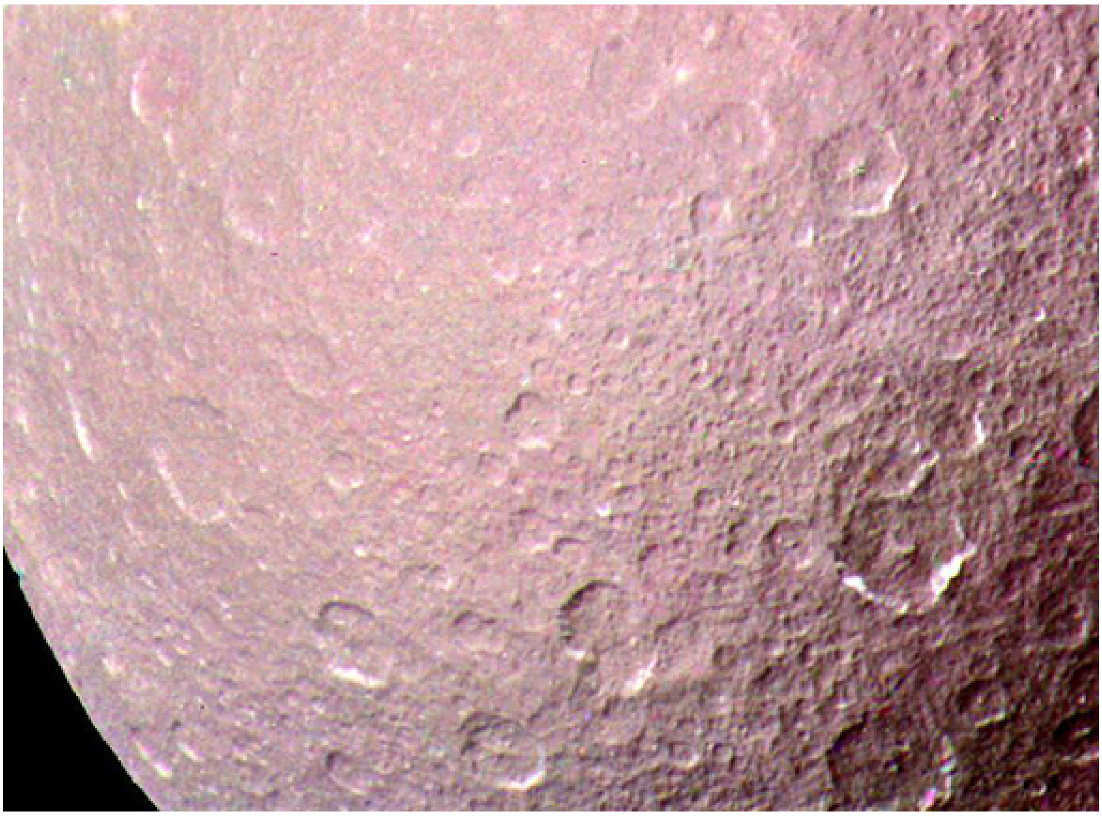


Figure 24 A classic colour view showing Rhea's heavily cratered surface, from Voyager 1 in 1980.

The area in view is several hundred kilometres across.

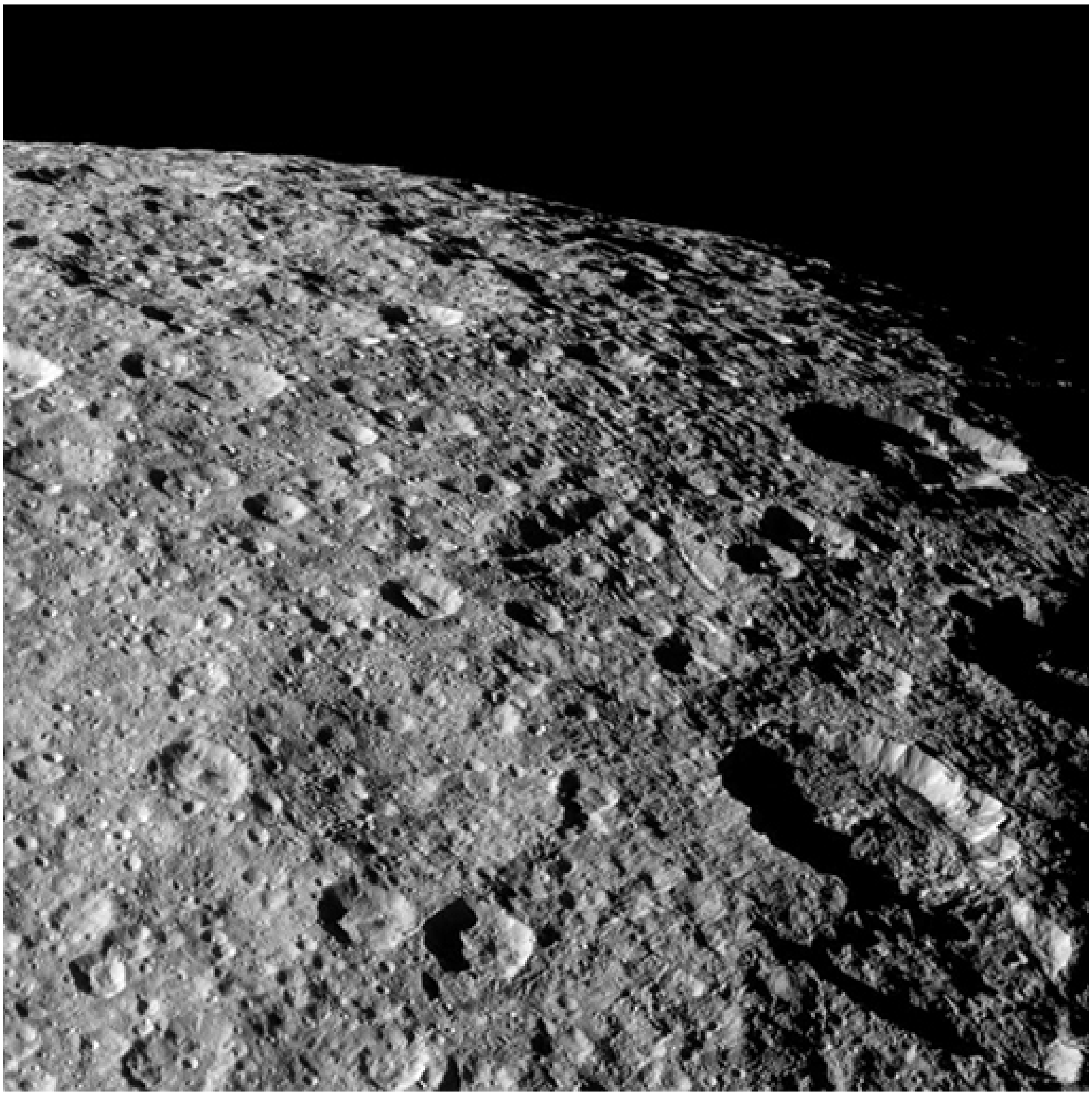


Figure 25 A 250-km wide view of Rhea seen by Cassini in 2012.

This surface is scarred by craters of a wide range of sizes. Some of the older craters are hard to see, because they have been partly overprinted by younger craters or covered by material thrown out of adjacent craters during impact.

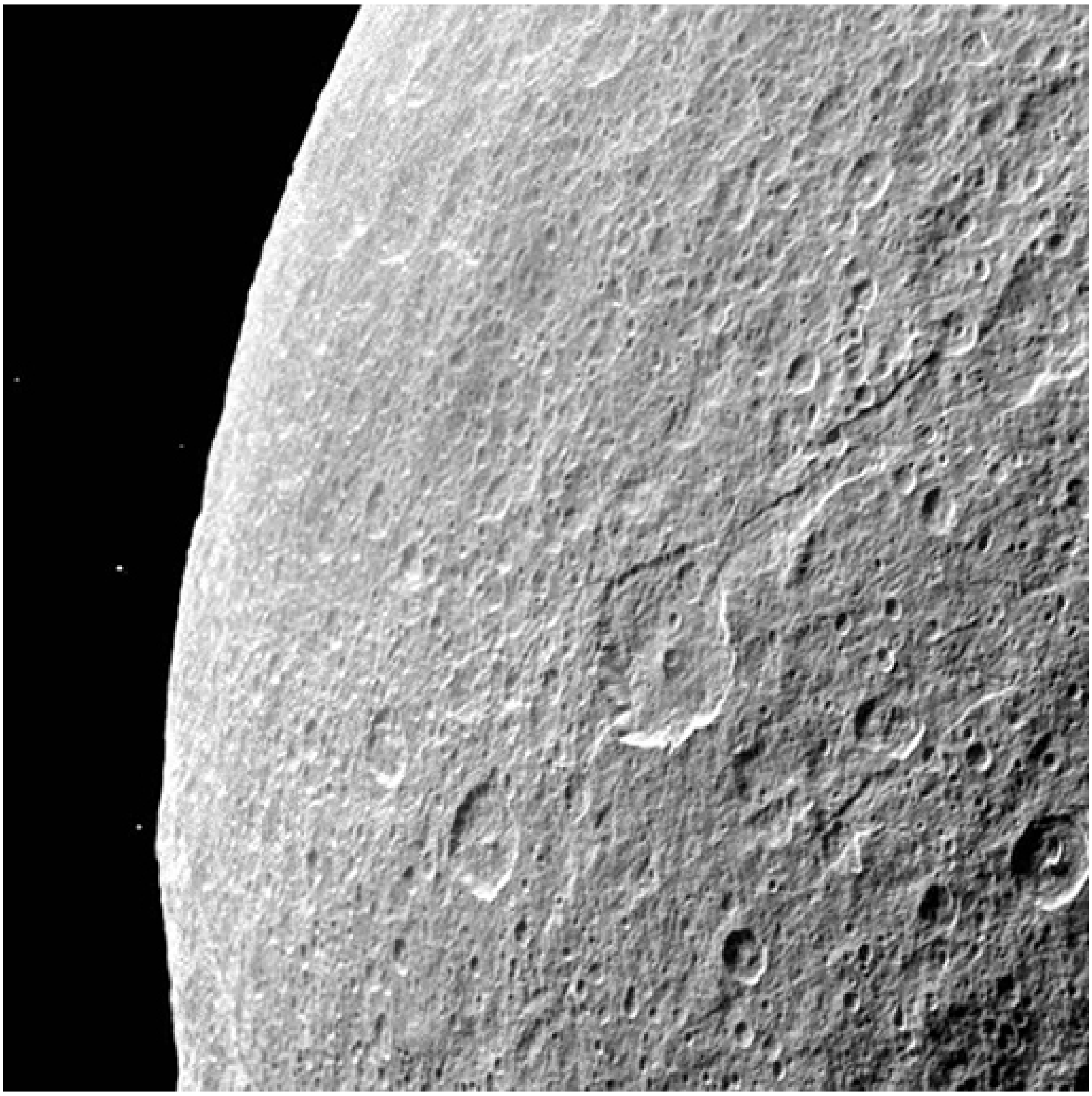


Figure 26 Rhea’s battered icy surface seen by Cassini in 2011.

Although dominated by craters, there has been some fracturing or faulting of the surface: look to the right of the large (70 km diameter) crater near the centre. This was actually the night side of Rhea and it is a long-exposure image made by the light reflected onto Rhea by Saturn. Two stars are visible to the left of the disc.

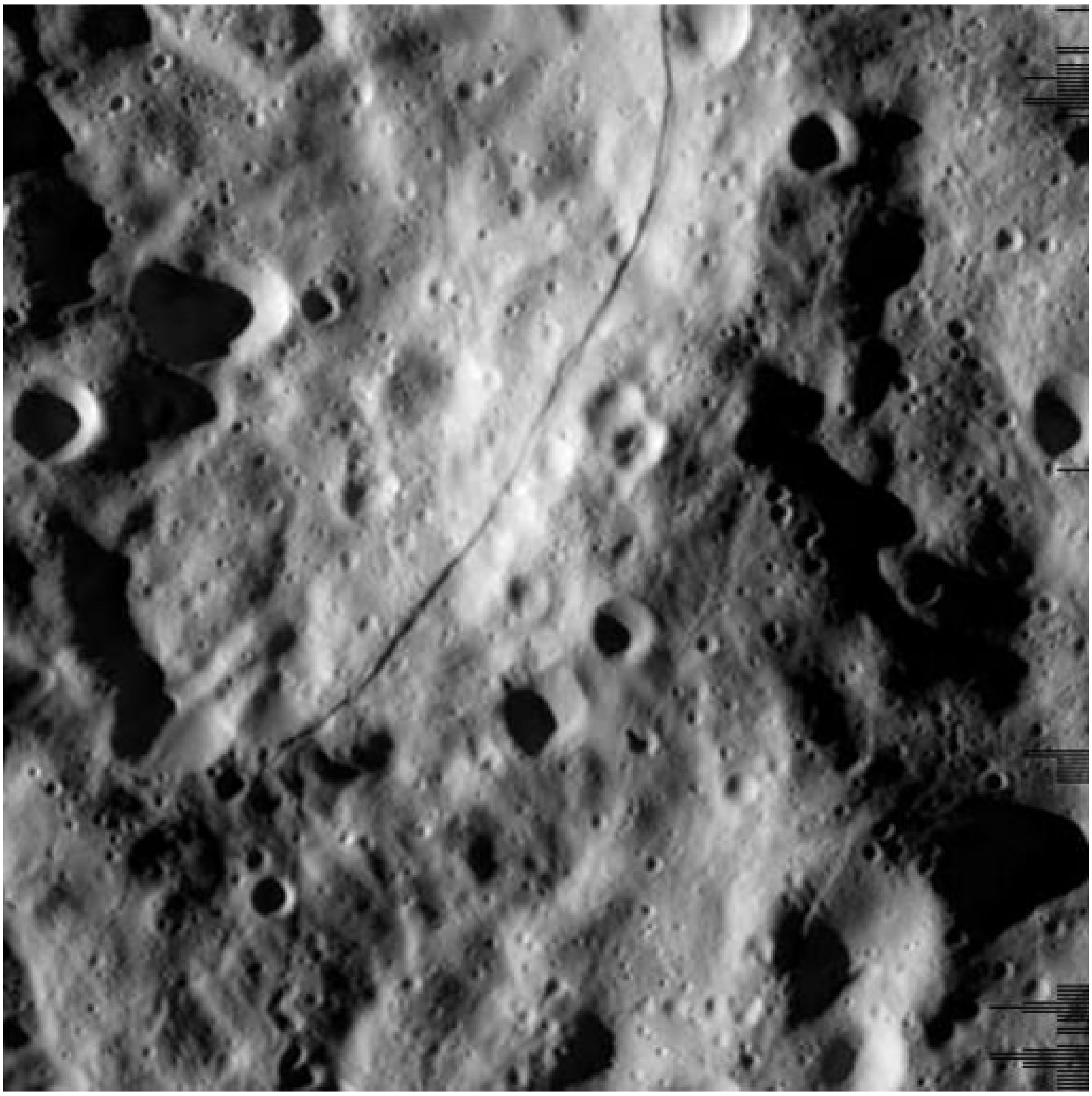


Figure 27 A narrow trough, only about 1 km wide, probably caused by faulting, revealed in the wispy terrain of Rhea by Cassini in 2013.

