

# Voyage to the Planets

## Lecture 2: The Moon, and Spaceflight

**Presented by**  
Dr Helen Johnston  
School of Physics

Spring 2016



## Tonight

- The Moon: our nearest neighbour
- Principles of spaceflight



# The Moon

## Basic data

	<b>Moon</b>	<b>Moon/Earth</b>
Mass	$0.07349 \times 10^{24} \text{ kg}$	0.0123
Radius	1738.1 km	0.2725
Mean density	$3.350 \text{ g/cm}^3$	0.607
Gravity	$1.62 \text{ m/s}^2$	0.165
Semi-major axis	$0.3844 \times 10^6 \text{ km}$	
Period	27.3217 d	
Orbital inclination (to ecliptic)	$5.145^\circ$	
Orbital eccentricity	0.0549	
Rotation period	27.3217 d	
Length of day	29.53 d	

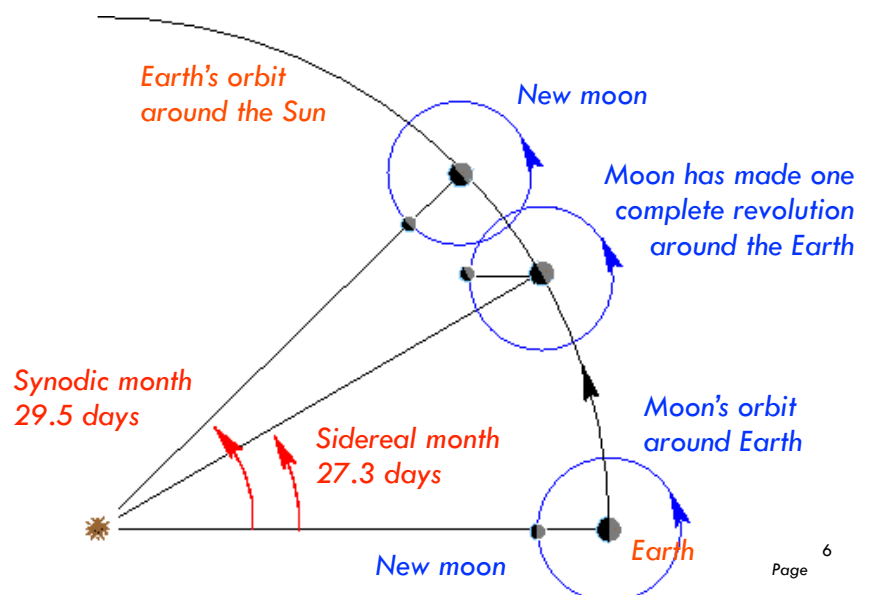
## Basic data

The Moon has

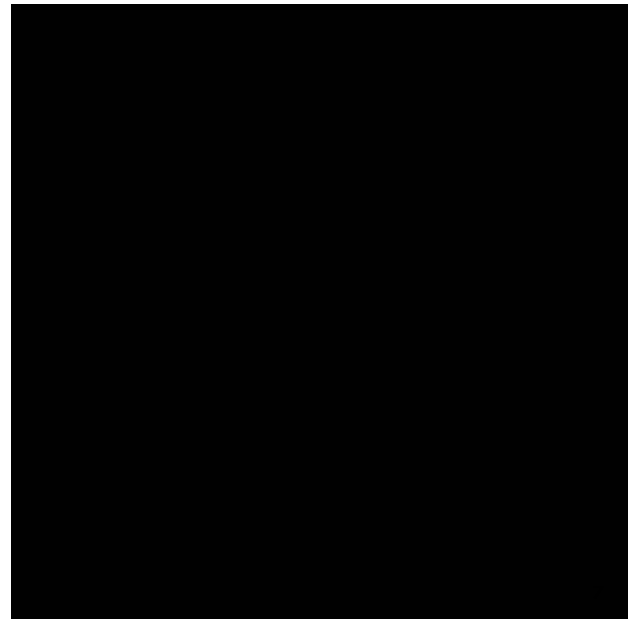
- 1% of the Earth's mass
- 27% of the Earth's radius
- a surface area of 38 million km<sup>2</sup>: about the size of Africa
- surface gravity 1/6 of Earth

The Moon is the largest satellite in relation to its primary of any moon in the Solar System, except for Pluto/Charon.

The Moon completes its orbit around the Earth once every 27.3 days. However, since the Earth has moved around the Sun in that time, it takes an additional 2.2 days before the Sun reaches the same position in the sky: this is the *lunar day*.

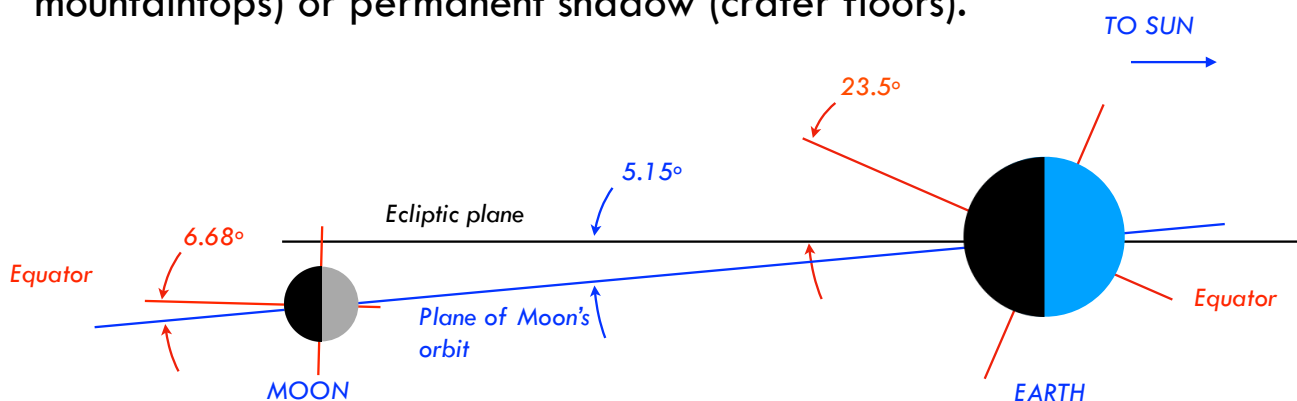


The moon rotates on its axis in the same time it takes to orbit the Earth, which means it always keeps the same hemisphere turned towards the Earth, so there is a side we never see: the *far side*. In fact, due to the  $7^\circ$  inclination of the moon's orbit relative to the Earth's equator, we see slightly more than one hemisphere. Over the course of time, we see about 59% of the lunar surface.



The University of Sydney

The plane of the Moon's orbit is tilted with respect to both the Earth's equator and the ecliptic. Unlike the Earth, whose axis is tilted at almost  $24^\circ$  to the vertical, the Moon's axis is nearly vertical ( $1.5^\circ$ ). This means the Moon has no seasons. Further, there are probably regions near the poles which are in perpetual sunlight (the mountaintops) or permanent shadow (crater floors).

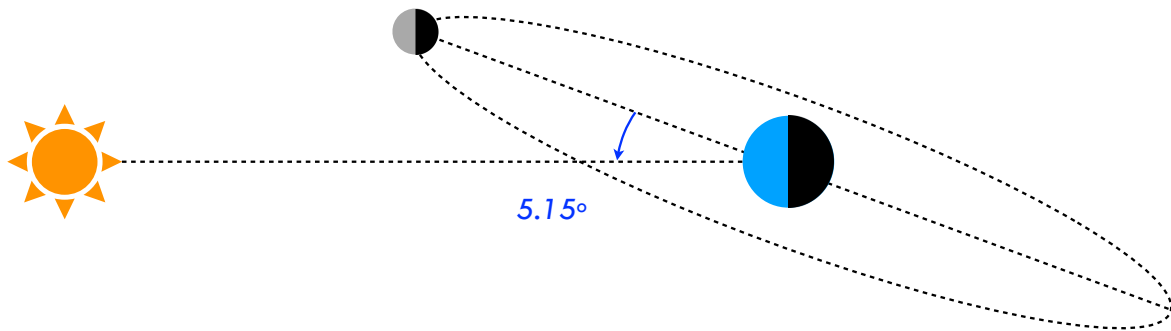


The University of Sydney

Page 8



The tilt of the moon's orbit explains why we don't get eclipses every month. The moon passes through the plane of the ecliptic twice a month. If this happens at full moon, there is the possibility of a lunar eclipse; if at new moon, there could be a solar eclipse.

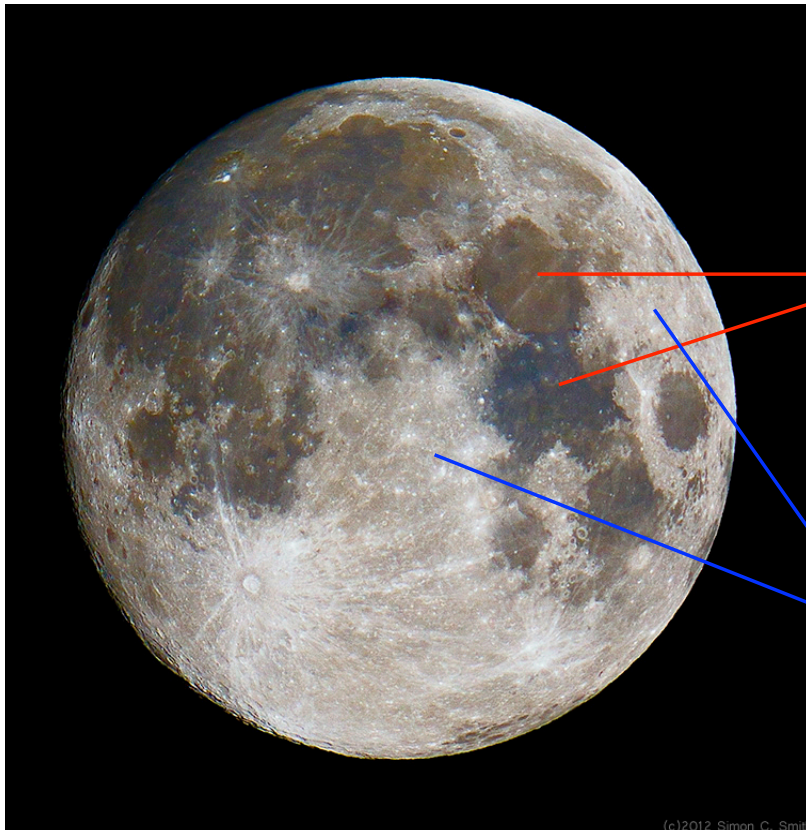


The moon's orbit is elliptical, with an eccentricity of 5.5% – large for major solar system bodies. These images show the difference in size between the full moon at perigee and at apogee: there is 30% more light from a full moon near perigee.





*"Supermoon" over Madrid, Spain*

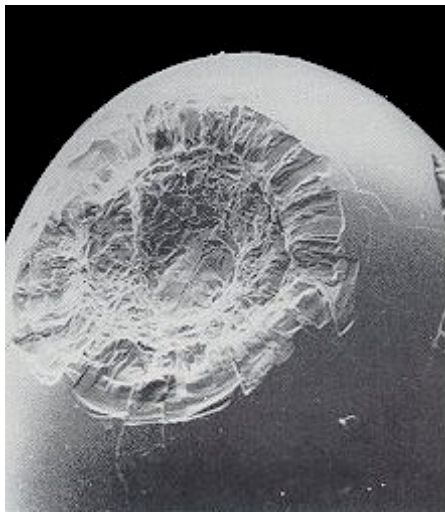


The moon's surface has two obvious terrains:

*maria* – smooth, dark lowlands, small craters

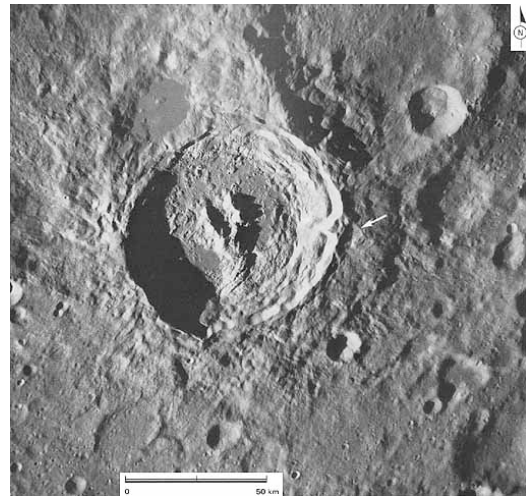
*terrae* – rough, bright highlands, large craters (>40–50 km diameter)

The whole lunar surface is covered with craters. Craters come in all sizes, from microscopic to planet-sized.



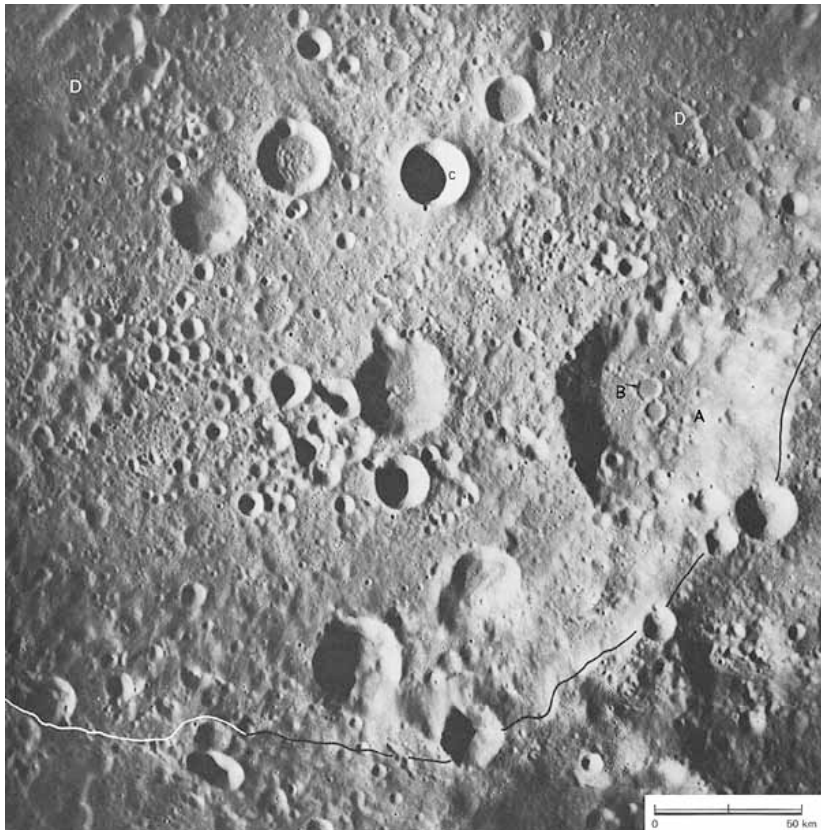
*Electron micrograph of a microcrater in the surface of lunar volcanic glass*

The University of Sydney



*The 75-km diameter King crater on the far side, taken by Apollo 16*

Page 13



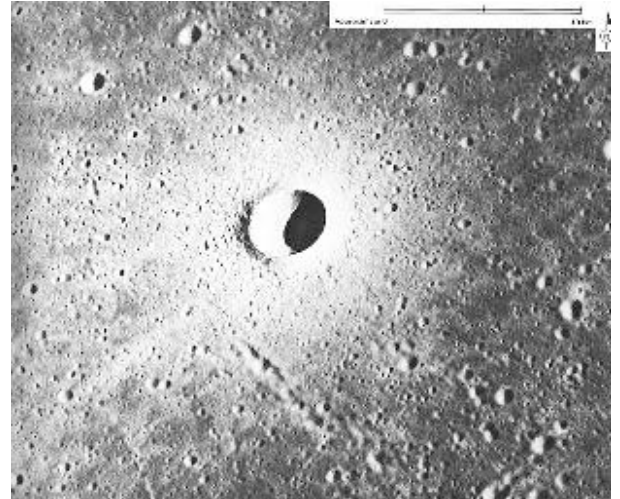
The craters show the ferocity of the bombardment of the Moon, with new craters overlapping and almost obliterating underlying older craters.

*A section of the far side crater Gagarin (rim crest outlined), showing the layering of craters.*

Page 14



Small craters (up to 10–15 km diameter) have simple bowl shapes, elevated rim crests, and depths 15–20% of the diameter. A rough deposit surrounds the crater to about a crater diameter, consisting of material thrown out of the crater during its formation: the *ejecta blanket*. Secondary craters are formed when debris from the main crater hits the surface.



*The very young crater Linne, taken by Apollo 15*

The University of Sydney

Larger craters (20–40 km) have flat floors and central peaks. Material in these central peaks may come from as deep as 10–20 km inside the lunar crust. Secondary craters are often aligned in rows, forming rays pointing away from the central crater.



*The crater Euler, showing the central peak and secondary craters forming rays pointing away from the central crater.*

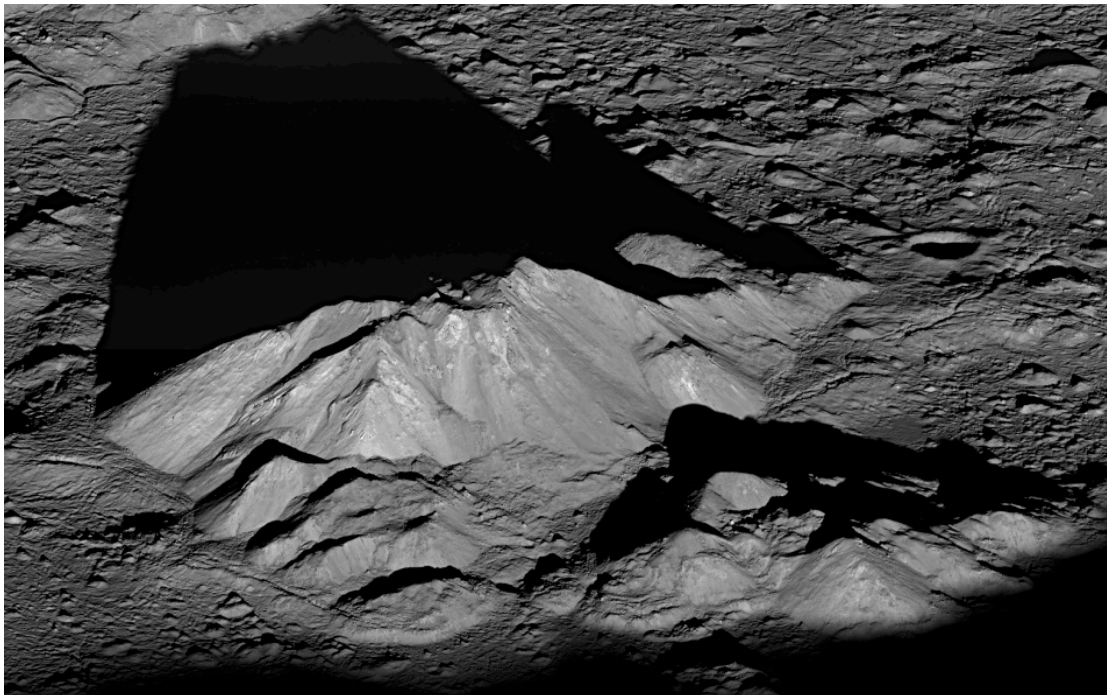
The University of Sydney

One of the youngest large craters, Tycho, is 87 km in diameter, and shows a ray system extending over 3000 km from its rim. Tycho is one of the youngest craters: 108 million years old.



The University of Sydney

ge 17

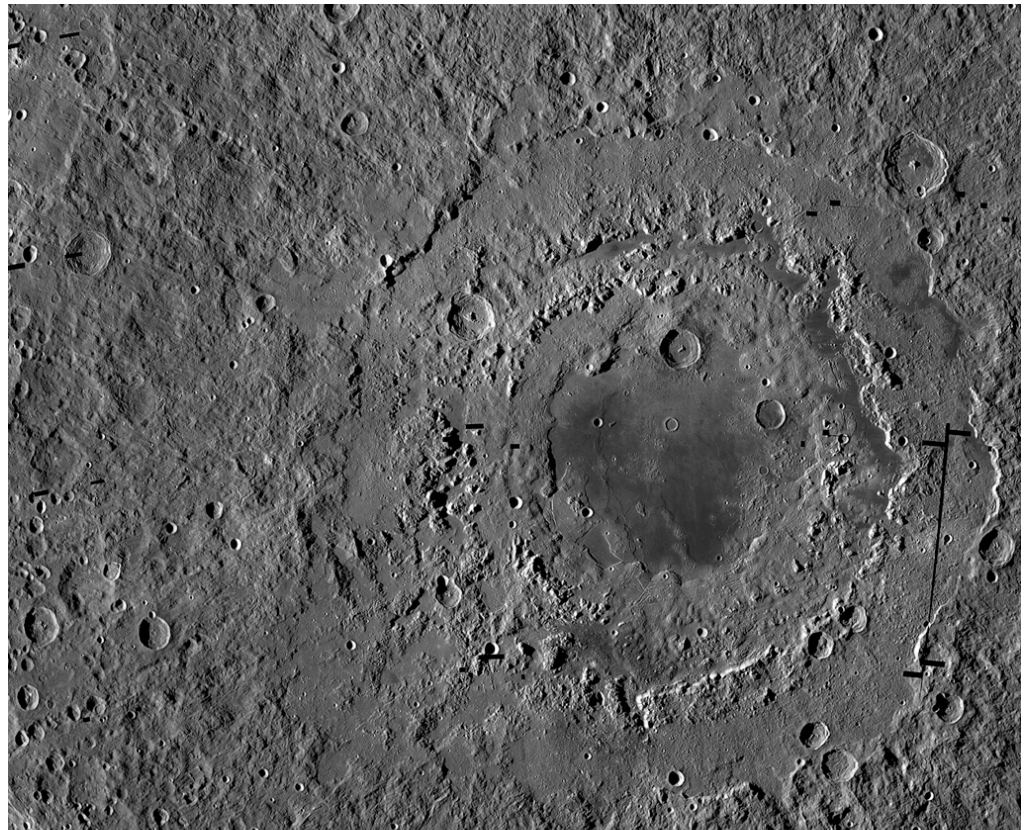
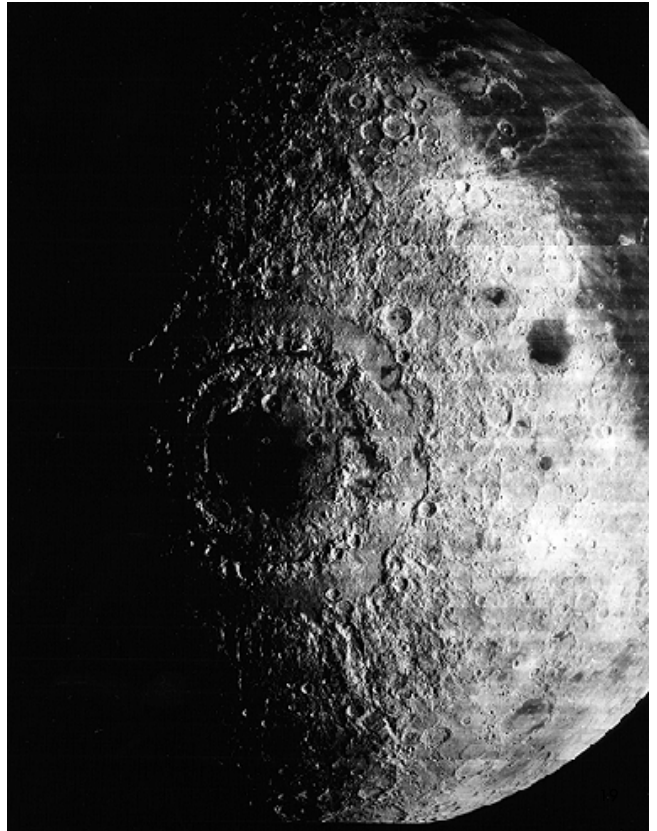


*Dramatic oblique view of Tycho's central peak, taken by the Lunar Reconnaissance Orbiter. The summit is 2000m above the crater floor.*



Even larger impacts produce *basins*: craters  $>300$  km in diameter with concentric rings. One of the best preserved lunar basins is the Orientale basin, showing at least five rings.

The University of Sydney



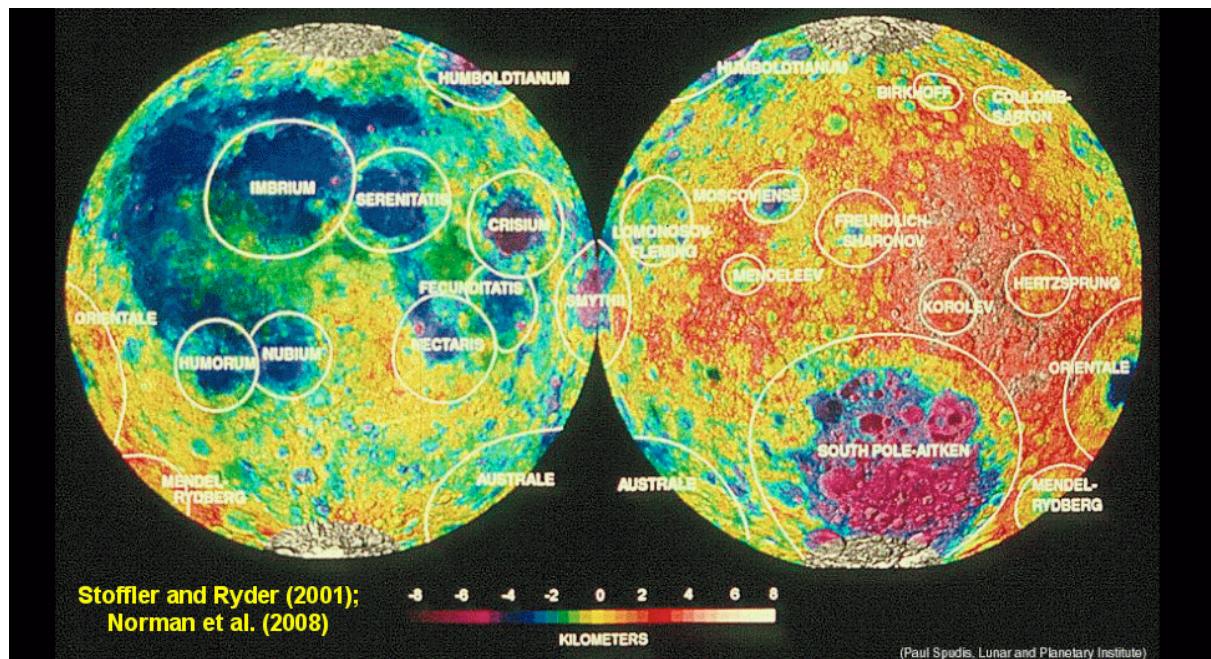
*LRO view of Orientale*



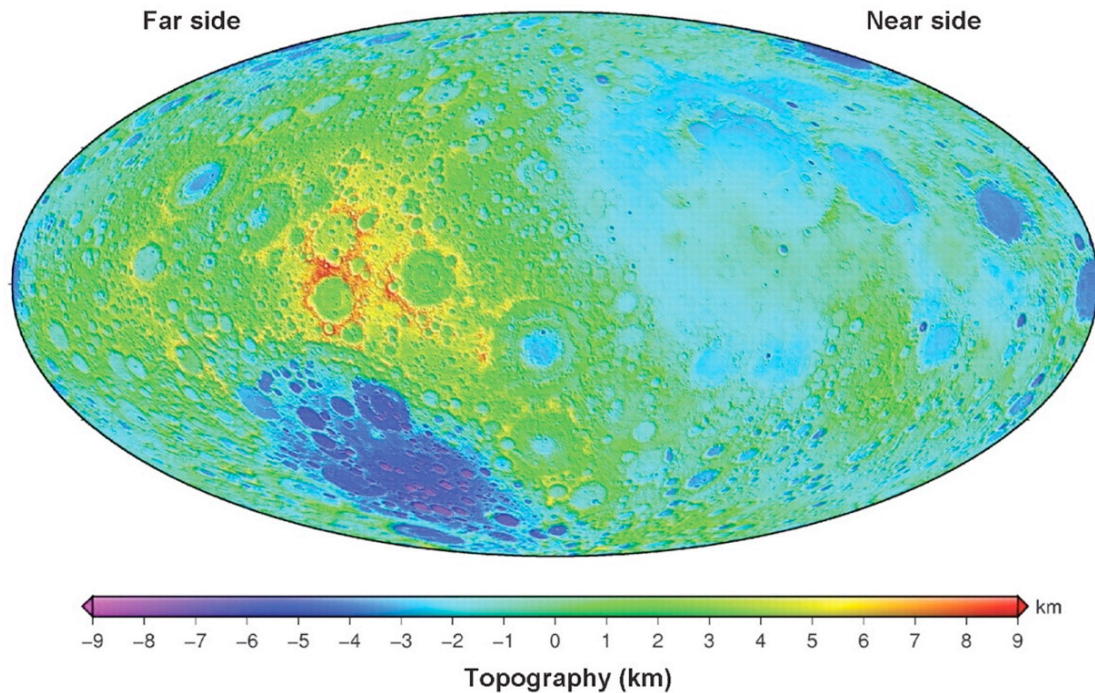
Galileo took this wonderful image of the Orientale Basin in full sunlight. Contrary to expectations, the ejecta is mostly light crustal rocks, so the impact that formed the basin did not penetrate into the mantle.