See also: Google maps of moons. Visit this link for an introduction to the Google maps of moons, and click the appropriate link in the blog play with them!

3.2 Miranda

Miranda is the fifth-largest moon of Uranus. It was discovered in 1948 by Gerard Kuiper and was the last moon of Uranus to be discovered before Voyager 2 flew by in 1986. At the time of the flyby, the south pole of Uranus, which has an extreme axial tilt, was pointed towards the Sun. Its moons' orbits are all in the plane of its equator, so their south poles were pointed sunwards too. Consequently, their northern hemispheres were in darkness and could not be seen. We have nice images of the illuminated southern hemisphere of Miranda, but its other side remains a mystery.

The surface of Miranda is very interesting geologically, with features observed that are unique among known objects in the Solar System. These features are known as coronae (the plural of 'corona'); defined as ridges and valleys peppered with fewer craters than the surrounding terrain. These are separated from the more heavily cratered regions by sharp boundaries. These features give Miranda a very interesting appearance, looking like a jigsaw puzzle that was put together from mismatched pieces. One early explanation for this (now discredited) is that the moon was shattered by a large impact and then reassembled from the pieces. Other possibilities are that the coronae result from meteorite impacts that caused the icy surface to melt, followed by slush rising to the surface and refreezing or that the coronae are above sites where tidal heating was concentrated in the distant past, which would mean that the coronae have some kind of cryovolcanic explanation.

If tidal heating was responsible for the coronae, it could have resulted from a past episode of orbital resonance with one of Uranus' other satellites, probably Umbriel or Ariel.

Like other moons of Uranus, Miranda is thought to consist of roughly equal amounts of water-ice and silicate rock.

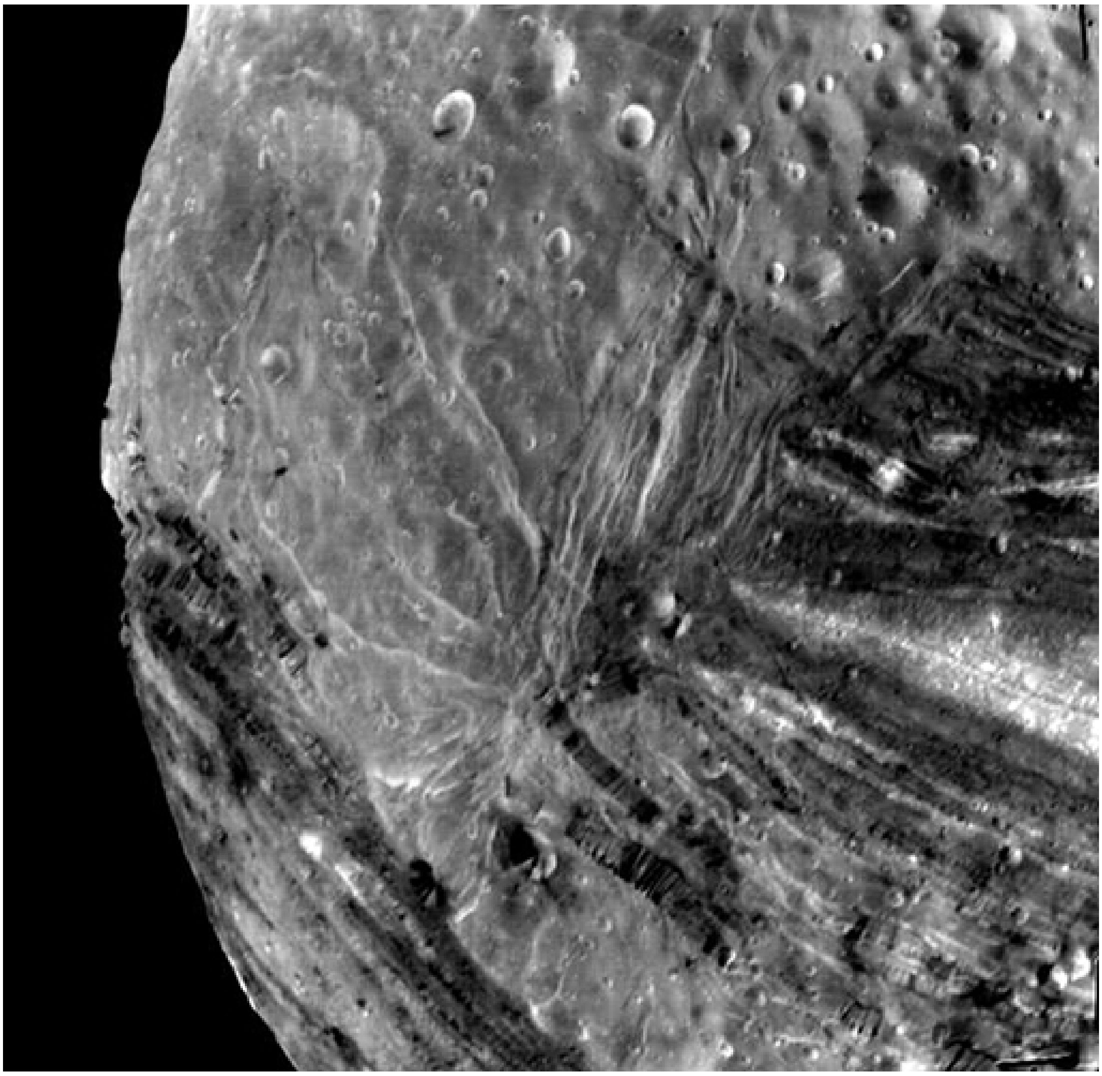


Figure 28 Voyager 2 image of Miranda. The remarkable variety of terrain is clearly visible.

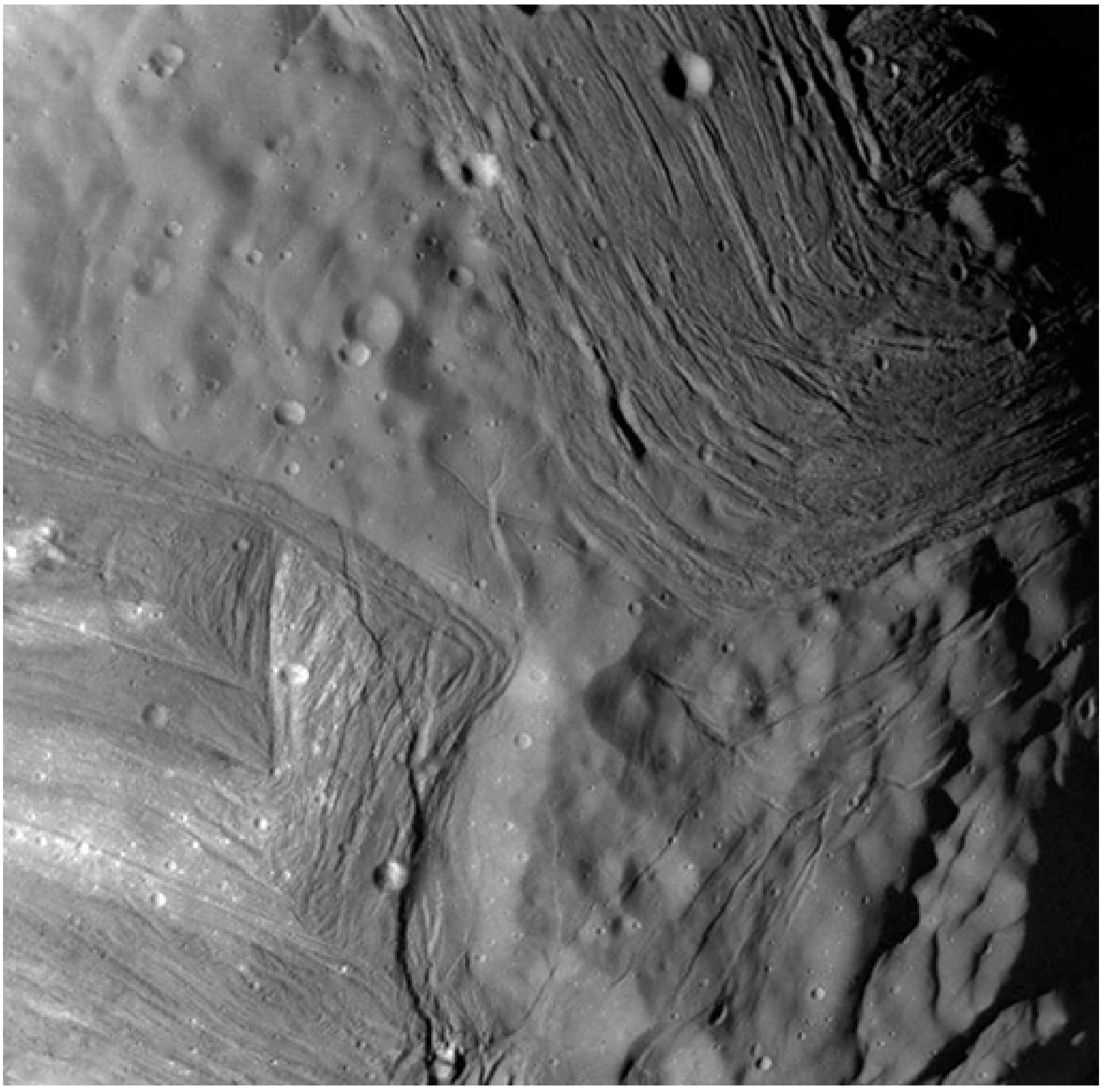


Figure 29 A 220-km wide view of Miranda, showing part of Inverness Corona, with its chevron pattern, in the lower left and part of Elsinore corona in the upper right.

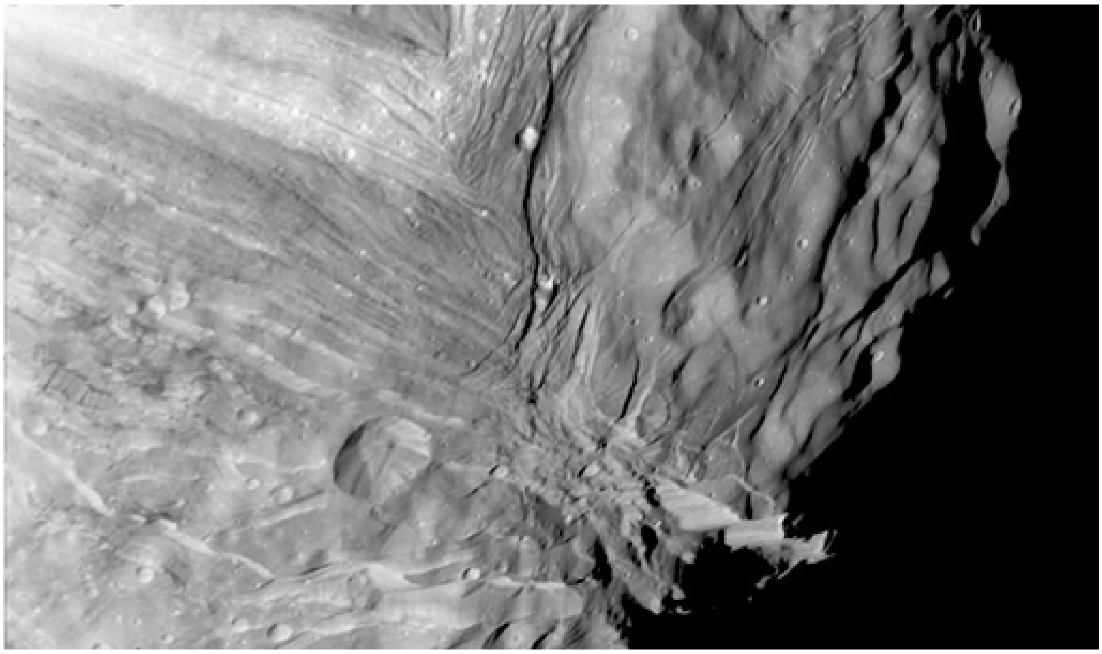


Figure 30 Cliffs and fault scarps near the tip of Inverness Corona on Miranda. The view is about 150 km across.

3.3 Ariel

The terrain on the right is remarkable for the number of straight-sided, presumably fault-bounded, troughs. The more fully sunlit region in the upper left has fewer troughs.

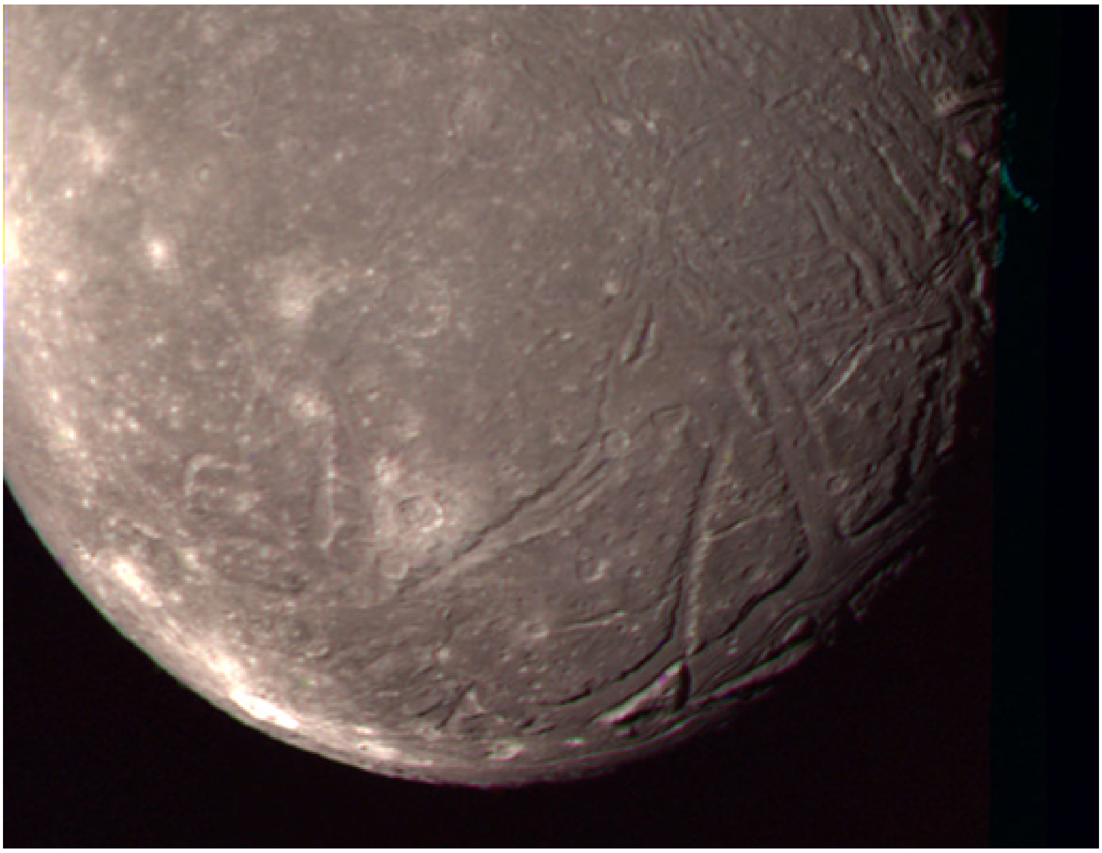


Figure 31 A Voyager 2 colour image (admittedly not very colourful) of Ariel.

Ariel is the fourth-largest moon of Uranus. It was first observed in 1851 by William Lassell and was seen in close-up in 1986 by Voyager 2. It is thought to be composed of a rocky core and icy mantle. Like Miranda, it is thought to be made up of roughly equal proportions of water-ice and rock, with the rock possibly including some material that is carbonaceous in nature. Carbon-dioxide-ice has also been detected on Ariel and there may be ammonia-ice too.

Multiple geological features have been observed on the surface including craters, ridges and plains. The south pole is characterised by extensively cratered terrain; this is thought to be the oldest region, as the density of craters indicates a lack of resurfacing. The cratered terrain is bordered by regions of terrain cut by steep-sided troughs. These can be hundreds of kilometres in length and up to 20 km in depth – that's nearly 12 times the depth of the Grand Canyon. The troughs are thought to be caused by parallel geological faults causing the floor to drop down. Evidence that Ariel has the most recent geological activity of all the moons of Uranus is provided by the smooth, relatively crater-free material covering the floors of some of these troughs and spilling out beyond their ends. This is thought to represent cryovolcanic flooding, with 'lava' formed from a mixture of ammonia-ice and water, erupted from below as a result of tidal heating. Lava made of an ammonia–water mix would be liquid even at −100 °C and is not too hard to imagine on the surface of a moon whose normal surface temperature is about −200 °C.

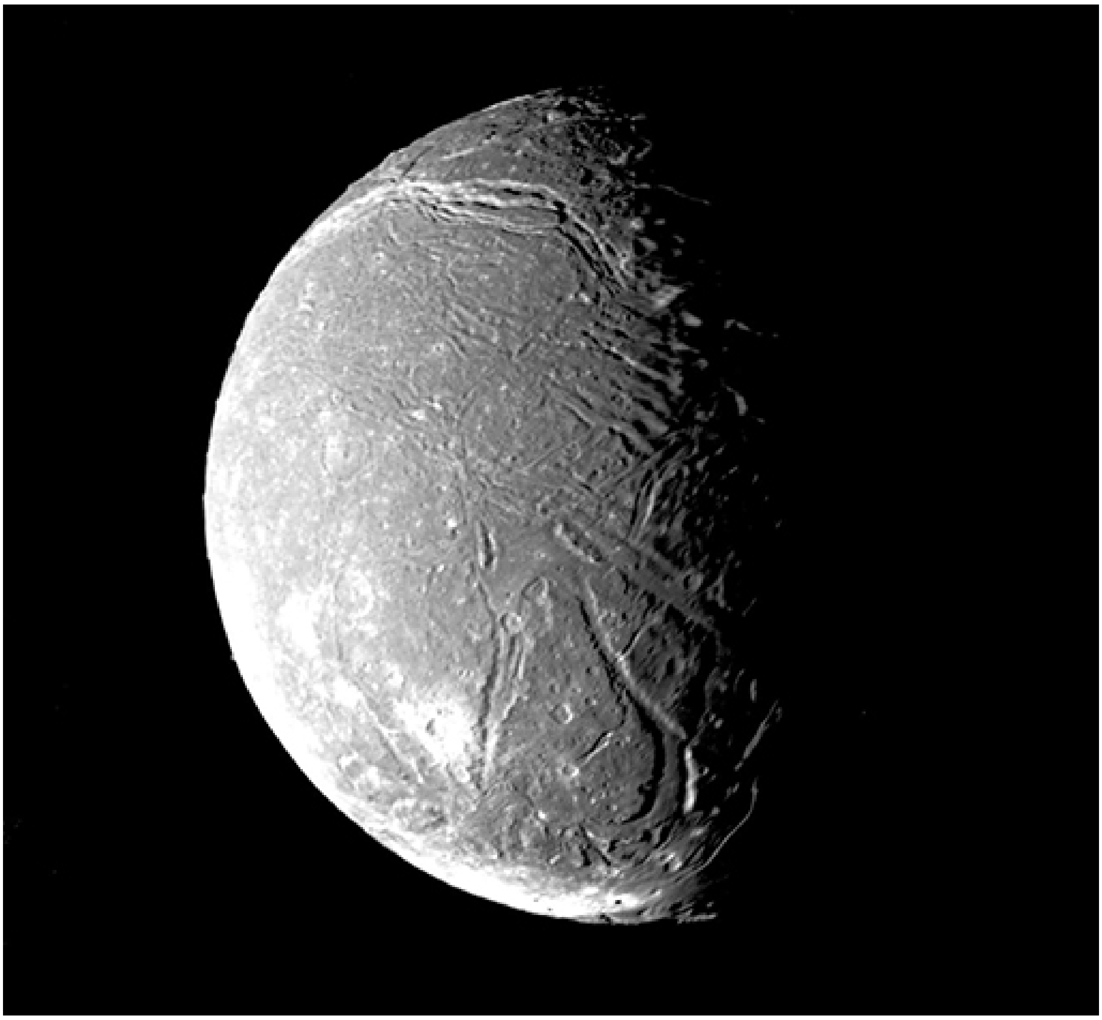


Figure 32 The most detailed Voyager 2 mosaic (i.e. composite image) of Ariel. It includes the area covered in the previous view, but extends beyond that to show some intensely faulted terrain near the top.

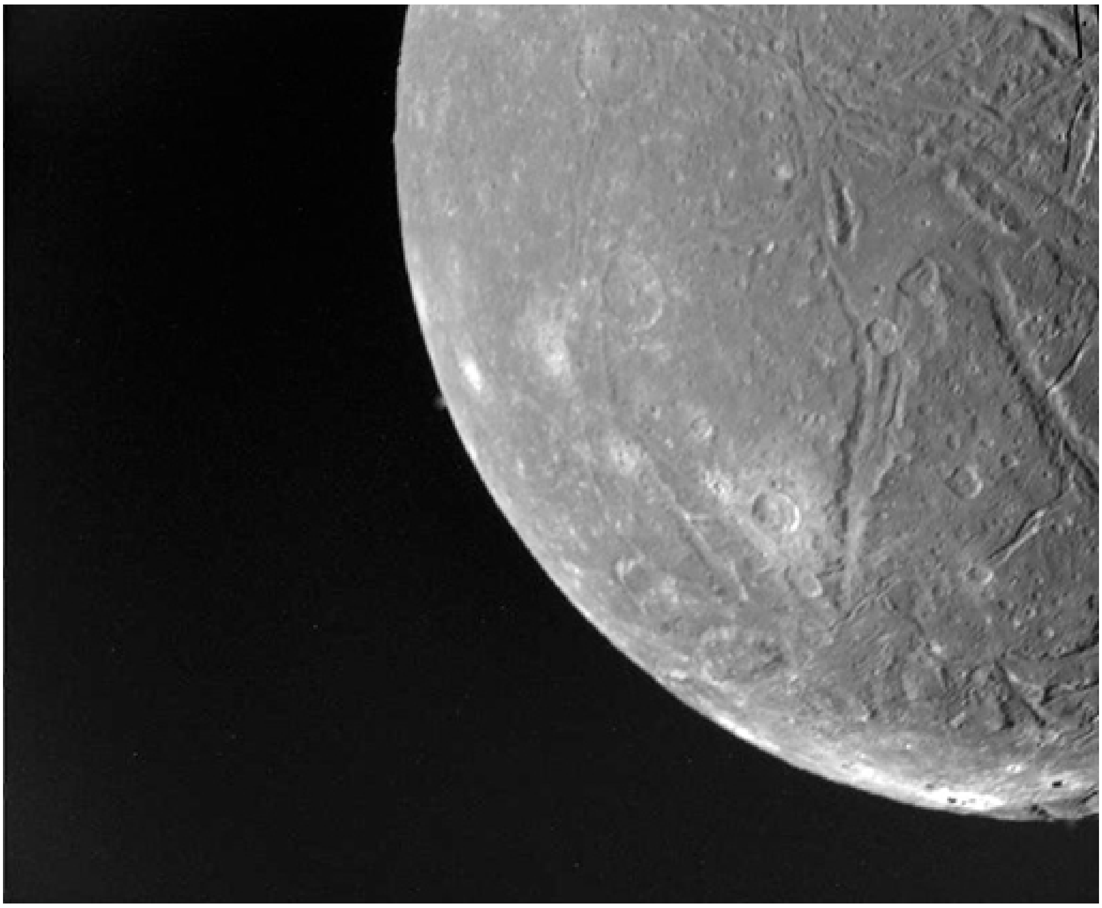


Figure 33 A more detailed view of the lower part of the previous image.

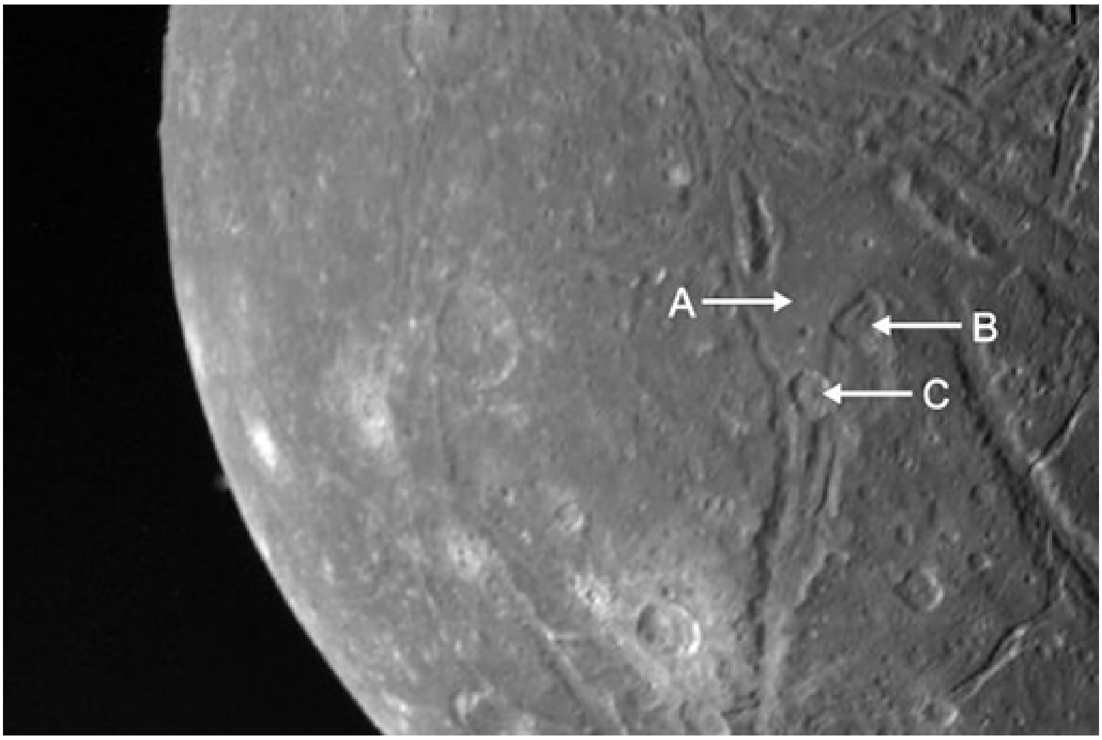


Figure 34 Detail of smooth cryovolcanic lava (A) on Ariel that has spilled out beyond the end of a trough and covered half of a of 30-km diameter crater (B). To its lower left, a slightly smaller crater (C) has been formed by an impact into the lava surface; this crater

must therefore be younger.