The University of Sydney



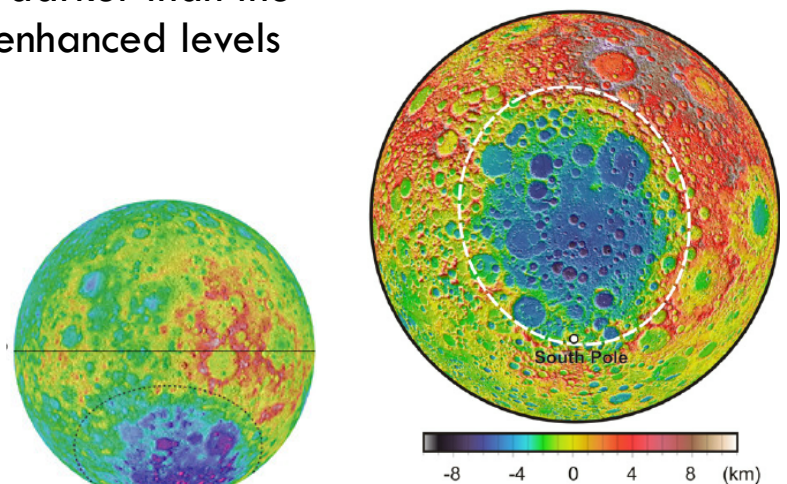
There are at least 20 basins satisfying this criterion, possibly as many as 60.



*Lunar topography measured by the Japanese satellite Kaguya (SELENE). The highest point is 10.75 km. high; the lowest is -9.06 km, in the South Pole-Aitken Basin.*

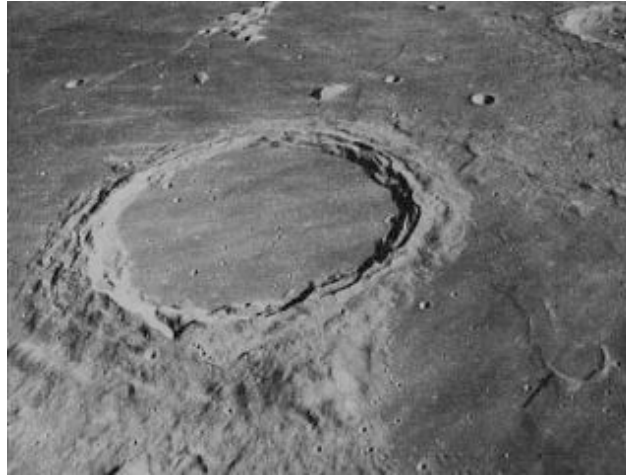
The South Pole-Aitken basin is the largest, deepest impact crater in the Solar System. The rim crest is about 2500 km in diameter, and the average depth is about 8 km.

The basin floor is significantly darker than the surrounding rocks, and shows enhanced levels of iron and titanium.





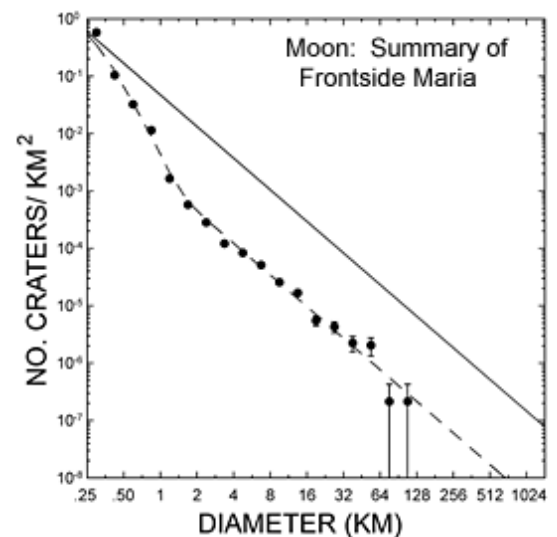
By studying the *superposition* of craters, we can work out the relative age of various structures: young units overlap old ones.



*Archimedes, the large crater, must have been formed before the flooding of the Imbrium Basin, since it is partially buried and filled by basalt.*

We can measure the *crater density* (number of craters of a given size per unit area). By comparing with the ages of rocks brought back from the moon, we find a correlation between the age of the surface and the density of craters.

It appears the rate of bombardment tapered off about 3.9 billion years ago, and has been more or less uniform ever since. This means we can use the density of craters as a measure of the age.

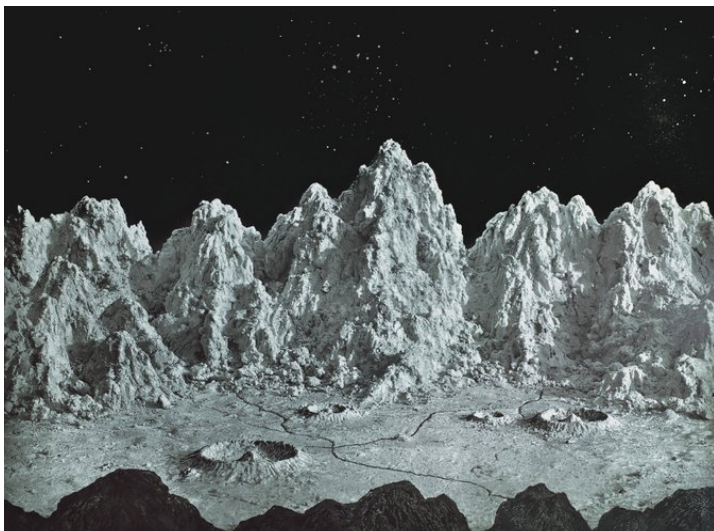


The heavily cratered highlands of the moon are much older than the maria, which have far fewer craters.



Page 27

One consequence of the constant bombardment is the erosion of surface features on the Moon. Unlike the jagged landscape of craggy pinnacles of pre-space age depiction...

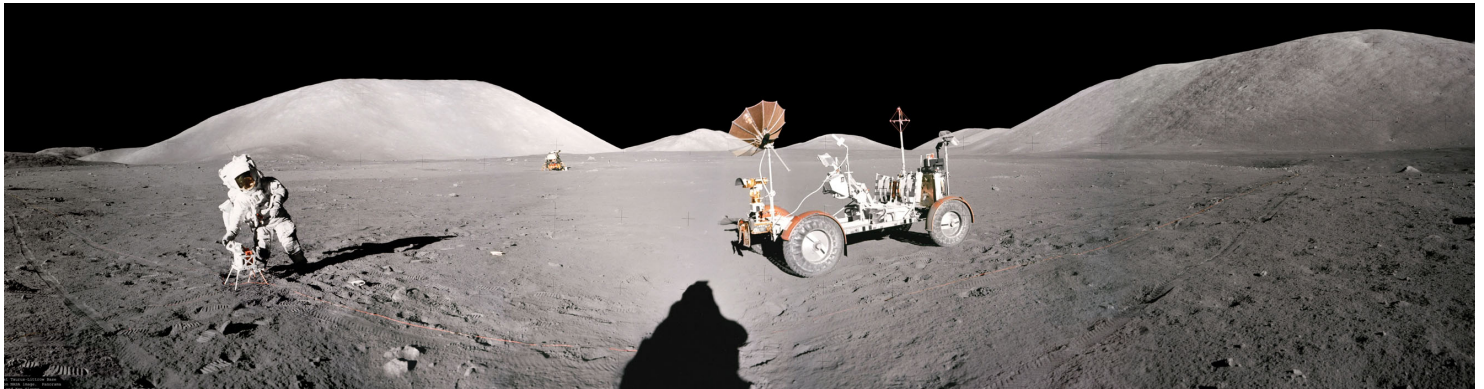


(above) "Conquest of Space": painting of the lunar surface by Chesley Bonestell (1949). (left) Lunar mountains, by James Nasmyth, 1874

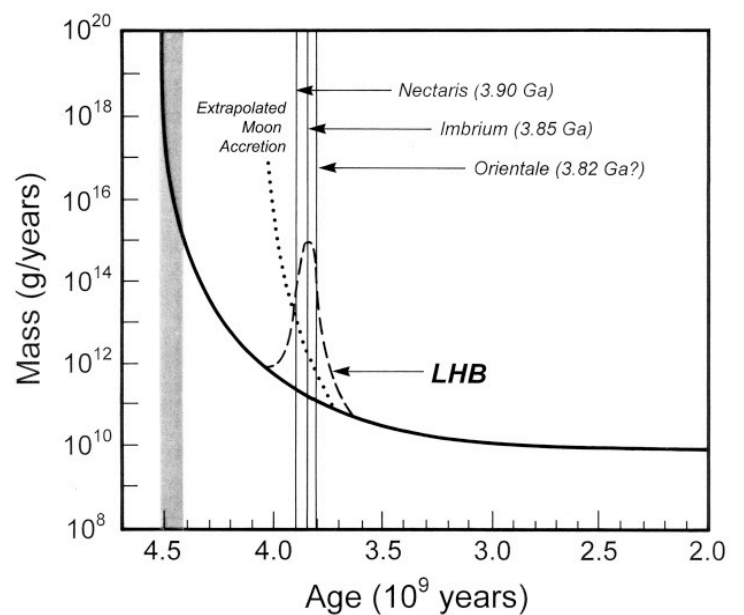
Page 28

... the surface of the moon is actually remarkably smooth.

*Astronaut/geologist Jack Schmitt, Apollo 17, on the lunar surface*



The ages of the nearside basins, measured from Apollo rocks, suggest there was a spike in the rate of impacts around 3.9 billion years ago: the *late heavy bombardment*.





Rocks are still hitting the Moon; by studying impact rates on the Moon, we can better understand the dangers to the Earth from meteorite collisions.

It is estimated that on average 180 new craters at least 10 metres are created each year.

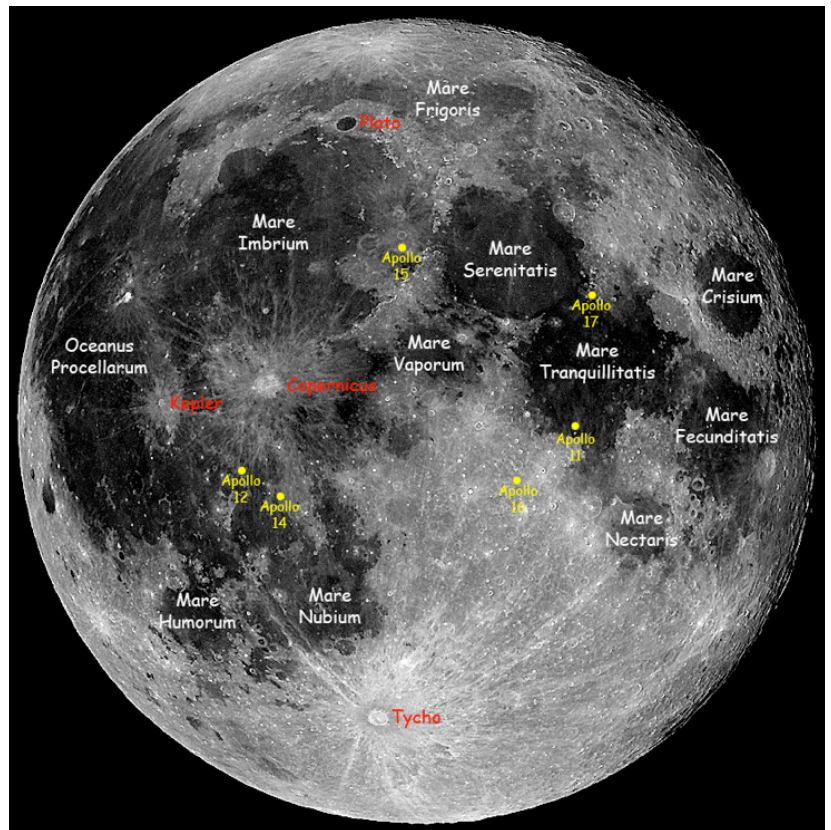
On 11 September 2013 an object with the mass of a small car hit the lunar surface in Mare Nubium, producing an easily visible bright flash.