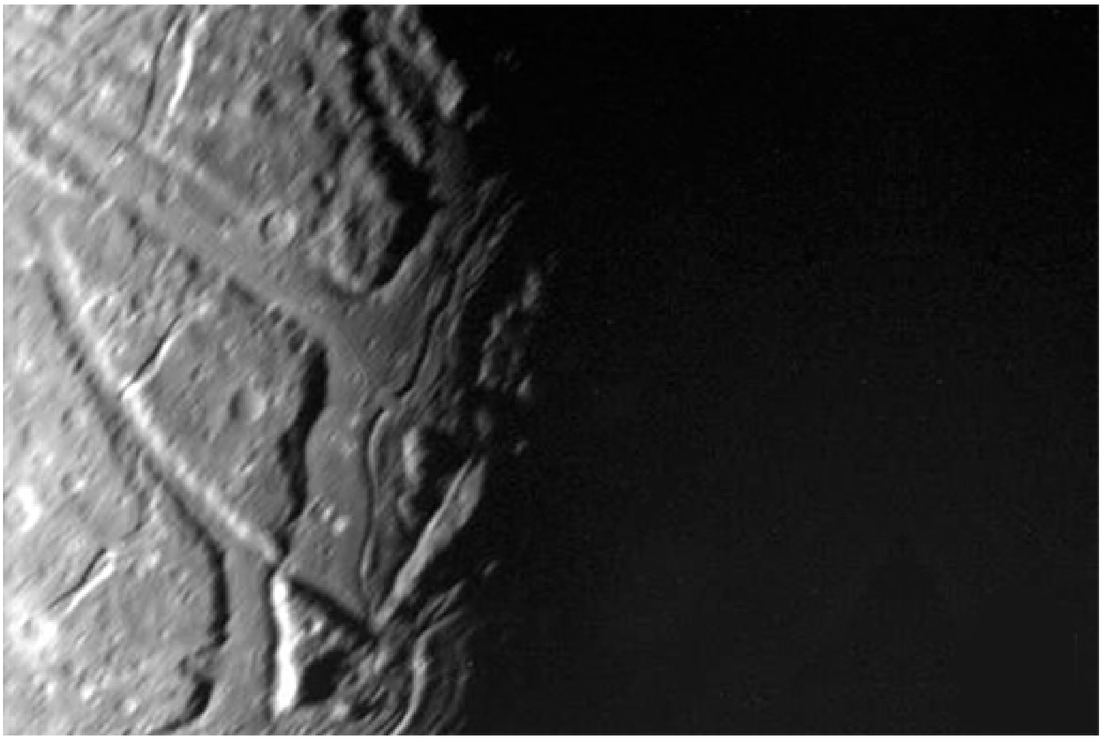


Figure 35 A 1000-km wide region of Ariel, crossed by faulted troughs that have been partly filled by cryovolcanic lavas.

5 This week's quiz

This quiz allows you to test and apply your knowledge of the material in Week 7.

Complete the Week 7 quiz now.

Open the quiz in a new window or tab then come back here when you're done.

4 Summary

This week you have looked at the process involved in gathering and learning about moons. You have also considered the significance of the four great missions. Exploring the only moon in the solar system with an atmosphere was another aspect of this week's learning. Next week the course looks at the case for renewed human exploration of the moon.

You should now be able to:

- the missions that have explored moons in the outer Solar System
- the surface and atmosphere of Titan
- some medium-sized icy moons.

You can now go to Week 8: Moons and the future.

Week 8: Moons and the future

Introduction

What does, or should, the future hold for moons exploration? Here Jess introduces the final week: future exploration, the search for life and the Week 8 quiz.

Video content is not available in this format.

By the end of this week, you should be able to:

- consider the case for renewed human or robotic exploration of the Moon
- be aware of some efforts being made to accomplish this
- understand the debate about life in the Solar System, including the important role of moons
- be aware of plans for future missions
- understand what it takes for an environment to be habitable.

1 Flights of the imagination

Many questions remain about the moons in the Solar System. Is there life on Europa? Is there a saltwater ocean below the surface of Ganymede? Can we build a base on the Moon? And what will the answers to these questions mean to us?

Figure 1 Artist's impression of astronauts controlling a suite of robot surrogates while orbiting Mars. The surrogates include a roving vehicle, climbing robot and miniature sample-return rocket.

Now you get to apply what you've learned so far about moons to questions concerning the future of space science and exploration. You consider the potential for building bases on the Moon and for landing on other moons. And you ask how the answers to our questions will forever change the way we see moons in the Solar System.

Where do you think we should explore next? If the south pole of the Moon seems like a good idea to you (and by now you should be in a position to judge), then you may like to become involved in the world's first crowd-funded mission, Lunar Mission One.

1.1 Humans or robots?

In this video, Ian Crawford discusses the advantage of human exploration over robotic missions; however, there are pros and cons for each. Robotic missions are a lot cheaper than manned missions and do not need to return to Earth, but humans are a lot more efficient at exploration. Missions to the Moon still hold a lot of prestige. Recent missions from Japan, China and India have been used by those countries as a way to demonstrate technological capability. Scientific knowledge to complement that of the Apollo era has also been obtained and international collaboration has been strengthened.

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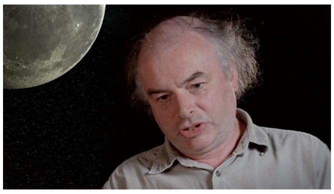

See also:

- Jack Schmitt radio interview. Hear the ‘robots or humans?’ opinion of Jack Schmitt (of Apollo 17) in this 2015 radio interview.
- Luna 27 interview. David Rothery talks to James Carpenter of the European Space Agency - ESTEC about the planned Luna 27 lunar lander mission (3 minutes)
- A lunar space station? The successor to the International Space Station could be in orbit close to the Moon, according to agreements emerging in 2017.
- Why we go to the Moon An article by Paul Spudis dated October 2017.

1.2 The Moon goddess and the Jade Rabbit

The Chinese sent orbiters to the Moon in 2007 and 2010, and named them Chang’e 1 and Chang’e 2, after the Moon goddess of Chinese mythology. They then used Chang’e 3 to deliver a 140 kg robotic rover to the surface in December 2013, which they named Yutu (meaning ‘Jade Rabbit’, named after the Moon goddess’s pet). The lander was equipped with an astronomical telescope to observe distant objects in ultraviolet light (which cannot be done from Earth because of our atmosphere), and the rover had probes and cameras to study the lunar regolith. The Chang’e 3 mission can be seen as a test of the robotic exploration strategy discussed by Ian Crawford in the previous video, but it may also be a precursor to a future Chinese manned landing.

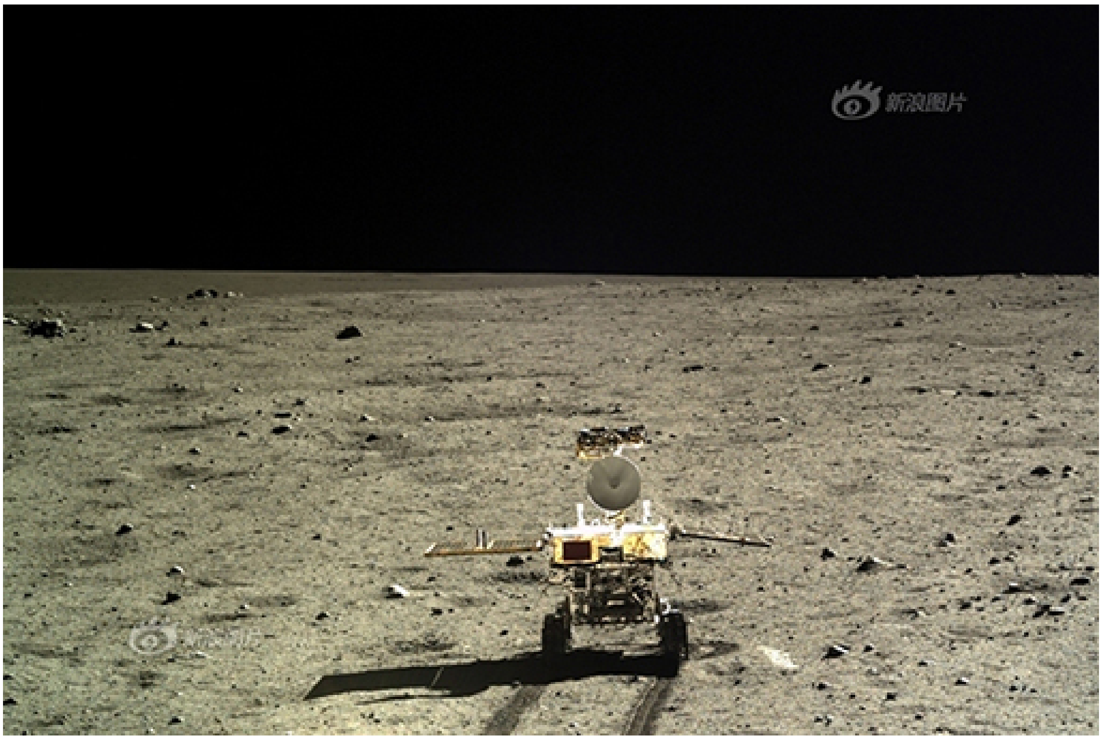

Figure 2 Yutu imaged from the Chang'e 3 lander, 22 December 2013. The landing site is in the northwest of the Mare Imbrium.

The lander and Yutu were shut down during each lunar night, which lasts nearly 15 Earth-days. Yutu awoke to find itself unable to move on the third lunar day (23 Feb), but continued to function, and provided analyses suggesting a previously unsampled variety of mare basalt. Lots of images from Chang'e 3 and Yutu can be found hereand if you go to this link you will find a remarkable interactive 360-degree panorama constructed from Chang'e 3 lander images (the Earth in the lunar sky is faked though).

China's next lunar mission, the 'Chang'e 5 Test Mission' was launched in October 2014 on a return trajectory to the Moon (without landing) as an engineering test for the future Chang'e 5 sample return mission.

The lander's astronomical instruments continued to function as well. If you want to follow the progress of the mission, try the links below. The surface package finally ceased to function in late July 2016, after nearly 1000 days of surface operations.

China's next lunar mission, the "Chang'e 5 Test Mission" was launched in October 2014 on a return trajectory to the Moon (without landing) as an engineering test for the Chang'e 5 sample return mission planned for November 2017 but delayed following the failure of a Long March 5 rocket in July 2017.

Chang'e 4, a lander on the Moon's far side is scheduled AFTER Chang'e 5, in the 2018-2020 time frame.

Next, you have a chance to weigh up some of the costs of sending objects into space. It's a very basic non-scored quiz. Don't worry if you don't know some of the answers. Take an educated guess.

See also:

- Yutu update July 2014 A summary of known information into July 2014.
- Chang'e 4 announcement Plans for the first ever lunar far side landing.

- Chang'e 3 update and Chang'e 4 plans. The status of Chang'e 3 and plans for the Chang'e 4 far-side landing and the necessary relay satellite, summarised in January 2016.
- Chang'e 4 farside landing plans as of June 2016. News of plans for 2018/9 far side landing, and confirmation that Chang'e 5 sample return mission from the near side will probably precede this.
- Chang'e 5 plans An informative blog about China's Moon plans from the Planetary Society, dated April 2017.
- Chang'e 5 ready for launch. News as China readies for the Chang'e 5 launch.

1.3 How small? How expensive?

Now you have a chance to weigh up some of the costs of sending objects into space. It's a very basic non-scored activity. Don't worry if you don't know some of the answers. Take an educated guess.

Activity 1 The costs of sending objects into space

Allow approximately 15 minutes.

What is the approximate cost of sending 1 kg into Earth orbit?

○ $3000

No, it costs more than that. Try again.

○ $10 000

Well done.

○ $230 000

No, it costs somewhat less than that. Try again.

○ $600 000

No, It costs a lot less than that. Try again.

How heavy was the Mars rover *Curiosity*?

○ 20 kg

Incorrect. It was heavier than that. Try again.

○ 899 kg

Correct.

○ 1000 kg

Incorrect. It was a little lighter than that. Try again.

How much did the *Curiosity* rover cost to design, build and launch?

○ $2 million

Incorrect. It cost even more than that. Try again.

○ $100 million

Incorrect. It cost even more than that. Try again.

○ $2.5 billion

Correct.

How much did the International Space Station cost?

○ $10 billion

Incorrect. It cost even more than that. Try again.

○ $20 billion

Incorrect. It cost even more than that. Try again.

○ $150 billion

Correct.

How much has the New Horizons mission to Pluto–Charon cost?