The University of Sydney

## Maria

The *maria* are smooth plains of basaltic lava flooding impact basins. Large impacts cracked the crust open and allowed molten rock from the moon's interior to flood out and erase earlier cratering.



The University of Sydney

Nearly all the maria are on the near side of the moon; so although they are so obvious to the naked eye, they actually occupy only 16% of the lunar surface.

The University of Sydney

*Rotating moon from the Lunar  
Reconnaissance Orbiter*



The Moon shows hundreds of lava channels called *rilles*, which look like rivers.

*Apollo 15 landing site at Hadley Rille: the view from above, and  
Jim Irwin and the lunar rover on the rim.*



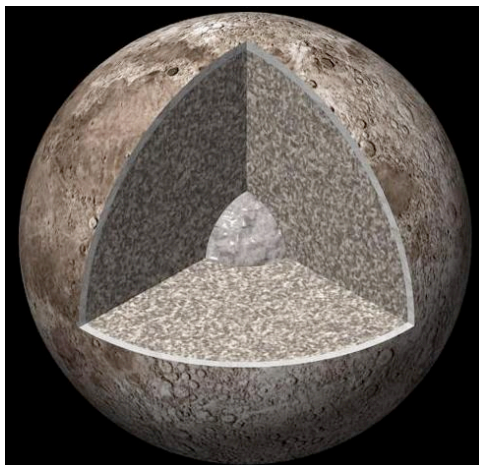


The six Apollo moon landings brought back 382 kg of moon rocks. This rock falls into three main types:

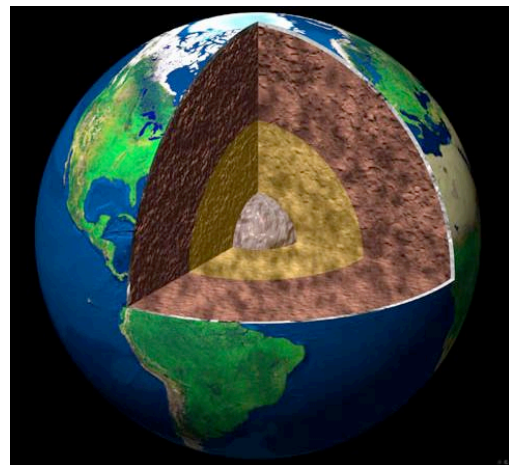
- **anorthosite**: plutonic rock (formed by slow crystallisation of magma), light-coloured, which forms the ancient highlands
- **basalt**: dark lava rocks, like those from the Hawaiian volcanoes, which fill the mare basins
- **breccia**: composite rocks formed through crushing during meteorite impacts.

The moon has no rocks associated with water (sandstone, shale, limestone). The chemical composition is similar to rocks from Earth, except there are no volatiles (elements with low boiling points): hydrogen, helium, water.

Lunar rocks are also deficient in iron compared to Earth rocks. The low density of the moon ( $3.3 \text{ g/cm}^3$  compared to  $5.5 \text{ g/cm}^3$  for the Earth) implies that the moon's core contains only 2% of its mass, in contrast to Earth's core, which contains nearly a third of Earth's mass.

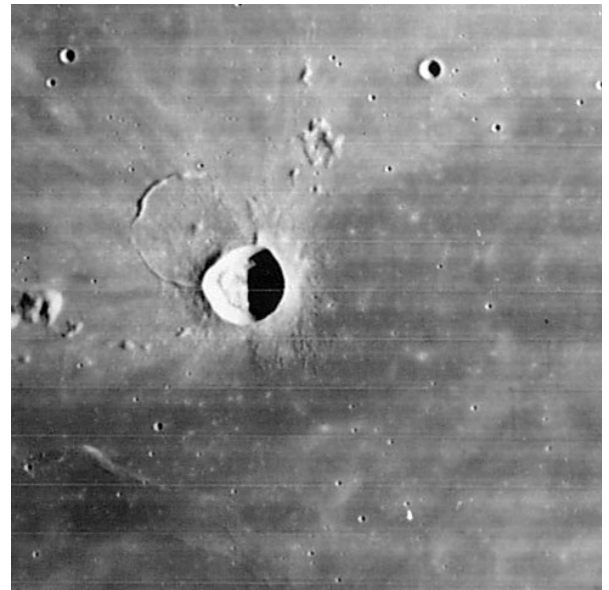


*The Moon's interior, showing crust, mantle and core*



*The Earth's interior, with crust, mantle, liquid outer core and solid inner core.*

The rocks brought back from the moon are all at least as old as the oldest rocks found on Earth. The highland breccias have ages up to 4.6 billion years (the age of the Moon), whereas the lowland basalts all have ages around 3.9 billion years. This suggests the Moon has been geologically inactive for 3.9 billion years, although the presence of a few young craters overlain with lava implies there may have been lava flows as recently as 1 billion years ago.

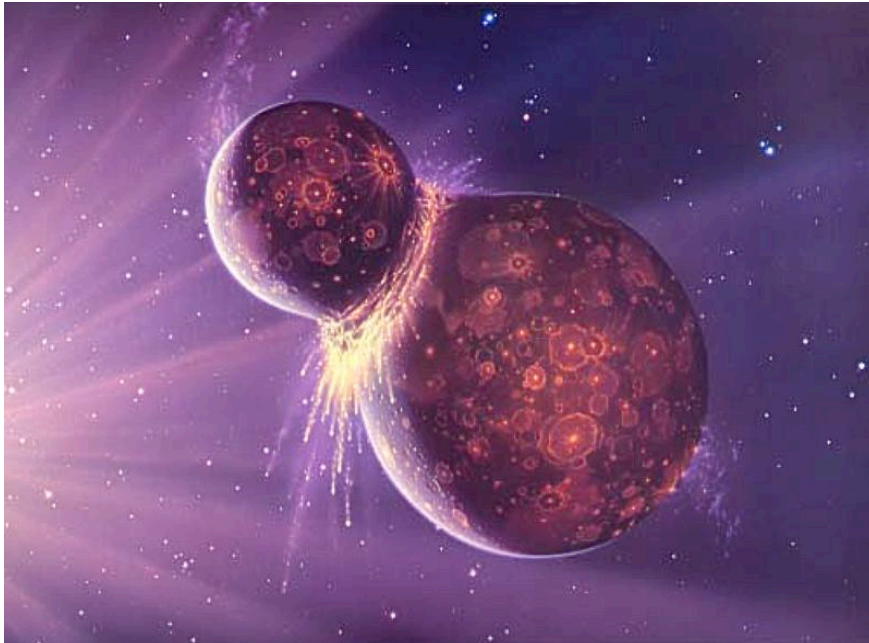


*The 20 km diameter crater Lichtenberg has rays, so must be young, but it is partly covered by lava, which must therefore have erupted after the crater formed.*

Together, these features imply that:

- Early on, the moon was entirely molten. Low-density rock floated to the surface of this magma ocean  $\Rightarrow$  *lunar highlands*.
- Heavy bombardment followed, mostly by objects  $< 10$  km in size
- Later another period of bombardment occurred, including some very large ( $> 100$  km) asteroids. These formed the *basins*, and cracked the crust to let lava flow out to form the *maria*.

The “Big Whack” theory explains these observations by suggesting that the moon was formed as the result of a collision between the



proto-Earth and another planet-sized body. Material from the impact was thrown into orbit and coalesced into the Moon.

Page 39

This theory explains the lack of heavy elements in the Moon (the Earth was already differentiated so only mantle material was ejected) and the lack of volatiles (they were vaporised and escaped into space), as well as the evidence that the moon's surface was molten at some stage.



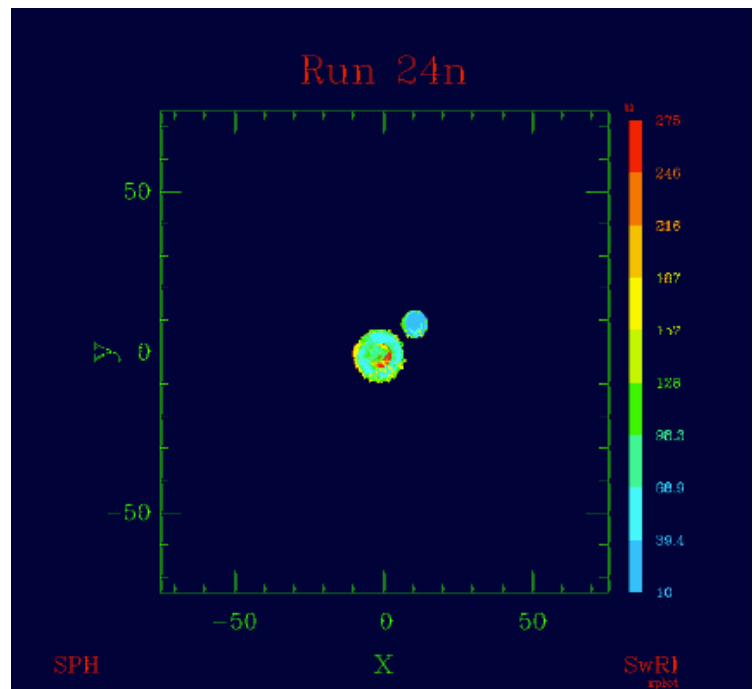
Page 40



Calculations showed that the impactor had to be the size of Mars in order to eject enough material into orbit to form the Moon.

*Animation showing the impact of a Mars-size proto-planet with the young Earth. The animation covers only 24 hours, ending with the Earth surrounded by a disk of debris, from which the Moon will coalesce.*

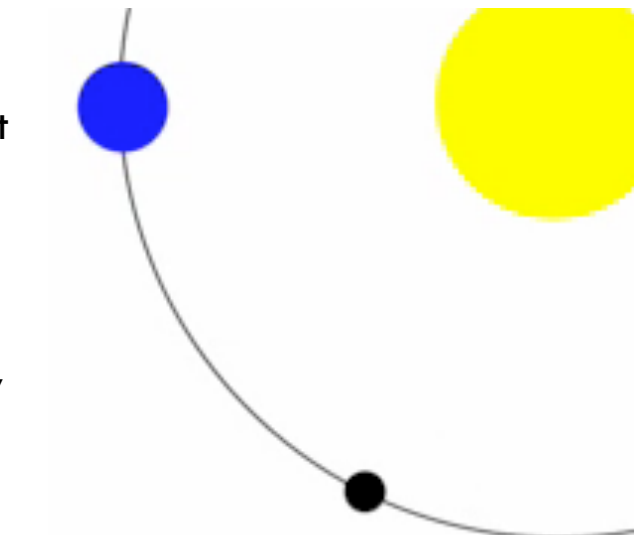
The University of Sydney



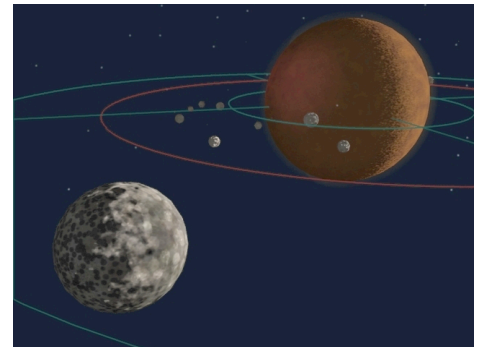
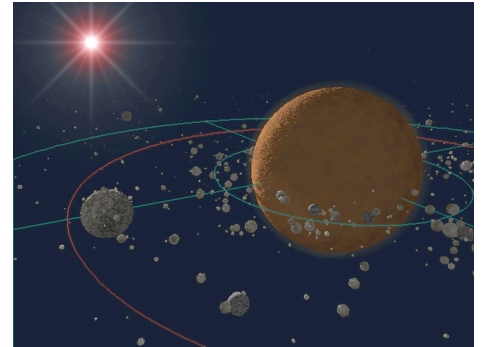
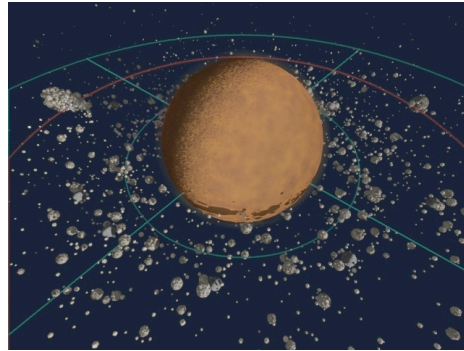
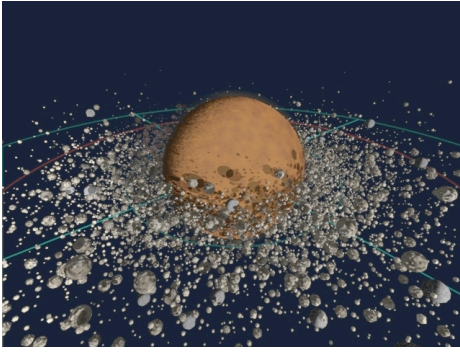
The impactor must have struck at quite a low (relative) velocity, and have formed at a similar distance from the Sun.

A recent suggestion is that the impactor formed at one of Earth's Lagrange points, and then drifted into a chaotic orbit that would impact the Earth with a suitably low velocity.

The name *Theia*, the mother of Selene, has been suggested as the name of the impactor.



*Animation of the impactor forming in Earth's L4 point, and then drifting into impact.*

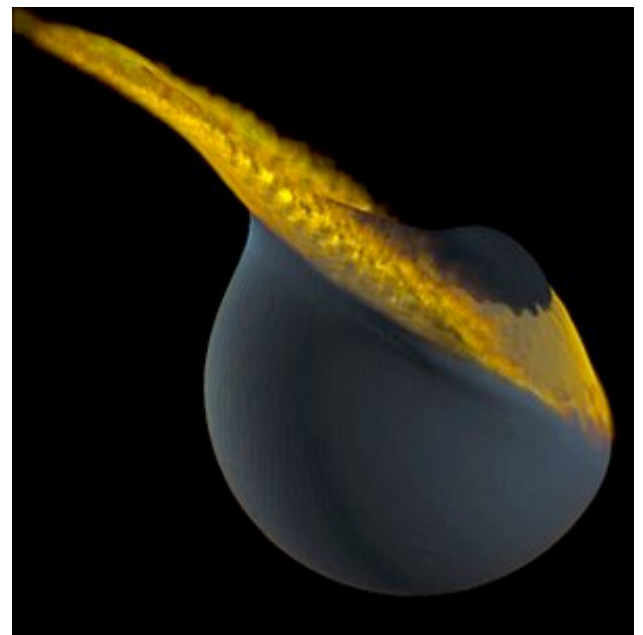


Simulations show that the orbiting disk could condense into the Moon in just a year's time, with about 50% of the disk material falling back to Earth.

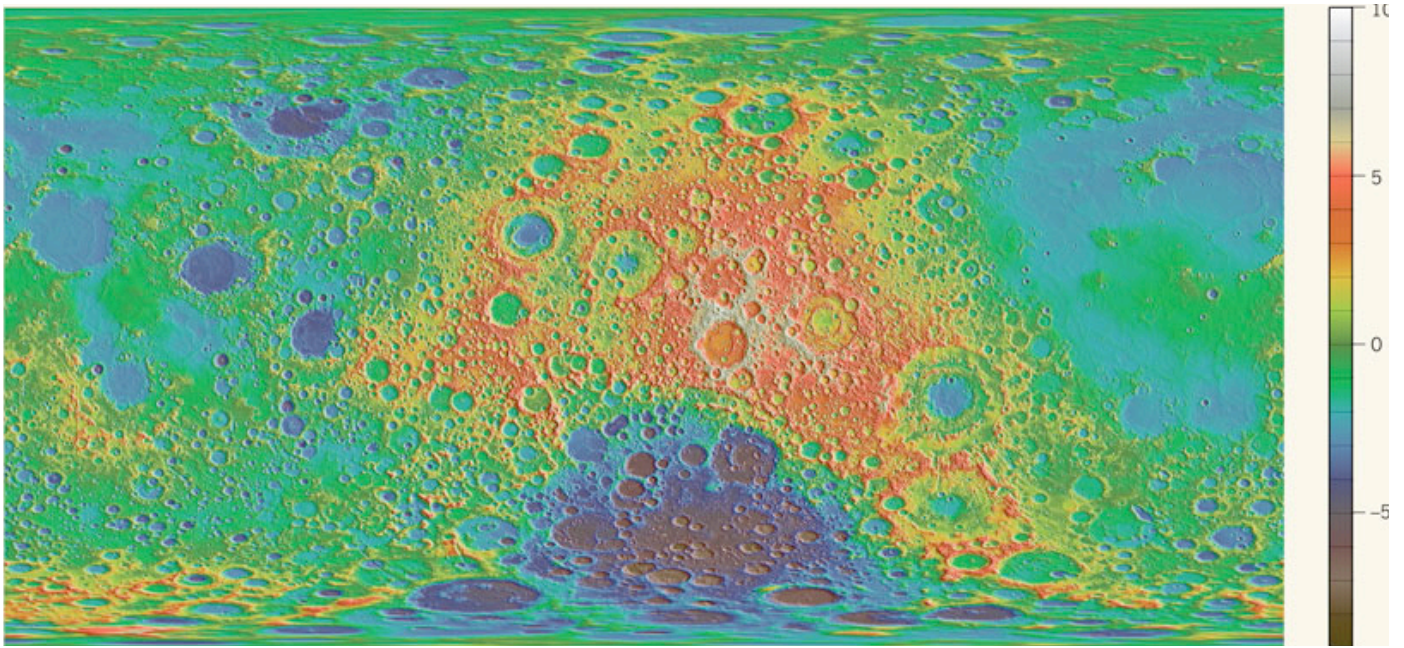
*The University of Sydney*

Some scientists suggest that a **second** moon which coalesced out of the debris may have later perished in a slow motion collision with its "big sister".

The second moon formed in a stable point, but several million years later drifted towards the Moon. The low-velocity collision would have deposited material on the backside of the moon, causing the lunar dichotomy.



*The University of Sydney*



*Cylindrical projection of lunar topography obtained from LRO, centred on the farside highlands. Elevations are in km; the South Pole–Aitken basin is the dark region below the highlands.*

## EVOLUTION OF THE MOON

# Spaceflight or, how to get where we want to go



Why is spaceflight so expensive?

The problem with rockets is they have to lift their own fuel: about 1.3 kg of fuel for each 1 kg.

In order to lift a 65 kg rocket, you need 90 kg of fuel

... but now your rocket weighs 155 kg. So you need 215 kg of fuel, which means your rocket weighs 280 kg....



What breaks the loop is that your rocket gets lighter as you go up, burning fuel, so you need less fuel as you rise. This was described in the *Tsiolkovsky Rocket equation*

$$\Delta v = v_{\text{exhaust}} \ln \frac{m_{\text{start}}}{m_{\text{end}}}$$

For ordinary rocket fuels, a one ton craft needs *20 to 50 tons* of fuel to leave Earth orbit.

This is just to launch the spacecraft itself. If you want to carry enough fuel with you to do any manoeuvring, you need more fuel to launch that too.

So realistically, we have to plan missions to need as little fuel as possible: which means using *orbits*.

*Comparison between the launch vehicle needed to get Voyager 2 out of the Solar System and what you'd need for a round trip*  
(From <https://what-if.xkcd.com/38/>)



## What is an orbit?

Consider throwing a ball from a tall building. It travels forward, but at the same time, it starts to fall.

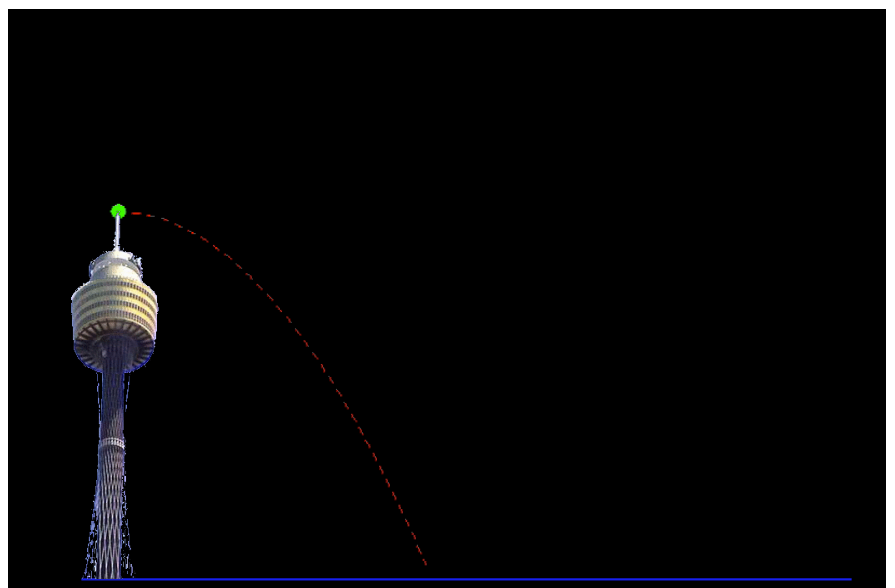
It keeps travelling forward until it hits the ground.

*The University of Sydney*



What happens if you throw it faster? It falls at the same rate (and in the same time!), but travels further forward before it hits the ground.

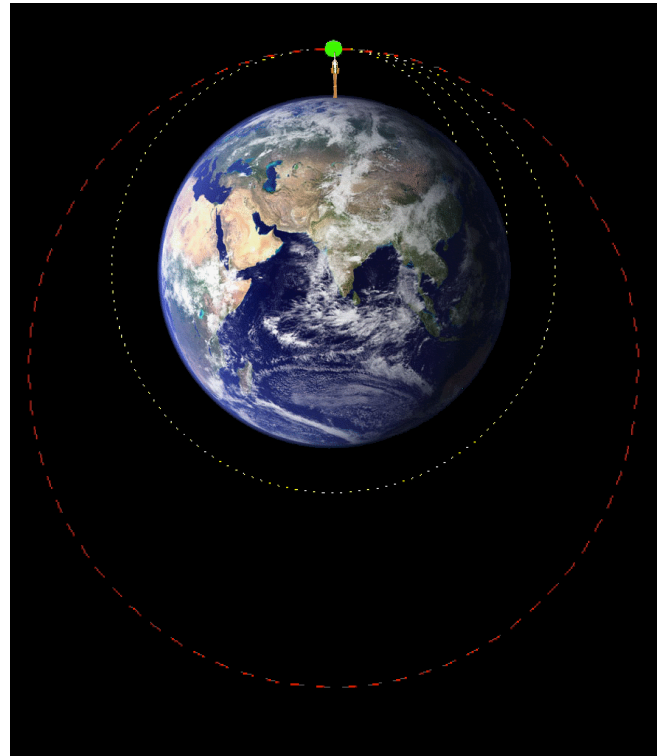
*The University of Sydney*



What happens if we throw even faster? As the ball starts to fall, the Earth's surface curves away.

Eventually we throw fast enough that as the ball falls one metre closer to the ground, the ground curves away by one metre. The ball never hits the ground: it falls **around** the Earth.

Even faster, and the ball gains height even though it was not thrown upwards.



## Freefall

In a spacecraft falling around the Earth, objects (and astronauts) experience weightlessness. The astronaut and the floor are falling at the same rate, so there is no force counteracting the pull of gravity.

As a result, the astronauts feel no weight, and things float. It is not that the spacecraft is outside the pull of gravity: gravity is still making it orbit! But everything in the craft is falling: **freefall**.

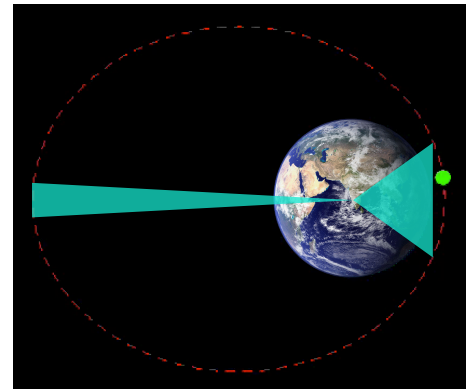


## Orbits

In general, orbits are ellipses. The point closest to the Earth is called *perigee*, the point furthest away is *apogee* (Or *perihelion*, *aphelion* for orbits around the Sun; in general, *periapsis*, *apoapsis*).

Kepler's second law says that satellites move faster at perigee than at apogee: the triangles joining the satellite to the centre of the Earth sweep out equal areas in equal time.

*apogee*  
*slow*



*perigee*  
*fast*

## Changing orbits

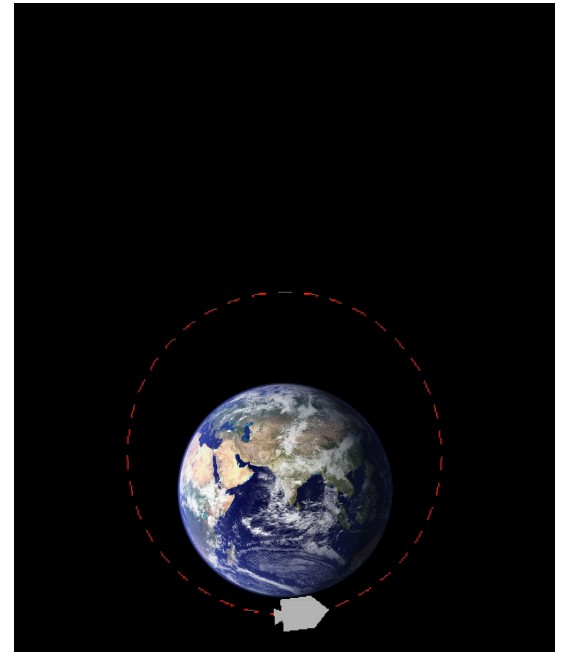
Limits on the amount of fuel a spacecraft can carry mean that nearly all its manoeuvring is done in short impulsive bursts (several seconds to several minutes). The rest of the time the spacecraft is *inertial* – coasting without engines. As we will see, this means that for nearly its whole journey, a spacecraft is obeying Kepler's laws of orbits. So now, let's find out about how to change orbits.



Consider a spacecraft in orbit. What happens if we burn in the forward direction?

The burn raises the altitude of every point on the orbit except the burn point, so the orbit gets larger. The shape of the orbit changes, but how it changes depends on where we are in the orbit when we burn.

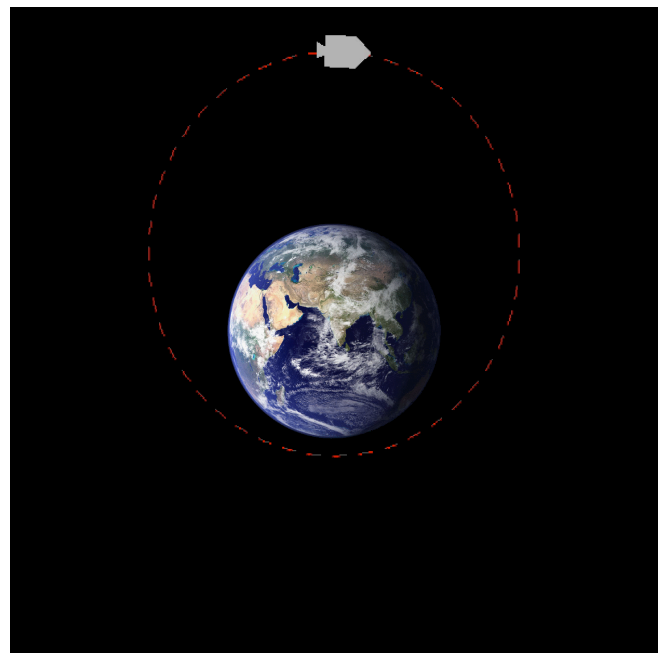
A burn at perigee *increases* the ellipticity of the orbit. The harder the burn, the more elliptical the final orbit.