○ $6 million

Incorrect. It cost even more than that. Try again.

○ $45 million

Incorrect. It cost even more than that. Try again.

○ $650 million

Correct.

○ $1 billion

Incorrect. It cost less than that. Try again.

1.4 The JUICE mission to Jupiter

In this video, John Zarnecki discusses the advances in space instrumentation over the past few decades. Increased sensitivity, low size and low mass are key improvements.

The JUpiter ICy moons Explorer (JUICE) mission is intended to be launched by the European Space Agency (ESA) in 2022. If the launch is successful, the spacecraft will arrive in the neighbourhood of Jupiter in 2030. It will initially focus on Europa and Callisto and finally it will orbit Ganymede for several months to obtain detailed images of the surface from an altitude of just 200 km.

Callisto, Europa and Ganymede are all suspected of having oceans below an icy surface, so ice-penetrating radar will be used, giving an indication of the character of the subsurface environment and whether liquid water really lies beneath. The scientific emphasis of the mission will be on trying to understand the habitability of each of these moons and the possibility of it hosting microbial life. Being so far away from the Sun is an irrelevance, given that tidal forces from Jupiter could provide the energy to melt the ice under the surface.

JUICE will contain a suite of instruments including optical cameras, spectrometers, sub-millimetre wave instruments, laser altimeters and radar. Countries from around Europe will supply different parts according to funding and expertise.

Work at the e2v centre for electronic imaging (CEI), based at the Open University campus in Milton Keynes is being done in preparation for the JANUS optical camera system. JANUS is designed to study global, regional and local morphology and processes on the moons and perform mapping of the clouds on Jupiter. The imaging detectors being used will need to withstand long-duration radiation damage from the space environment, particularly from charged particles concentrated by Jupiter's magnetic field (which is one reason why JUICE will not spend any time close to Io, the innermost Galilean moon).

You can discover more information about the work carried out at the centre for electronic imaging.

JUICE passed its ESA review and was approved for implementation in November 2014.

Video content is not available in this format.

In early 2014 NASA revived its interest in further exploration of Europa, as you can see at some of the links below, and in December 2015 Congress (in setting NASA's future budget) directed that the Europa mission should include a lander.

See also:

- BBC news article on the JUICE mission - video. Juice team members Andrew Coates and Michele Dougherty discuss their 'exciting' Jupiter mission.
- ESA's JUICE page. The offical JUICE page of the European Space Agency.
- David Rothery in conversation with Louise Prockter: Missions to Europa. A short bonus video recorded 10 September 2015, containing news of missions to Europa. You met Louise in a the 'Ice and Ganymede' video early in week 2. Since this bonus video was recorded, the mission has been further developed and has been named Europa Clipper. There is a link to the official mission page in Step 8.23.
- A Europa lander. Article about the 2015 US Congressional directive to include a lander as part of NASA's Europa mission.
- NASA's Europa mission. A 3 minute video about NASA's Europa mission, published in June 2015.
- David Rothery in conversation again with Louise Prockter about missions to Europa A follow on from the September 2015 conversation, with up to date news.
- Simplified Europa lander proposed. A description of March 2018 plans for the Europa lander.

1.5 Splashdown on Titan?

You have seen how much moons vary around the Solar System. Each world has a different set of questions and challenges. Concept studies look at how we might overcome some of these challenges through engineering and what science we can gain.

The Titan Mare Explorer (TiME) concept study aimed to provide the first direct exploration of an ocean environment beyond Earth by landing and floating on a methane–ethane lake on Saturn's moon Titan. TiME was under serious consideration by NASA until August 2011, when it was dropped in preference to a geophysical mission to Mars. The plan for TiME was to look for any similarities and differences with Earth and other Solar System bodies, as well as investigating the chemistry of the lakes. It is likely that a parachute descent system would be used to place the instrument on the liquid surface. Missions such as these could observe the surface chemistry and weather systems of unknown worlds.

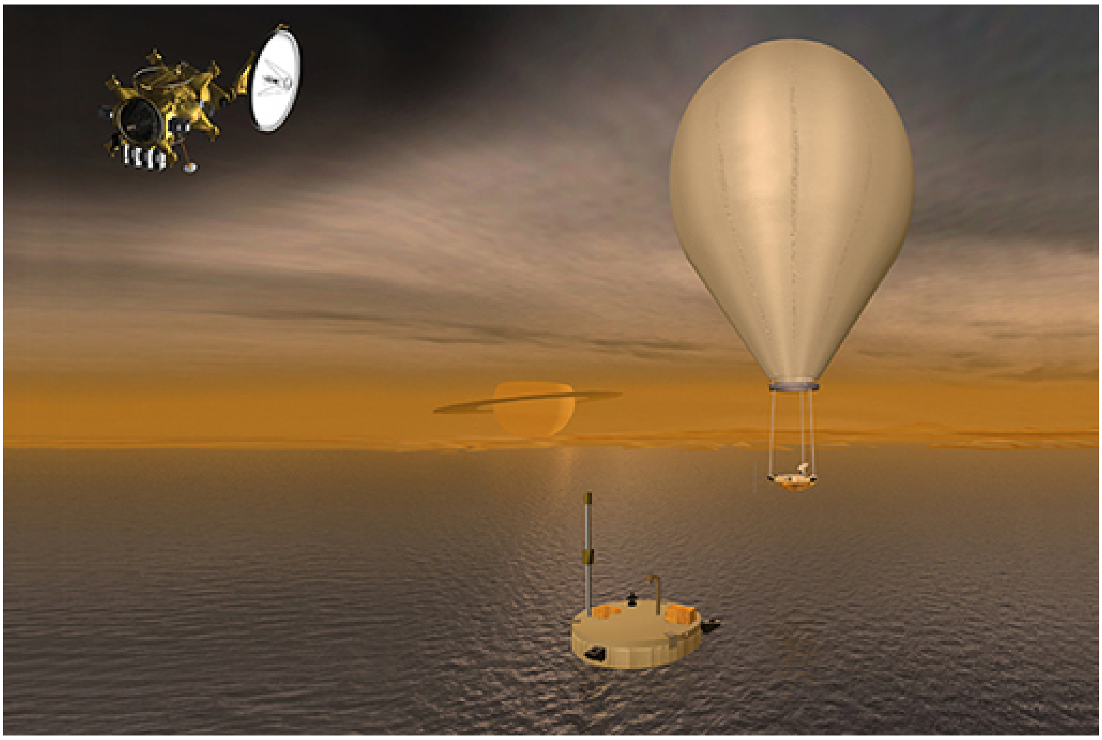

Figure 3 A future mission to Titan?

See also: December 2017 announcement by NASA of funding for development of a drone-like rotor-driven craft to flit about Titan, for possible launch in the 2020s. Dragonfly mission to Titan

1.6 Moon artillery

Penetrators are being designed to get instruments onto the surface of Europa, without the need for a more expensive 'soft landing' and to look into its subsurface without having to drill. Penetrators are essentially instrument-carrying ballistic shells. Such a shell fired into Europa from an orbiter or flyby spacecraft could allow us to measure directly whether the environment has the correct chemical signatures for biological material. This type of technology can also be used on rocky surfaces such as the Moon. This work has shown promising results and has been proposed for future missions to both Europa and the Moon.

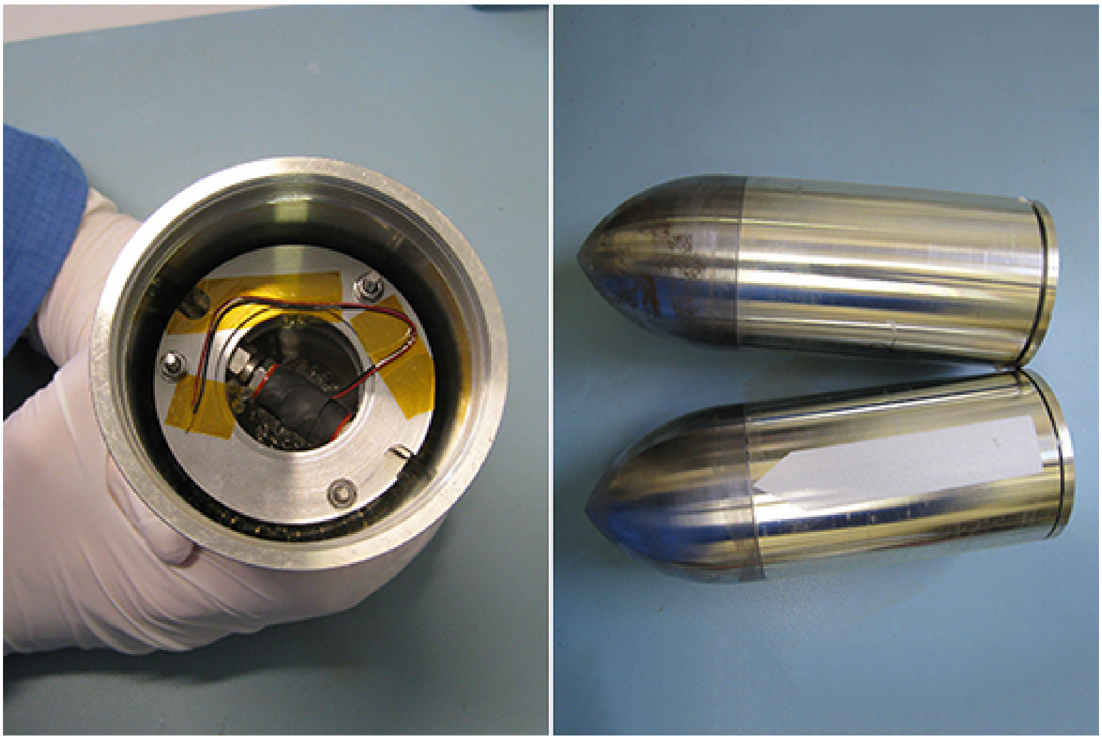

Figure 4 Views of an impactor shell under development at The Open University

A research group at The Open University has been testing miniaturised mass spectrometer instruments for use in high-impact penetrator systems, such as that shown in Figure 4. These miniaturised systems are designed to analyse the subsurface material on moons and small bodies, but first they must survive the shock of very high deceleration during impact, so avoiding the need for soft-landing systems and drilling. Because they end up one metre or so below the surface, penetrators also enable us to make measurements of interior heat and structure. A single spacecraft could in principle deliver several penetrators to different places on a target body.

For more information on high-speed mass spectrometer impact testing, follow this link.

1.7 Penetrators at work

In collaboration with Astrium UK and the Mullard Space Science Laboratory (in London), the instruments housed in penetrators have undergone a series of impact tests into compact sand and ice targets to simulate conditions on places such as the Moon and Europa.

Even after a penetrator was fired at just under the speed of sound, the structure and instruments inside remained intact after the impact, proving the technology to get functioning instruments to the surface of another body in this way. They are much less heavy than conventional landing systems, so more can be achieved for the same mass. This concept will be developed in the next few years, when power and communication systems will also be researched.

This video has no sound

Video content is not available in this format.

1.8 Ice penetrators

It would be very difficult and expensive to land a spacecraft on one of the airless icy moons. The costs would escalate if the whole craft had to be sufficiently sterile to meet the most stringent planetary protection criteria. A neat solution would be to send down a ‘penetrator’, which would be a small projectile to hit the ice at a speed of about 1 km s^{-1}. It would come to rest 1 metre or so below the surface and could be equipped with miniaturised instruments capable of surviving the extremely rapid deceleration upon impact. Because of its small size it could carry only a small battery and might operate for only a few days, but nevertheless it would offer major advances in knowledge. It would also be easier to sterilise than the whole spacecraft.

This short video (which has no audio commentary) is an animation of a ‘penetrator’ designed in the UK by the aerospace company Astrium. What measurements would you most like it to make when embedded in the ice of a moon such as Europa?

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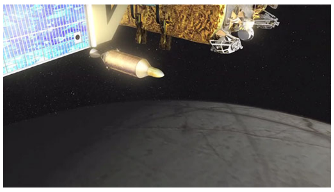


1.9 New Horizons in the making

New Horizons is a NASA mission that aims to map the surface geology and chemistry of Pluto and Charon and investigate the atmosphere of Pluto during a flyby mission.

As well as scientific instruments, the New Horizons spacecraft is carrying a collection of more than 430 000 names stored on a compact disc, part of a scheme by NASA to engage the public.

What will Pluto and Charon be like? Will they share similarities with Triton? Triton’s retrograde orbit makes it likely that it was captured into orbit about Neptune. Strong evidence suggests that Triton was originally part of a two-body system, similar to Pluto and Charon (the smaller moons are an irrelevance in this respect), before it was captured, after straying too close to Neptune.

Figure 5 The New Horizons spacecraft being prepared in ultra-clean facilities.

However, neither Pluto nor Charon turned out to look much like Triton

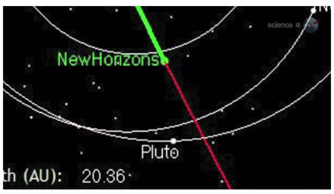
1.10 New Horizons Pluto–Charon flyby

In July 2015 the New Horizons mission flew close past Pluto and Charon – its destination after almost a decade in flight. New Horizons explored the Pluto–Charon system and provided more detail than ever seen before, though it did not find any new moons.

When it was at Pluto, the radio signal that it used to send its data back to Earth took about 3.5 hours to reach us, travelling at the speed of light. New Horizons passed close to Jupiter en route, sending back pictures of Io’s erupting volcanoes.

This NASA video was released in 2011, before Pluto’s 4th and 5th moons, now named Nix and Hydra, had been discovered. When the narrator says that New Horizons ‘still has four more years of travel to go’, he is of course out of date. Also, New Horizons did not stop when it reached Pluto. It flew close past a Kuiper Belt object known as 2014 MU_{69} on 1 January 2019. Observations of this passing in front of a star as observed from Patagonia in July 2017 suggested that it either has an elongated/dumbell shape or else is a double object (a primary and a nearby moon!) were vindicated when the close up images by New Horizons revealed it to indeed be a contact binary - so no moon to add to the list!

Video content is not available in this format.



See also:

- Charon seen by New Horizons. A bonus video in which David Rothery talks to John Spencer of the New Horizons team. Recorded March 2016.
- Thiolins to not simply walk into Morlok Macula. A likely explanation for Charon's dark north polar region (Mordor Macula) based on analysis of New Horizons data.

1.11 Pluto and friends

Imaged by New Horizons on 1 July 2013 – still two years away from reaching Pluto – this was the first view on the approach to Pluto and Charon.

Figure 6 Charon (left) and Pluto (right) imaged by New Horizons

New Horizons flew past Pluto and Charon in July 2015. Visit this NASA link to see where New Horizons is now. You can search images there to see marvellous close-ups of Pluto, Charon and the smaller moons from the 2015 flyby, of the smaller and more distant Kuiper Belt object 2014MU$_{69}$ in the 31 Dec 2018 flyby, and videos of exciting press conferences when the new data were discussed.

See also:

- Charon seen close up. David Rothery's October 2015 article about Charon as revealed by New Horizons
- Rapid rotation of Pluto's small moons. Rapid and inclined rotation of Pluto's small moons discovered by New Horizons.
- Collisions in the Kuiper Belt. Ideas about how collisional mergers occurred to grow Kuiper Belt objects, including a nice image of the contact binary 2014MU$_{69}$.

1.12 Moon Trumps again

Have a go at our Moon Trumps game online or pick up your own pack of Moon Trump cards to play in places the internet can't reach.

Of the five attributes on the cards, the values of the first four are (almost always) well established. However, in deciding what values to put on 'potential for life' we had to make our best guess. As we discover more, the future may prove us wrong, in both the absolute values and in the relative placings of each moon.

Do you think we've got it about right?

Remember, you can play Moon Trumps any time on OpenLearn or you can buy your own pack of Moon Trump cards, to play with your friends and family, via the same link.

Next, before the end-of-course test, you will learn more about ways in which life could exist on and in moons.

2 Life, what is it?

How can life be defined and detected? What conditions does life require? Which moons are most likely to contain habitable environments?

To find out if something is alive, we usually look for a few key signs. Does it breathe? Does it move? Does it eat? Does it excrete? What is its temperature compared to that of the surrounding environment? But these criteria do not apply to all living things. In plants, with an entirely different metabolism from ours, we look for the colour green as an indication of life. What would you say are the criteria for determining whether or not something is living?

In searching for life on moons we would not expect evolved life forms, but much simpler, microbial life – perhaps organisms analogous to bacteria and archaea – and would be surprised to find anything more complex than fungi and lichen. These were among the earliest the forms of life on Earth, and they continue to inhabit the most extreme environments on Earth.

For biologists the two criteria for life are being able to self-replicate and to undergo Darwinian evolution.

Beyond Earth we cannot yet study objects in sufficient detail to form judgements on these two criteria. And so space missions have to look for other signs of life: for the waste products of metabolism, for changes in the environment and, if we're lucky, for observations of shapes and movements. To date, no mission has found any sign or trace of life. Missions have, however, found habitable environments, in other words environments that could harbour life.

The focus is on microbes, because they are known to live in widely diverse environments – from very salty lakes to dilute groundwater, from the cold of the Antarctic to the heat of hot springs, in rocks and in other biomass. Whatever the environment on moons, these simple forms of life stand the best chance of being capable of living there.

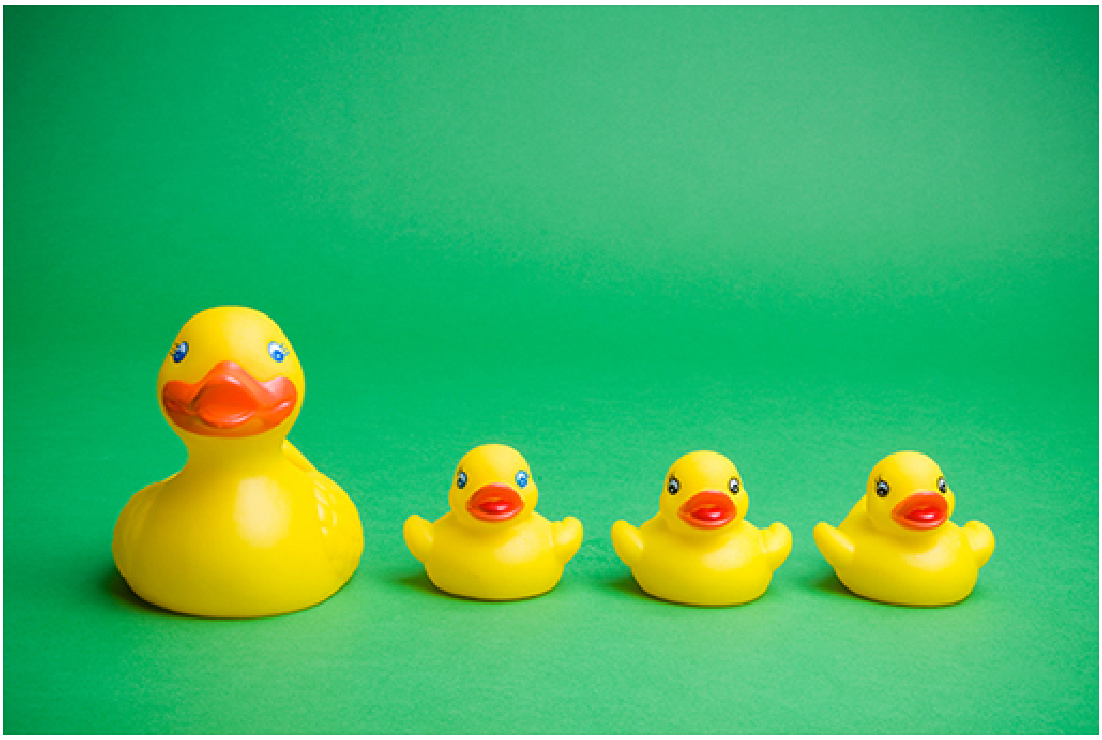


Figure 7 Life, what is it?

See also: What on Earth! - animation. This animated short proposes what many earthlings have long feared – that the automobile has inherited the planet. When life on Earth is portrayed as one long, unending conga-line of cars, a crew of extra-terrestrial visitors understandably assume they are the dominant race. While humans, on the other hand, are merely parasites. An Oscar® nominee, this film serves as an entertaining case study.

2.1 Life chemistry

There are 111 named chemical elements. Each element is abbreviated by one or two letters, usually derived from its name. Some of the symbols are Latin or Greek in origin. Iron, for example, is abbreviated as Fe, from the Latin 'ferrum'. There are a lot of elements, but which ones are important for life?

Looking at the chemistry of living things, only a very few chemical elements play a key role. To better remember them, the abbreviation CHNOPS is used: **C**arbon, **H**ydrogen, **N**itrogen, **O**xygen, **P**hosphorus and**S**ulfur. (Note that the chemical symbol for each of these elements is just the first letter in upper case.) In a human body 99.6% of the mass consists of those elements, and only 0.4% is made up by all the other elements we know, such as iron (Fe), calcium (Ca), magnesium (Mg) and sodium (Na). The three most abundant elements in our body are hydrogen (60.0%), oxygen (25.7%), and carbon (10.7%). Most of the hydrogen and oxygen occurs as water (H_2O). Carbon forms long and complex molecules that also include oxygen and hydrogen alongside nitrogen. The very same chemistry – with some variation – is common to all life as we know it.

Figure 8 Life chemistry

2.2 Markers of life

Metabolic processes are very specific chemical reactions. The existence of life in a location means that these reactions change the environment and influence the types of chemicals found.

One example of this is organic molecules that have the feature of chirality, also called handedness. Such ‘chiral molecules’ come in two forms: the left-handed form and the right-handed form. The chemical compositions of the two forms are identical but the structures are such that a right-handed molecule is a mirror image of a left-handed molecule and one cannot be superimposed on the other. Glucose is a well-known example of a chiral molecule. For a familiar macroscopic example of chirality, just look at your hands: they are mirror images of each other. It is impossible to hold them with palms facing in the same direction in a way that one hand covers the other. Chemical reactions that are associated with life have the tendency to prefer one mirror image over the other, while non-biological reactions have no such bias. In consequence, in a life-free environment the right-handed and left-handed versions are present in equal amounts. If life is present, one form of a chiral molecule will be much more abundant than the other.

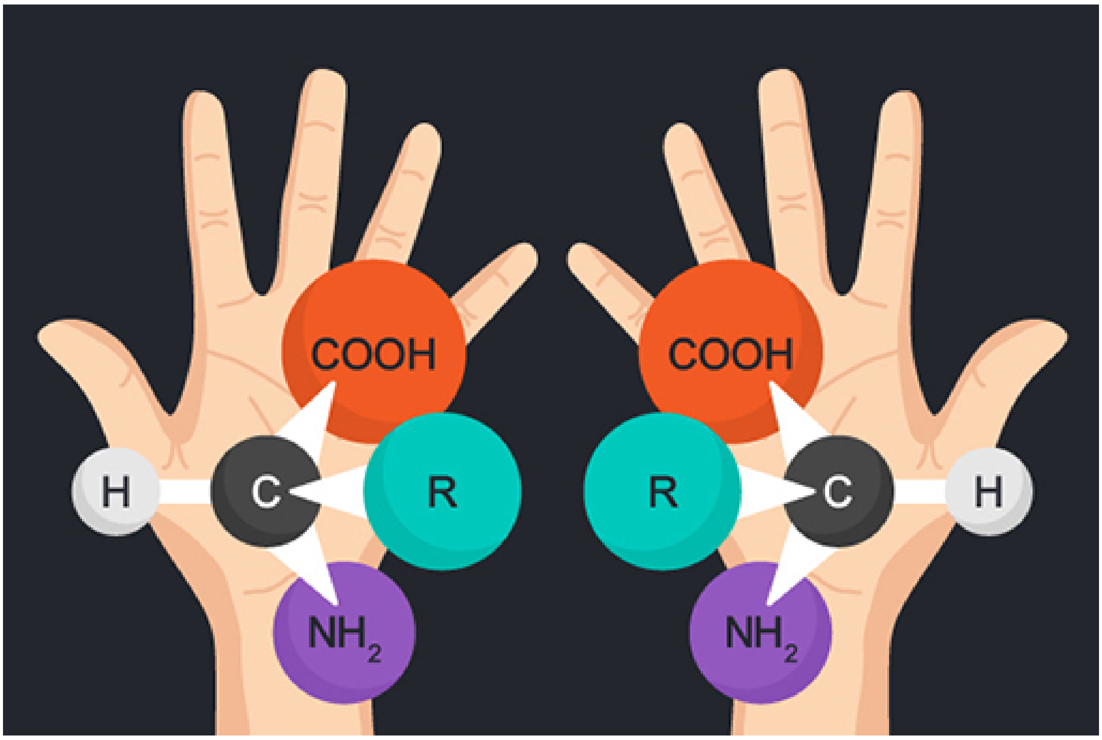


Figure 9 Left- and right-handed molecules.

2.3 Lessons from Earth

Life on Earth started about 3.5 billion years ago. Think about how many species live on Earth today and how great is their variety.

To understand what life forms might be on Mars and on some of the moons of the Solar System, we need to focus on the earliest forms of life known on Earth – the very primitive forms. Archaea, for example, are very simple organisms that reproduce by cell division and can undergo evolution by changes in their genetic information. Being simple gives them a great advantage: they can be found in the most extreme environments, those that are hostile to more evolved forms of life. (The Life Marker Chip, mentioned near the end of the video, will no longer be included on the ExoMars Rover.)

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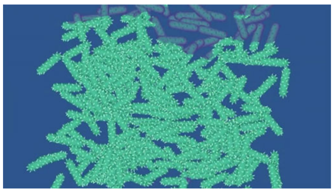

See also: Tree of life - Interactive. Take a moment to look at the first steps life took on Earth, represented by the dark green buttons in the interactive Tree of Life.

2.4 Fossil molecules

The Life Marker Chip mentioned in the previous video (and which has not found a place on the ExoMars mission, but might be used on a later mission) is designed to detect specific molecules that are typically produced by life as we know it. But there are other remnants that could be distinctive.