What if we burn at apogee?

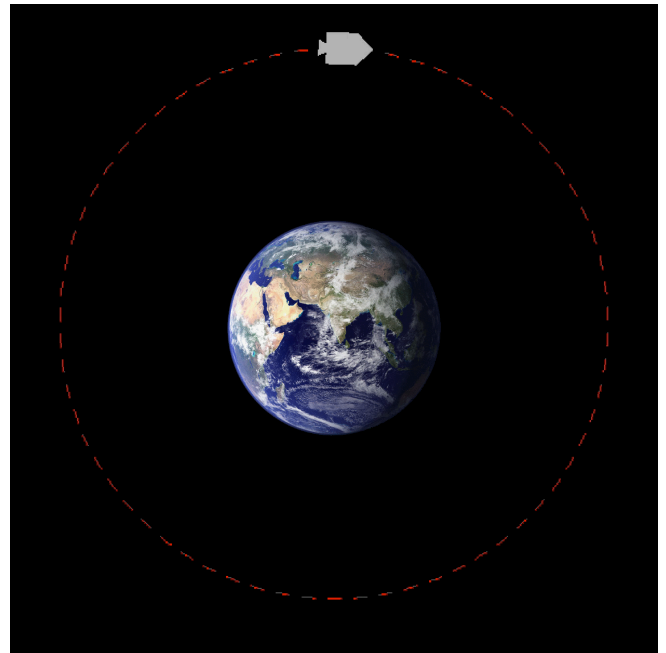
The burn raises the altitude of every point on the orbit except the burn point, so a burn at apogee *decreases* the ellipticity of the orbit.

The harder the burn, the higher the perigee is raised. A hard enough burn can circularise the orbit.

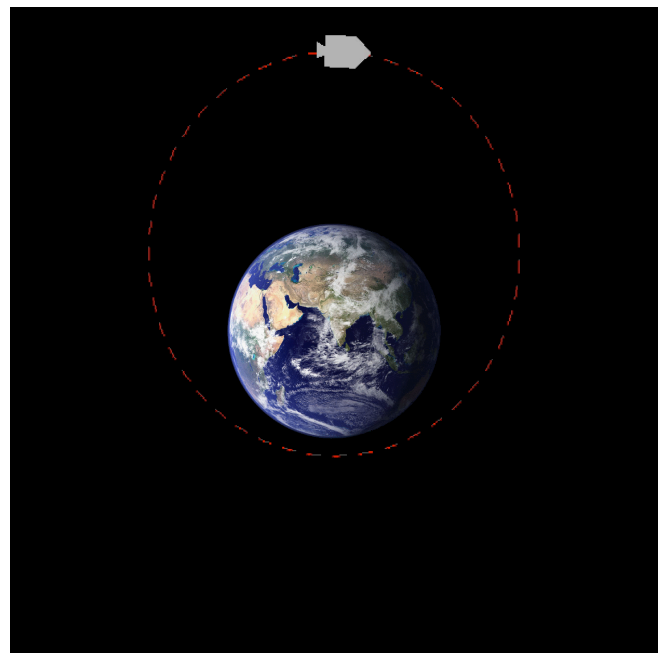


A retrograde burn has the opposite effect: it **lowers** the altitude of every point on the orbit except the burn point, so the orbit gets smaller. A burn at apogee **increases** the ellipticity of the orbit. Note that, in order to do a retrograde burn, the spacecraft has to turn around so its rocket fires the other way.

The harder the burn, the lower the new perigee is.



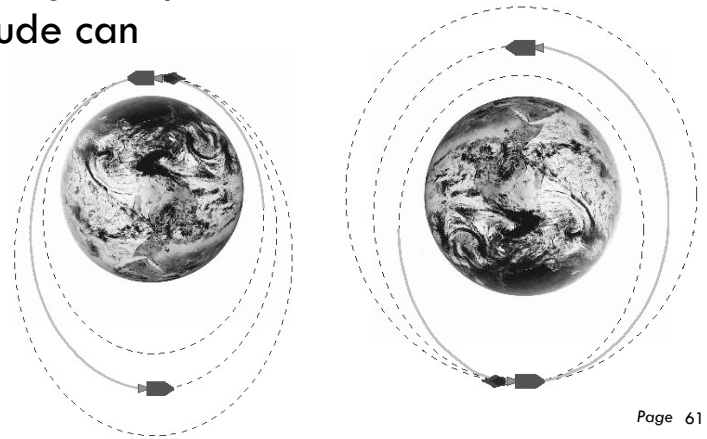
You can probably work out by now what a retrograde burn at perigee does: by decreasing the altitude of apogee, it makes the orbit more circular.



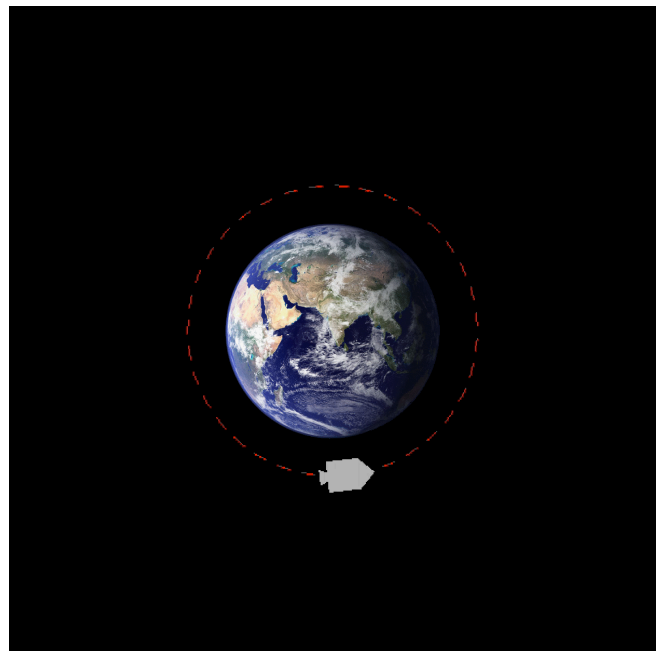
We can re-state all of the above as follows:

- In order to increase the altitude of the spacecraft's apogee, you need to fire the rocket at **perigee**.
- In order to increase the altitude of the spacecraft's perigee, you need to fire the rocket at **apogee**.

The opposite is also true: by decreasing the spacecraft's energy at perigee, the apogee altitude can be lowered.



Other burns change the orbit in other ways; for example, a radially outward burn turns a circular orbit into an elliptical one and increases its size.



Engineers describe the energy needed to change orbits by measuring the so-called “delta V”,  $\Delta V$ , or change in velocity, that the manoeuvre produces. Because a spacecraft has limited fuel, the mission designers must anticipate all orbital manoeuvres which will be required during the life of the mission. The “delta V budget” is a way of book-keeping the fuel left on board: think of it as the spacecraft’s petrol gauge.

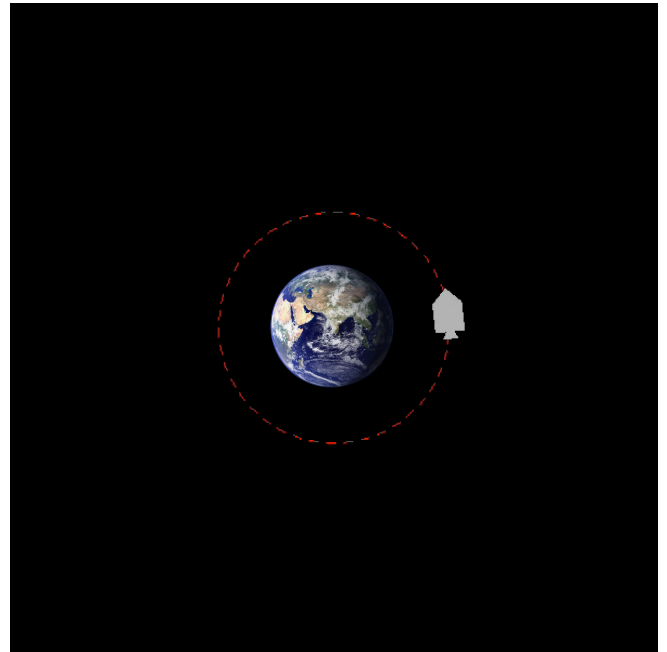
## Hohmann transfers

Now let’s use all of this for something interesting: getting where we want to go. Let’s consider the problem of getting from one (circular) orbit to another. This requires two burns, one to get to get from the initial orbit to an intermediate orbit, and one from the intermediate orbit to the final orbit.

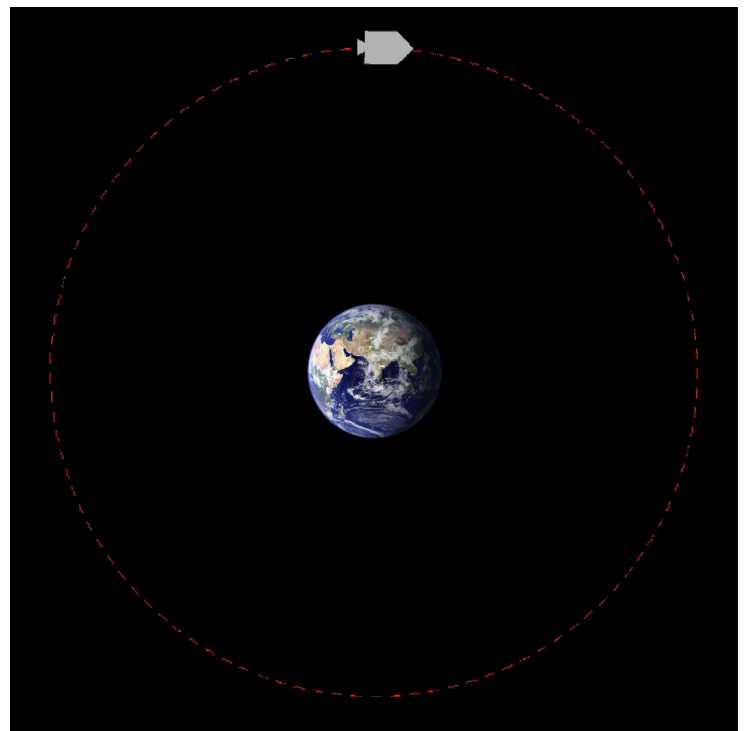
In 1925, Walter Hohmann, a German engineer, showed that the most energy-efficient transfer between two orbits is via an elliptical orbit with perigee at the lower orbit and apogee at the higher orbit. This manoeuvre now bears his name.

Suppose we want to get our spacecraft from the inner orbit to the outer. Do a forward burn into an orbit with apogee at the outer orbit. The burn point becomes the perigee of the transfer orbit.

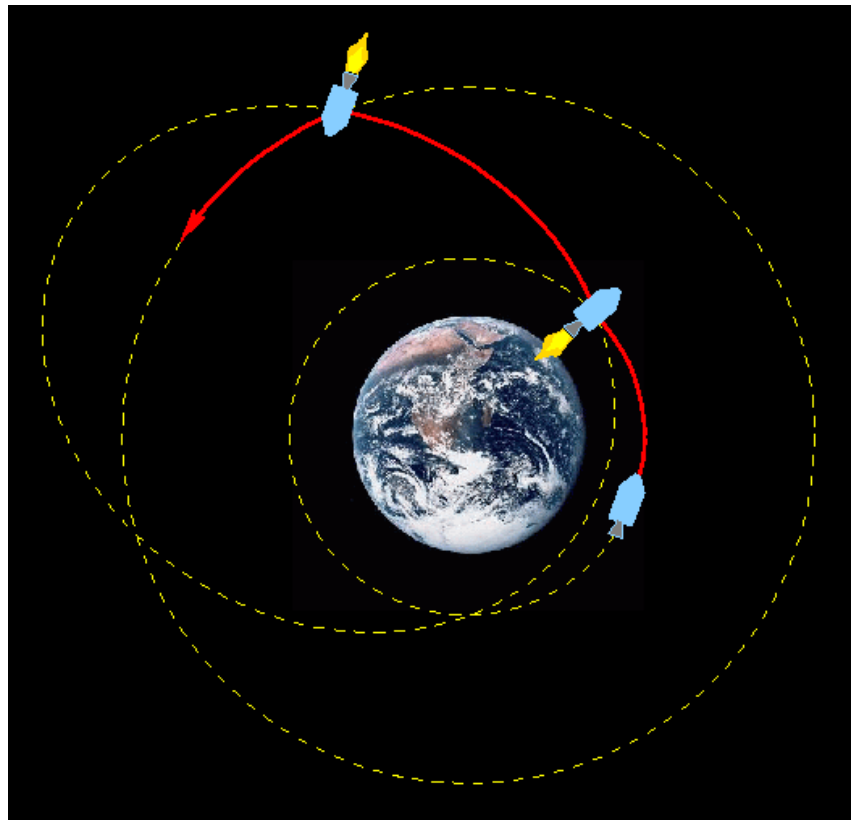
At apogee, do another forward burn to circularise the orbit.



And clearly the same can be done in reverse: with two retrograde burns, the spacecraft can be taken from the outer orbit to the inner.



Note that the Hohmann transfer is not the only way to get from one orbit to another: it is merely the most fuel-efficient way. The transfer orbit can be of any size, eccentricity and orientation, so long as it intersects both the original and destination orbits.



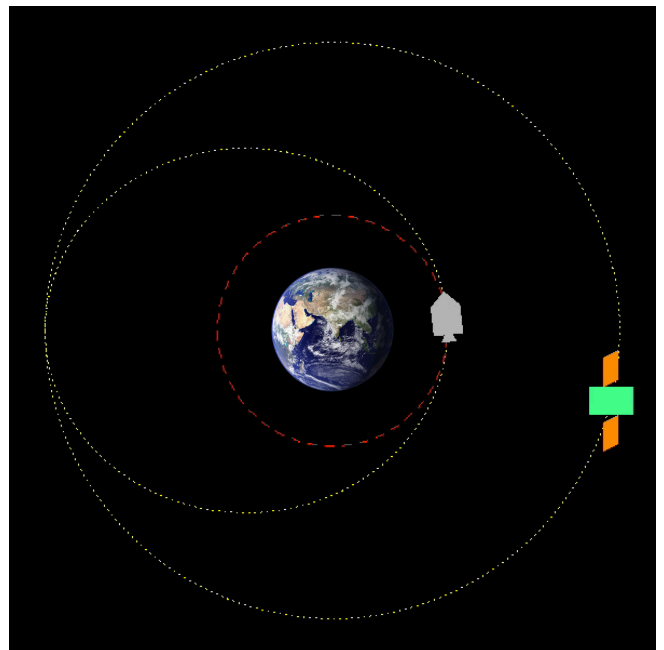
The University of Sydney

## Rendezvous

Now imagine we have to meet an object in a different circular orbit (say, a satellite which needs repair).

Our spacecraft performs a Hohmann transfer into the upper orbit, but in order to perform the rendezvous, the target satellite must be at the second burn point when our spacecraft arrives.

Because it is in a higher orbit and therefore moving slower, the satellite must start off ahead of the spacecraft in order to reach the rendezvous point at the same moment.



The University of Sydney

In order to perform the rendezvous, the first burn has to be timed so both spacecraft arrive at the point of the second burn at the same time. The opportunity for the burn arises regularly, at a frequency called the *beat frequency*, which is just the difference between the frequencies of the two orbits. So the time between rendezvous opportunities is

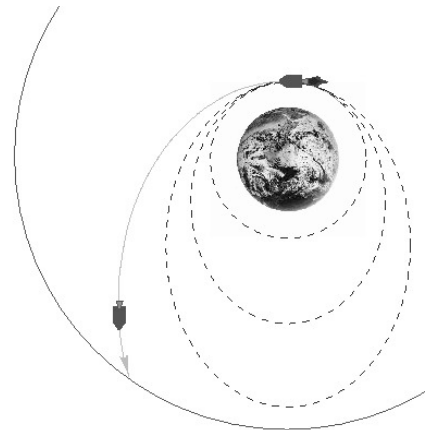
$$\frac{1}{t} = \left( \frac{1}{P_1} - \frac{1}{P_2} \right)$$

## Leaving Earth

Now let's consider how to reach other planets. First, we have to leave the Earth.

The spacecraft starts on a low-Earth circular orbit. A forward burn increases the altitude of apogee.

A hard enough burn can give the spacecraft enough  $\Delta V$  that gravity can never pull it back. The minimum velocity needed to escape from the Earth's surface is called the *escape velocity*, and is 11.2 km/s. The spacecraft's trajectory becomes a parabola, and the spacecraft never returns to Earth.

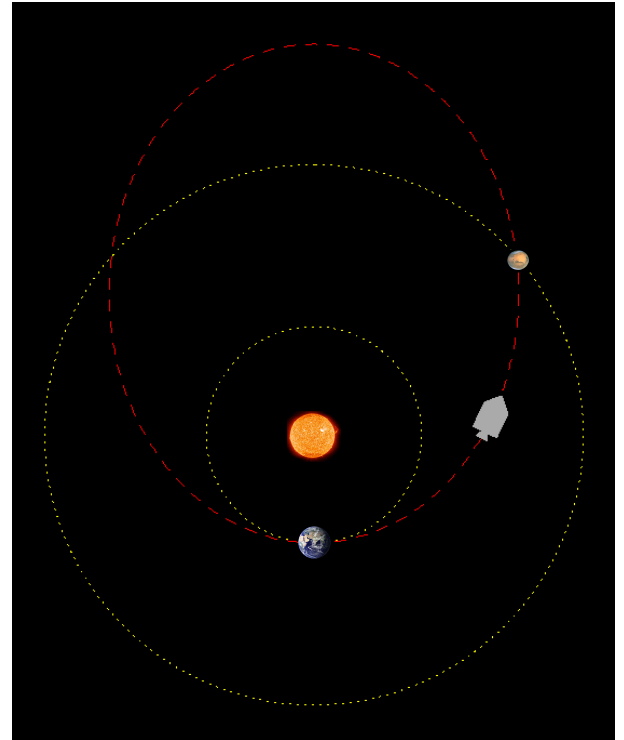


## Reaching other planets

How do we reach another planet, like Mars? We have to move from Earth's orbit around the Sun to Mars' orbit.

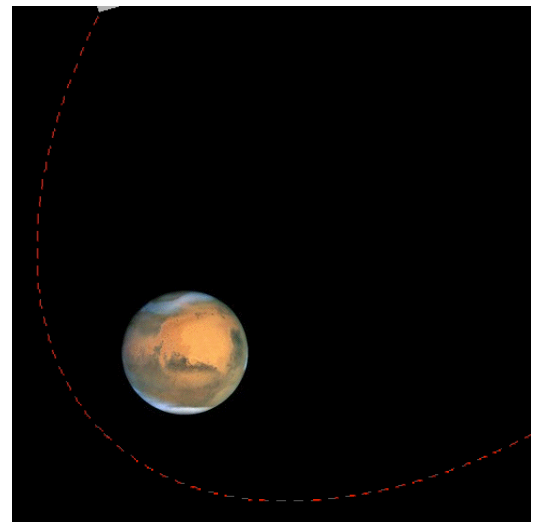
This is just the orbital rendezvous problem: we have to perform an orbital transfer, timing arrival to meet Mars.

A Hohmann transfer is the most fuel-efficient, but faster trips are possible. There is only one opportunity every 25–26 months for a Hohmann transfer to Mars.



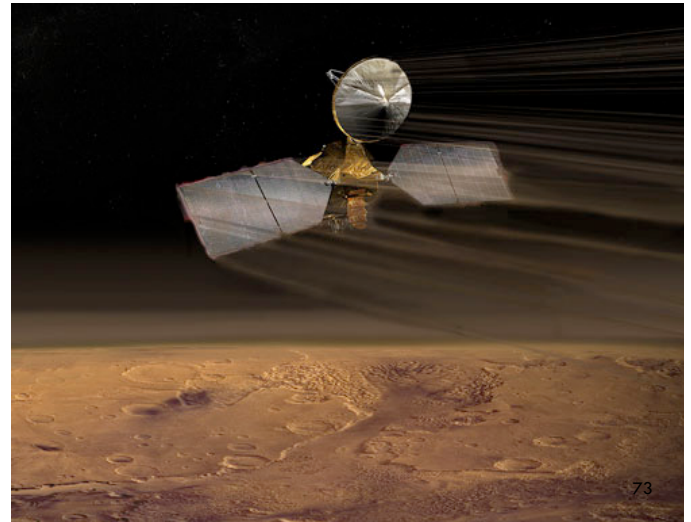
## Arrival at the planet

What happens when we arrive at the destination planet? If we want to enter a circular orbit around the planet, we'll have to do a reverse burn: essentially the inverse of what we did to leave Earth orbit, and using a similar amount of fuel – which we have to carry with us.





The last few planetary missions have used a different technique for getting into orbit: *aerobraking*, which uses the planet's own atmosphere to slow the spacecraft down into a circular orbit. The *Magellan* mission to Venus was the first to use the technique successfully; since then, several Mars missions have done it.

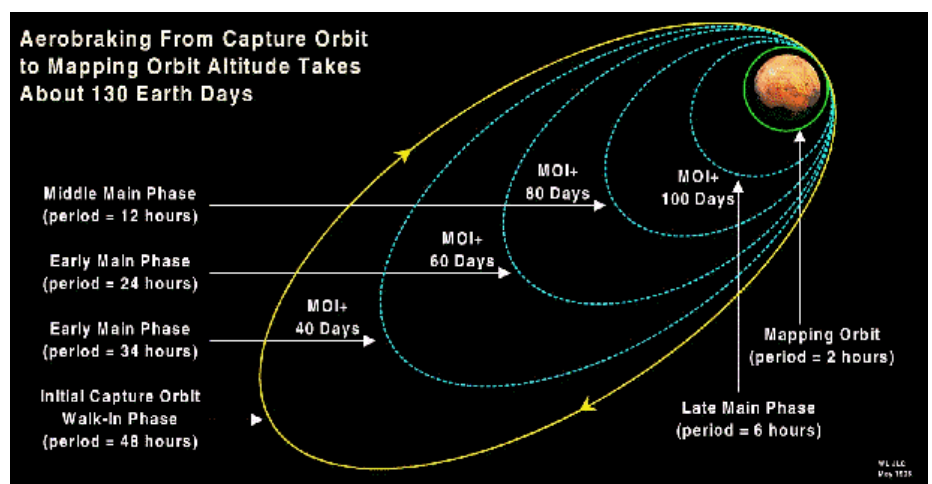


Artist's impression of the Mars Reconnaissance Orbiter during aerobraking.

The University of Sydney

73

The spacecraft is first captured into a highly elliptical orbit using its main engines, then dips in and out of the atmosphere to gradually circularise the orbit. *Mars Odyssey* required 380 passes and nearly three months to reach final orbit, while *Mars Reconnaissance Orbiter* took nearly six months, reducing the orbital period from 35 hours to 2 hours.

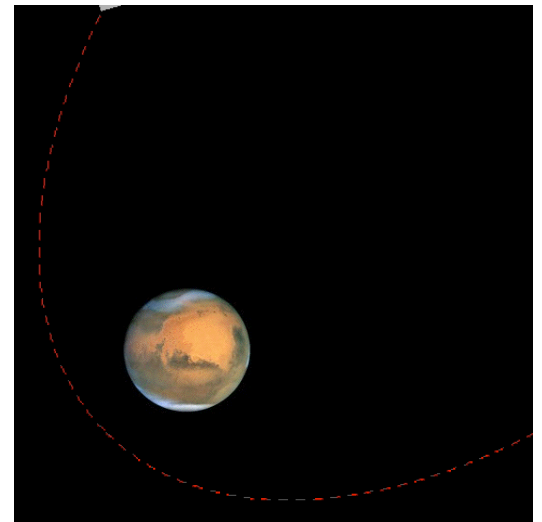


The University of Sydney

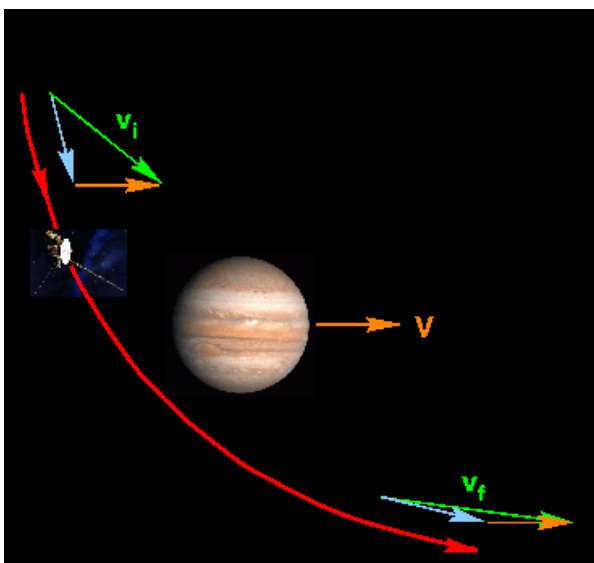
74

Instead of slowing down at the destination planet, we can just do a *flyby*: the gravity of the target planet will deflect the craft into a new direction, without us having to do a burn. This option is much cheaper on fuel than entering orbit, but gives us much less time in the vicinity of the planet.

The early planetary missions – *Pioneer* and *Voyager* – performed flybys of the outer planets. This gave them only hours to explore the planets and their satellites.



We can use this gravitational deflection to go somewhere else. We can actually increase the speed of the spacecraft, and hence go further than we could unassisted. This manoeuvre is called a *gravitational slingshot* or *gravity assist*.

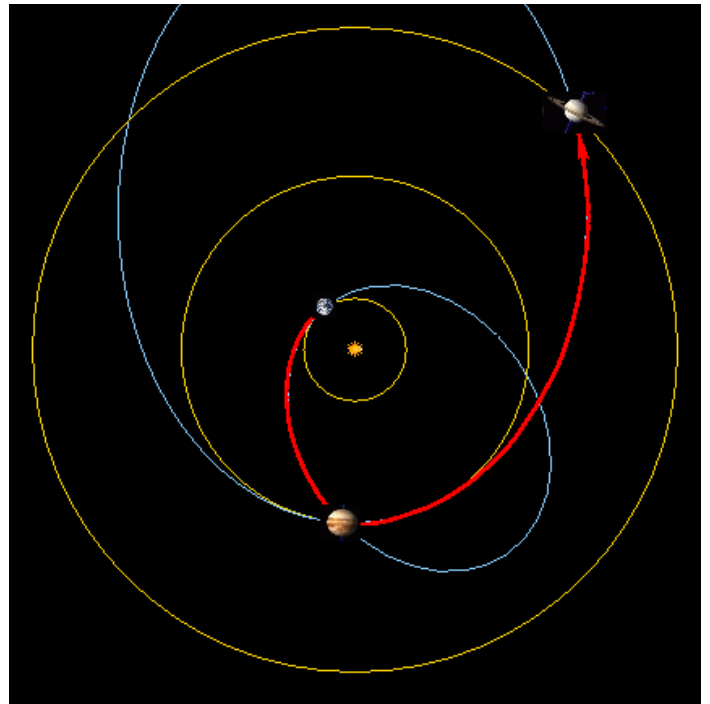


In the frame of the planet, the spacecraft's speed is the same before and after the encounter, but the direction has changed.

However, since the planet is also moving, then relative to the Sun the spacecraft has gained speed.