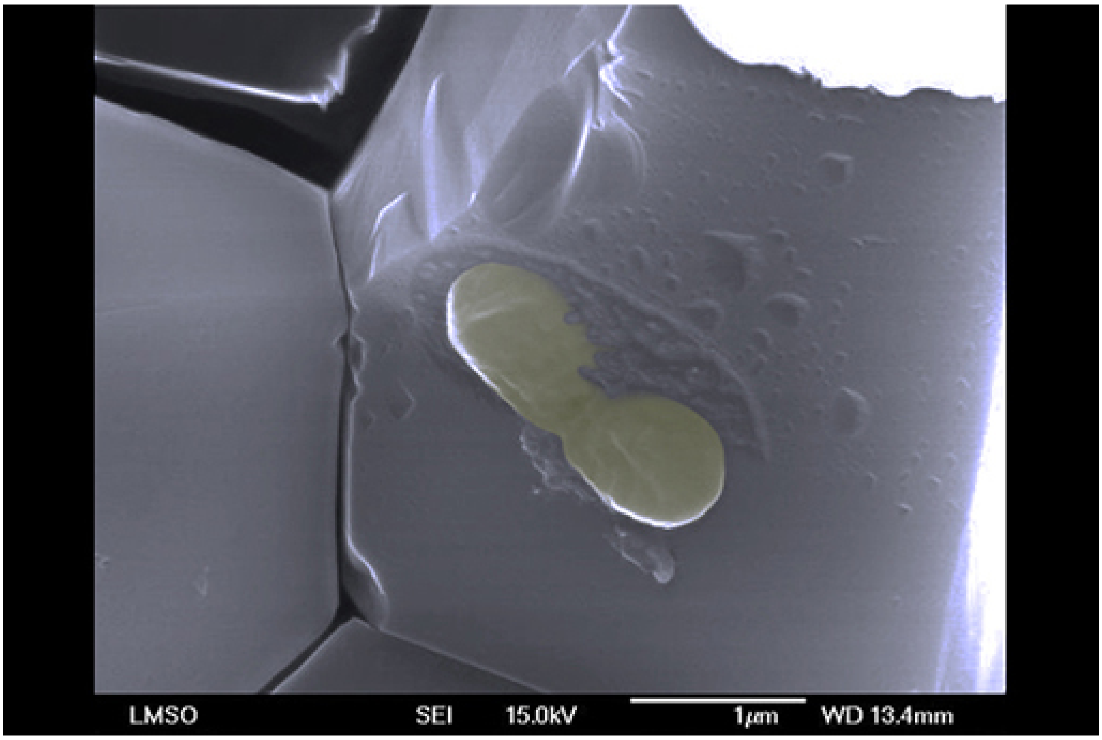

Figure 10 Silicified microfossils in quartz grains from the Kromberg Formation – 3.42 Ga old – in the Barberton Greenstone Belt. The dividing cells are revealed by acid etching but are still partly entombed in the quartz.

The image is a false-colour electron microscopic image of fossilised bacteria. Finding such small structures is not yet possible with spacecraft instrumentation. We therefore rely on other methods to find them, such as detecting their chemical signatures. But with every engineering development, with every new mission, more sophisticated instrumentation is developed and Earth-based laboratory capabilities may yet become available for use on spacecraft.

What is the gold standard and final proof? If we wanted to argue convincingly that there is life on a moon today, we would have to find it. We would have to take pictures, and observe it doing all the things life does, including reproduction. We might have to settle for chemical observations first, which might help us understand what exactly it is we are looking for.

2.5 The habitable zone

Since liquid water is essential to life as we know it, the surface temperature of the planet or moon really matters: it should be between 0 °C (the freezing point of water) and 100 °C (the boiling point of water).

The most important factor that determines temperature on a planet's or moon's surface is its distance from the Sun. If the planet or moon is too close, it gets too hot; if it is too far away, it is too cold. Currently, the only bodies inside the habitable zone of the Sun are the Earth and the Moon. But the Moon has a very hostile surface, with temperatures varying between +120 °C during the lunar day and −150 °C during the lunar night. The reason for these extremes is that the Moon is too small to hold an atmosphere, and so its sunlit side heats up quickly and its night side cools quickly.

Looking at Figure 11 suggests that there is little hope, from this point of view, of finding habitable environments elsewhere. However, the Earth–Moon comparison shows that being in the habitable zone is not the only determining factor.

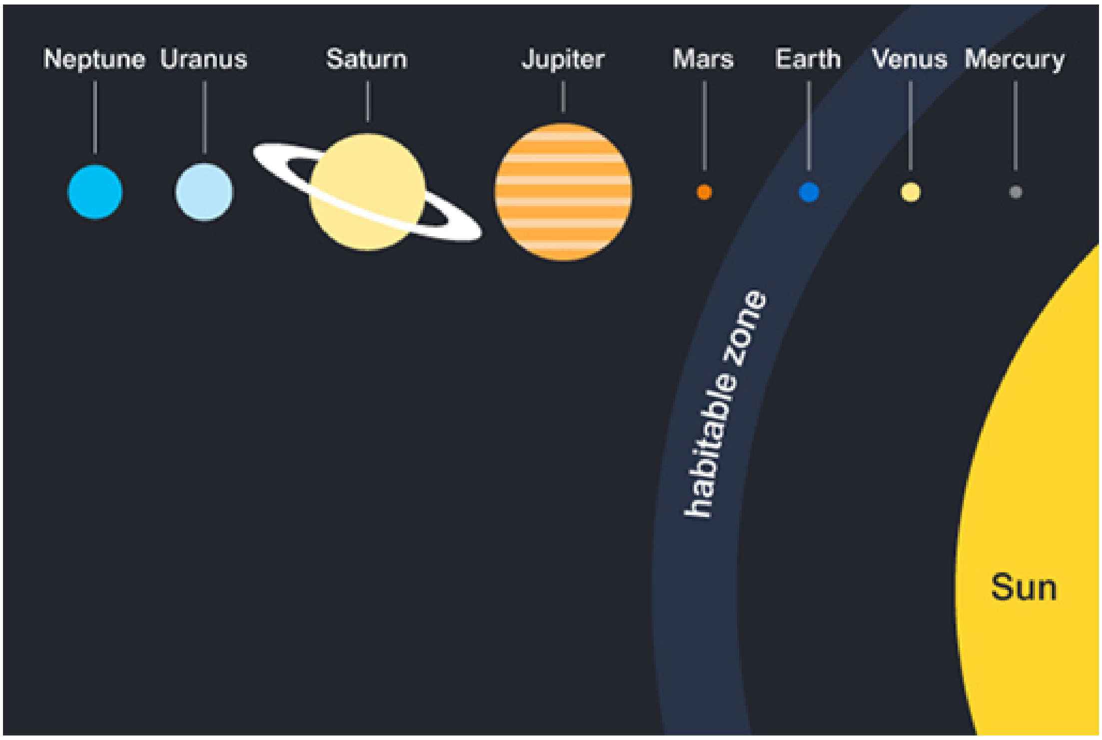

Figure 11 Distance from the Sun determines the zone where liquid water can occur, known as the habitable zone.

2.6 Habitable Earth

Comparing the Earth and the Moon shows that the presence of an atmosphere is of great importance to habitability. An atmosphere provides medium to moderate temperatures on the day and night sides of the planet or moon, and it carries important elements, such as oxygen on Earth. In addition, it may shield the surface from solar radiation. This has two effects: protection from damaging ultraviolet radiation and a decrease in energy reaching the surface. Moreover, an atmosphere may act as a greenhouse, because it absorbs radiation from the surface instead of allowing it to get lost to space.

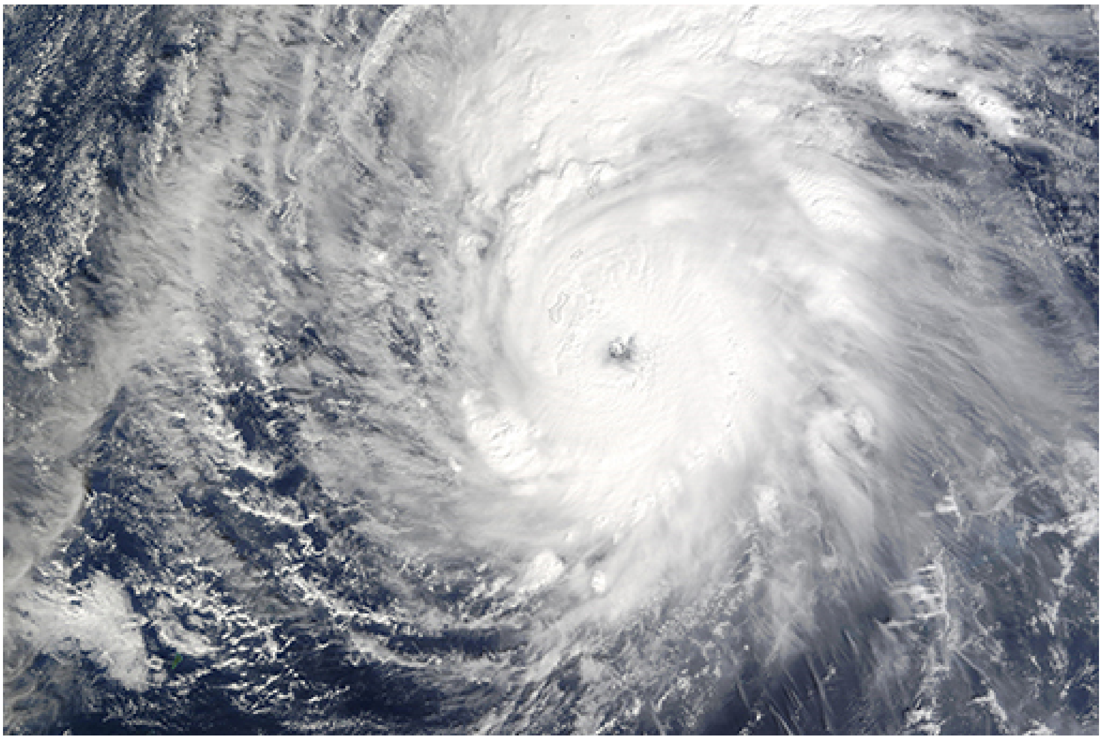

Figure 12 The Earth's atmosphere protects us from damaging radiation and keeps us warm.

Oceans are made of the key ingredient for habitable places: liquid water. The water provides shelter from radiation, it supports creatures with wobbly anatomies, e.g. jellyfish, it transports nutrients and waste products, and it moderates temperatures.

Water-ice can provide shelter from radiation and from adverse changes in surface conditions. But it is not liquid water. It cannot transport nutrients and waste products in the same way as a body of liquid water. In spite of these limitations, there are microbes living in the ice of Antarctica.

2.7 Habitable places

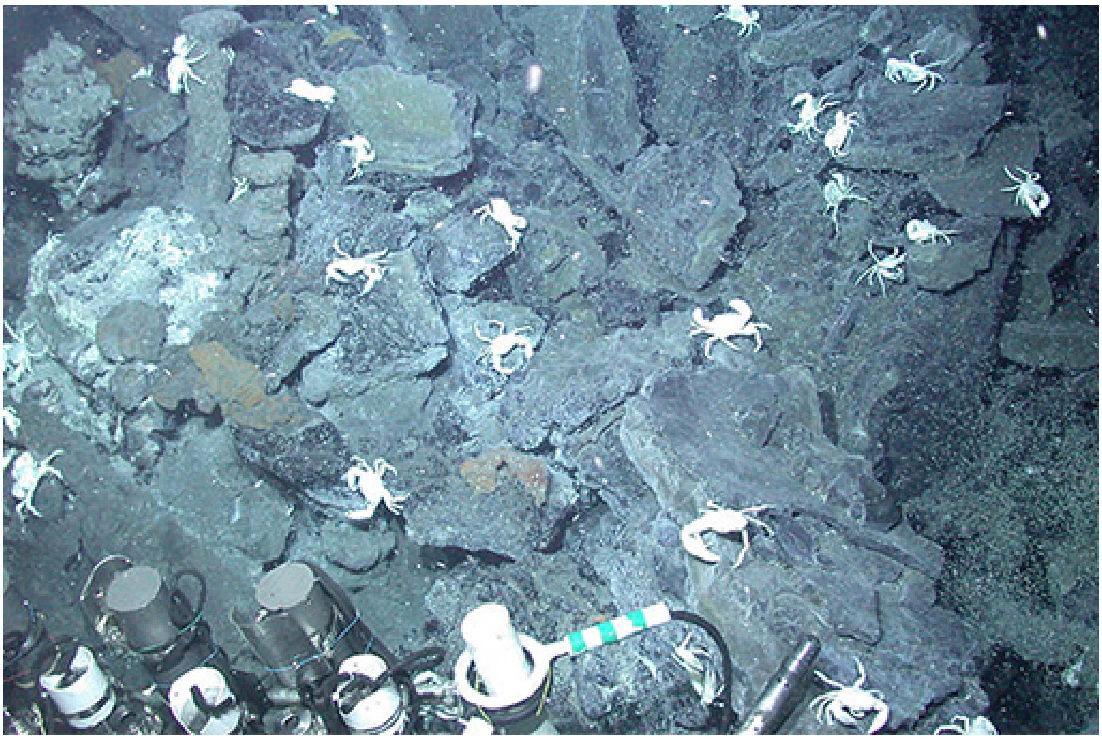

Figure 13 Life near a deep-ocean hot water vent.

Volcanoes can be a source of devastation but they can also give nutrients and heat. At mid-ocean ridges on the Earth, life takes great advantage of the warm water around volcanic vents and especially of the hot water vents where nutrients leave the volcanic system. A special food chain evolves there, with microbes taking advantage of the chemical energy supplied by the vents. Minerals formed from the precipitation of the hot volcanic waters can be the source of energy for some of the microbes, too. The microbes form the basis of the food chain. More complex life forms harvest the simpler life forms as food. The fact that there is no sunlight makes for the white skin of many of the animals. As a consequence, a diverse community of life forms develops around volcanic vents in the great depths of the terrestrial oceans. The number of known species increases with each research dive. Tube worms, spider crabs with diameters up to 80 cm and octopuses have been found. One might speculate that similar ecosystems could develop elsewhere in the Solar System.

Figure 14 The alkaline lake in the 52 000 year-old Lonar crater in India

Like volcanoes, impact craters are a two-edged sword where life is concerned. To witness a large impact would be a lethal experience because the impactor deposits a huge amount of energy in the target site, causing an explosion. Close to the centre of the impact, rocks become molten and vaporised, and a large depression is excavated. Further away from the site, pressure waves rush over the surface causing any loose material to fly and crash into anything in its path.

But after the dust has settled, the remaining energy, now turned into heat, can create a sweet spot for life, especially in cold and otherwise hostile environments. The depression may become a lake. If there is no rain, underground water may accumulate in the crater. Heat that caused the melting of rocks will take hundreds of thousands of years to dissipate.

The Chicxulub impact crater on Mexico's Yucatan peninsula is associated with the impact that led to the demise of the dinosaurs. Chicxulub's 180 km diameter crater will have taken close to 200 000 years to cool below 90 °C. This means that an impact in a frozen world will melt the water and make liquid water available to thousands and thousands of generations of microbes. It makes a habitat that endures for an immensely long time – in relation to the lifespan of a microbe.

2.8 Europa

Despite its hostile, cold surface Europa is one of the most intriguing places to look for life. It has a crust made from ice and an ocean underneath the ice, and so there are two places where life could have established itself.

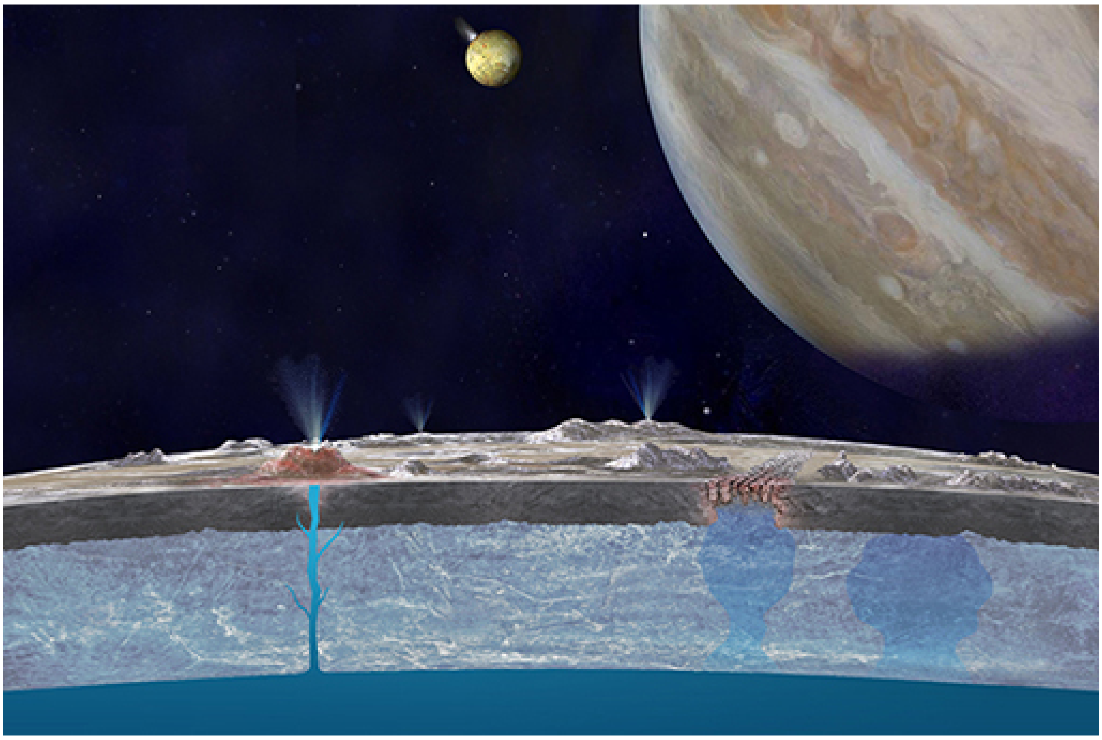

Figure 15 Artist's impression of a cross-section of Europa's crust

First, photosynthetic microbes could live in the diurnal tidal cracks, taking advantage of the liquid water there. A few centimetres down in a crack, they would be sheltered from radiation by the water or slush above them, but still able to use sunlight as an energy source. They would be relatively easy to detect because their remnants might be present where slush from a closing crack is pushed out onto the surface.

Second, the ocean beneath the ice has potential as a habitat because it is shielded from the adversities of space such as cosmic radiation and (small) impacts. Most importantly, it is made up of the key ingredient for a habitable environment: liquid water. Volcanoes or hot springs on the ocean floor might deliver the two other key ingredients: energy and nutrients – very similar to what has been observed at the mid-ocean ridges on Earth. To explore the possibility of life near Europa's ocean floor is much more complicated than looking at the tidal cracks, since a space probe would have to melt or drill through the ice, dive deep into the ocean and then transmit its findings back to Earth.

See also:

- Future exploration of Enceladus. Not Europa, but Enceladus. A BBC online article from Dec 2015 containing two excellent audio interviews. Well worth a listen if you want to learn more about life and how to find it.
- More Enceladus ideas. Ideas for future Enceladus exploration aired in 2016, reported in a New Scientist article.
- NASA's Europa Clipper mission. Latest news about the (now officially approved) NASA mission to Europa.
- Enceladus and Europa news 13 Apr 2017. David Rothery and the BBC's David Shukman talking about detection of hydrogen in Enceladus's plume and other news.
- Radio Sputnik (Moscow World Service) interview about Enceladus habitability . 10 minute radio interview on 14 April 2017 by David Rothery about Cassini's discovery of molecular hydrogen in Enceladus 's plumes.

2.9 Ganymede

Ganymede is the largest moon in the Solar System and has a magnetic field that shields it from certain types of radiation. Its outer layer is mostly ice. This ice might contain liquid water in molten pockets. Looking closer, Ganymede has two types of surface. The first type (the 'dark regions') is heavily cratered. This might tell us about its age, but it also means that a lot of disturbance has happened there. The second type of surface is known as the 'grooved regions'. These areas are less cratered than the first type.

Ganymede's ice is not pure, because the upper parts of the ice may contain rocky or carbonaceous dust. It is this material – in reaction with liquid water – that could provide energy sources and nutrients for life. To explore these pockets, a space probe would have to infiltrate them – similar to the approach on Europa.

Figure 16 Image of Ganymede, Jupiter's largest moon, taken by Voyager 1, 1979

A study released on 1 May 2014 suggested that if Ganymede's ice is salty enough there will be layers of salty liquid between types of ice stable at progressively higher pressures, and (important in the contest of life) between the lowest ice layer and the underlying rock.'

See also: Ice-brine-ice-brine layering in Ganymede? News released on 1 May 2014 of a study suggesting that if Ganymede's ice is salty enough there will be layers of salty liquid between types of ice stable at progressively higher pressures, and (important in the context of life) between the lowest ice layer and the underlying rock.

2.10 Titan

Titan has a dense atmosphere. But what makes it even more interesting is the chemistry of this atmosphere, which contains many of the key compounds believed to have been important in the early history of the Earth's atmosphere. The most abundant species making up 97% of the atmosphere is nitrogen, 1.4% is methane and about 0.1% hydrogen. There are also traces of carbon monoxide.

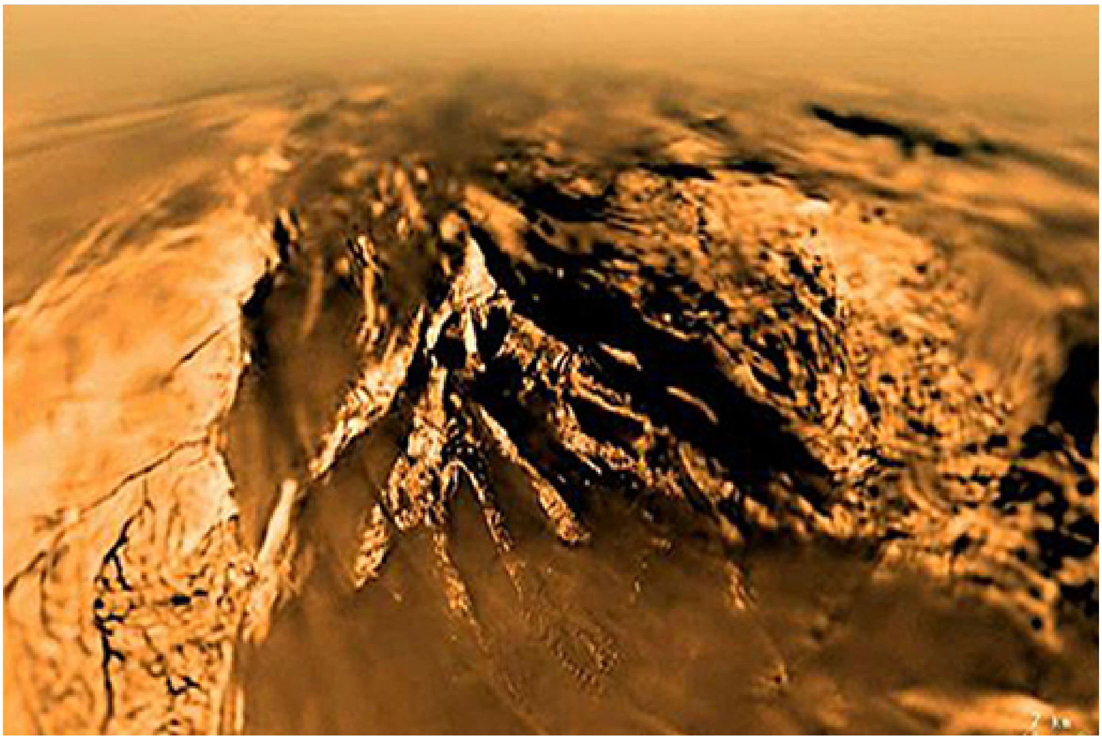

Figure 17 A view of Titan's surface, seen during the parachute descent, by the Huygens lander. The view across the foreground is about 50 km wide.

Approaching the surface, the Huygens probe found that only 0.01% of the sunlight measured on top of the atmosphere reaches the surface. This thick atmosphere has rain – not of liquid water but of methane. The surface looks much like Mars, but it is liquid methane that carves the river channels. Is this a place similar to the early Earth? It may be that the landscapes are similar – but methane is not water. Therefore potential life forms on Titan would have to be very different from anything we are familiar with on Earth, if they wanted to use rivers of methane in the same way terrestrial life forms use the rivers of water on Earth. Future missions will be able to build on the Huygens lander data and find out more about this familiar-looking yet very different world.

In this article, The Open University's Professor Andrew Norton considers the range of habitable conditions that could exist on moons in other solar systems.

See also: Habitable exomoons? An article by the Open University's Professor Andrew Norton musing about the habitability of moons of explanets (planets of other stars).

2.11 What Huygens found on Titan

John Zarnecki was the lead scientist on the Surface Science Package (SSP) and co-investigator for the Huygens Atmospheric Structure Instrument (HASI) – for the Huygens lander on Titan. In this video he explains the excitement of the first hours after landing and what the team deduced from the data returned to Earth.

Video content is not available in this format.

See also an interview recorded by David Rothery with Sarah Fagents (University of Hawaii) in May 2018 about a proposal to study Titan's habitability
https://www.youtube.com/watch?v=P7kW8mdSDyg

3 What's the Buzz?

Thoughts on moons, and that all-important end-of-course test.

Just before you review all that you've learned in the end-of-course test, here's a short video of someone special sharing his thoughts on the significance of the Moon and other moons. The interview was recorded for The Open University in 1999, but the extracts used here have never before been released.

When you've watched this, move on to the test.

Video content is not available in this format.

3.1 Presentation recording

In this course's first run in 2014, we hosted a live video presentation towards, in which we answered questions about topics from Weeks 7 and 8. You may find it interesting to watch the video recording.

View at: youtube:TcLsSrx996s

We are unable to offer a live session on OpenLearn, but if you have questions that are not answered in the video, they may be answered in the Moons Facebook group. Please note, there is no official online forum for this course, however, learners who completed a previous version of this course, and want to maintain their connection with moons have set up a Moons Facebook group. Feel free to drop in, to swap experiences with, or seek advice from, your predecessors.

4 This week's quiz

Now it's time to complete the Week 8 badge quiz. It is similar to the badged quiz that you took at the end of Week 4, with 15 questions in total.

Remember, this quiz counts towards your badge. If you're not successful the first time, you can attempt the quiz again in 24 hours.

Open the quiz in a new window or tab, then return here when you have done it.

Week 8 badge quiz

5 End-of-course round up

It's goodbye from Jess after she suggests how you could continue to investigate moons, or other science topics, if we have left you wanting more.

Video content is not available in this format.

You should now be able to:

- develop an awareness of the nature and diversity of moons in our Solar System, and their significance
- describe the compositions and nature of the surfaces and interiors of moons
- describe the nature and history of volcanic activity on several moons, assess and be aware of which moons may have subsurface oceans, and the implications for hosting native life
- describe and be aware of the history of discovery and exploration of moons, and of future prospects
- reflect and suggest ways in which resources from the Moon may help future space exploration.

Well done for completing this eight-week course, *Moons of our Solar System*. If it took you longer, there's no shame in that. It will depend on how much time you had available, and on how much time you spent on the non-core ('bonus') material such as related links.

If you have studied the full course and completed all the quizzes you will receive a Statement of Participation certificate as a record of your achievement. You can access and print it from your MyOpenLearn profile.

If studying moons has inspired you to look at more free learning in this area, you may be interested in joining the five and half million learners who visit OpenLearn each year. We've created an area on OpenLearn specifically for exploring more about moons.

You have now reached the end of *Moons of our Solar System*. We hope you have enjoyed the course and learned a lot about moons.

Acknowledgements

This free course was written by David Rothery and Simon Kelley. Further contributions were made by Susanne Schwenzer, Jessica Barnes, Jean-David Bodénan, Catherine Hill, James Mortimer, Elena Nickson, Phillipa Smith, Beth Steer and Felicity Williams.

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Figures

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