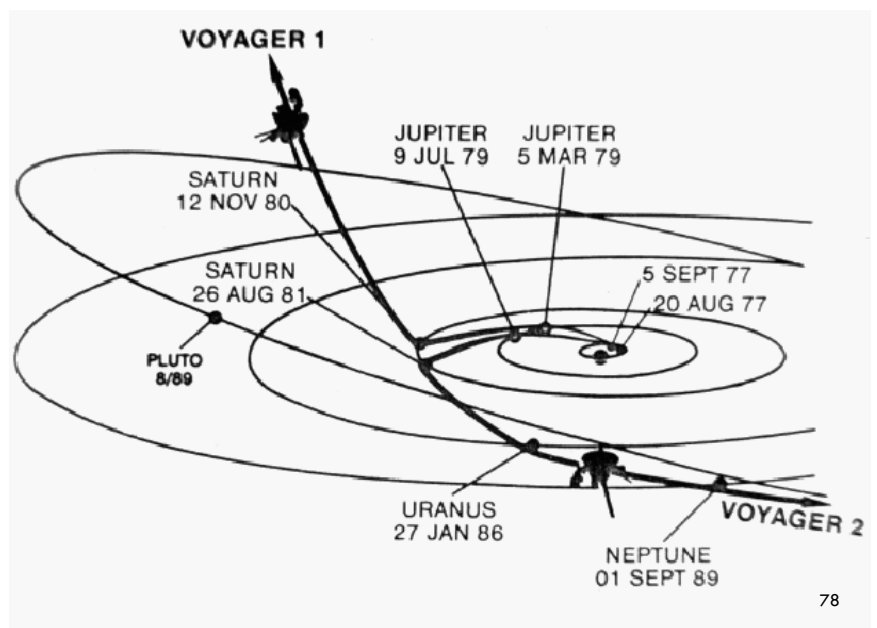
How to reach the outer planets using gravity assist: Spacecraft leaves Earth on an orbit intersecting Jupiter's orbit.

Jupiter slings the spacecraft into a new, larger orbit which intersects Saturn's orbit. All three planets must be in the right position or the manoeuvre will not work.



The University of Sydney

The *Voyager* missions used multiple gravity assists to visit nearly all the outer planets, which would not have been possible using the on-board propellant alone.

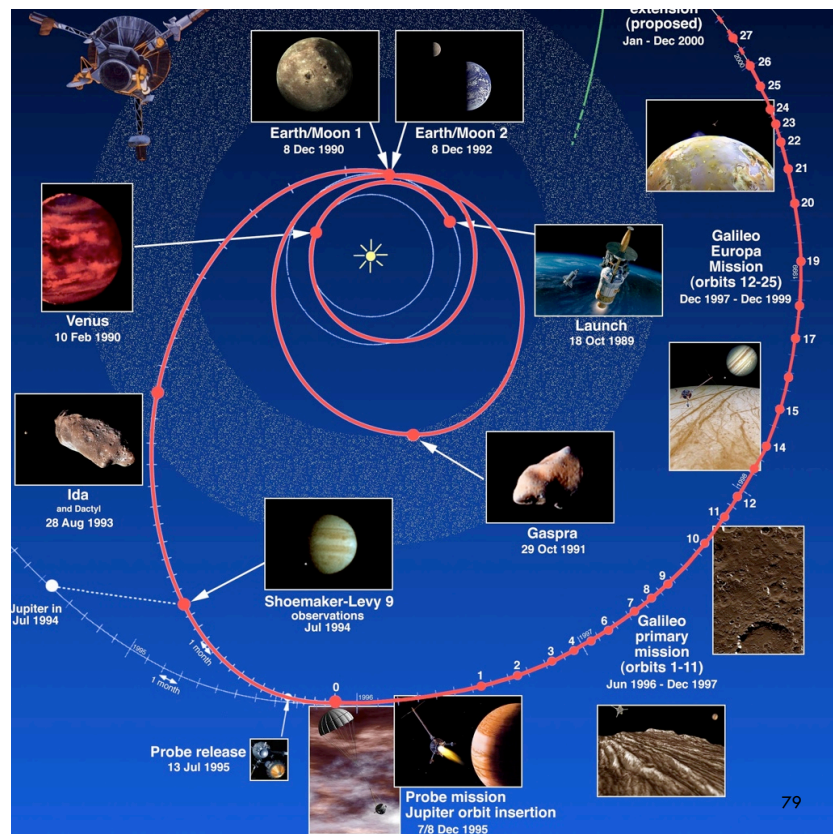


The University of Sydney

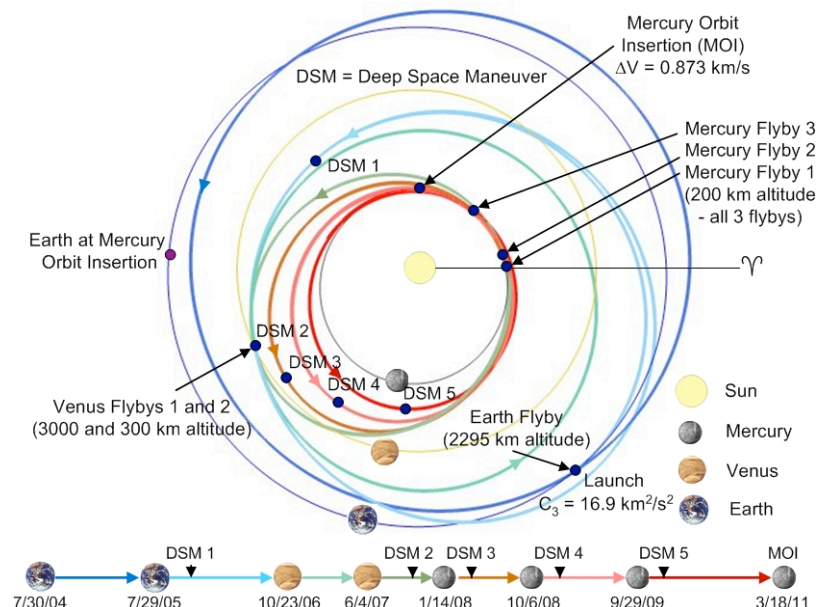
Many other spacecraft have used gravity assists.

*Galileo* used a VEEGA trajectory (Venus–Earth–Earth Gravitational Assist) to get to Jupiter.

*New Horizons* got a gravity assist from Jupiter on its way to Pluto.

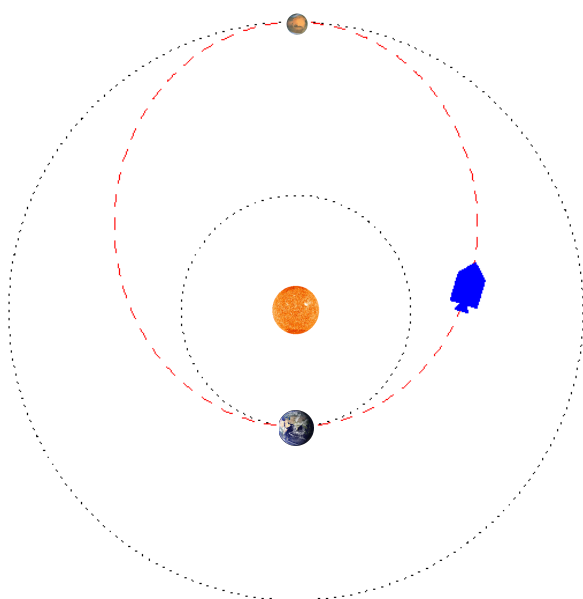


The *MESSENGER* mission to Mercury used multiple encounters with Earth, Venus and Mercury to slow the spacecraft down so it could enter orbit in 2011.



All this is the best we can do with chemically powered rockets: we are constrained by Kepler's laws to travel sedately along elliptical paths, because we just can't carry enough fuel for continuous propulsion.

The time taken for a Hohmann orbit to Mars is about 260 days, or 8+ months.



(Because Mars' orbit is elliptical, the actual transfer time varies quite a bit, depending on where Mars is in its orbit).



If we could accelerate at just 0.01g, then since we can travel a distance  $d = \frac{1}{2}at^2$ , then when Mars is near conjunction we can reach it in

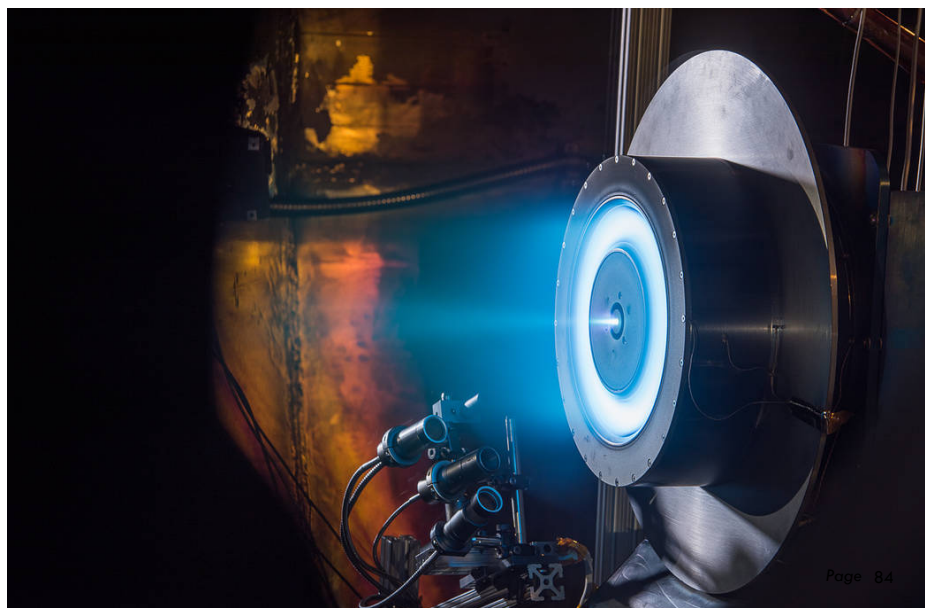
$$t = 2\sqrt{\frac{2 \times \frac{1}{2} \times 0.5\text{AU}}{0.01g}} = 21\text{d}$$

Which is much better than 8 months!

*\*this is only a very rough approximation, because we couldn't actually fly in a straight line to Mars*

NASA and ESA have both built ion propulsion systems, which accelerate ions electrically to produce continuous propulsion. The acceleration is currently tiny – only  $10^{-5}$  g – but it's the first step.

The Dawn mission used an ion drive, to reach the asteroids Vesta and Ceres.



*A prototype ion thruster being tested.*



## Further reading

### For the Moon:

- **"The Once and Future Moon"** by Paul D. Spudis (Smithsonian IP, 1998) is a marvelous book, written by a lunar geologist, which gives an excellent overview of lunar geology, the history of lunar exploration, and a case for returning to the moon.
- If it's picture books you're after, **"Full Moon"** by Michael Light (Knopf, 1999) is a lovely coffee table book of all the best pictures from the Apollo missions.
- There's also sorts of useful data and statistics at "Chuck Wood's Moon: Compendium of Lunar Science and History" at <http://www.lpod.org/cwm/DataStuff/Data.htm>
- The HBO miniseries **"From the Earth to the Moon"** is an excellent dramatisation of the Apollo moon programme. The episodes about teaching the astronauts how to do lunar geology are the most applicable to this course.
- **"The Big Splat: or How our moon came to be"** by Dana Mackenzie (John Wiley & Sons, 2003) is a very readable book about theories of the origin of the moon, and how we arrived at the current consensus. An extremely enjoyable read.
- The "two moons" theory is described at "Earth may once have had two moons", <http://www.bbc.co.uk/news/science-environment-14391929>
- You can browse all the images taken by the Lunar Reconnaissance Orbiter, and see features as small as 73 cm on the lunar surface (!) at <http://lunar.gsfc.nasa.gov/>

## For Spaceflight:

- **"To Rise from Earth: The Complete Guide to Spaceflight"** by Wayne Lee (Blandford, 2000) is an excellent introduction to anything to do with space flight, including a complete discussion of orbital mechanics with no mathematics at all.
- **"It's ONLY rocket science: An introduction in plain English"** by Lucy Rogers (Springer, 2008) is another book explaining the basics. I didn't enjoy it as much as Wayne Lee's book, but it covers lots of material in readable form.
- NASA has a website called "Basics of Space Flight", <http://www.jpl.nasa.gov/basics/> which began life as a training document for NASA engineers, but which they quickly realised had much wider appeal. An excellent site to start exploring from.
- To understand the rocket equation, check out "The Tyranny of the Rocket Equation" [http://www.nasa.gov/mission\\_pages/station/expeditions/expedition30/tryanny.html](http://www.nasa.gov/mission_pages/station/expeditions/expedition30/tryanny.html), and xkcd's "Everybody Out" <https://what-if.xkcd.com/7/> and "Voyager" <https://what-if.xkcd.com/38/>
- "The Slingshot Effect" by Bob Johnson has a very thorough discussion of gravity assist techniques: <http://www.dur.ac.uk/bob.johnson/SL/>
- NASA has a movie explaining the aerobraking technique which was used to get Mars Global Surveyor and Mars Reconnaissance Orbiter into orbit: <https://mars.nasa.gov/resources/20178/>

## Sources for images used:

- Lecture title: Apollo 11 service module "Columbia" viewed from the Eagle, from <https://pics-about-space.com/apollo-11-moon-landing?p=2#img6715942733813473089>
- Title image: from ESO, The waning moon <http://www.eso.org/public/images/eso9903c/>
- Lunar libration: Antonio Cidadao's Lunar and Planetary Observation and CCD imaging <http://www.astrosurf.com/cidadao/animations.htm>
- Moon's orbit: redrawn from "The Once and Future Moon" by Paul Spudis, figs 1.5 and 1.6
- Moon at perigee and apogee: image by Catalin Paduraru, from APOD 2016 November 13 <https://apod.nasa.gov/apod/ap161113.html>
- Supermoon over Madrid: photo by Gonzalo Arroyo Moreno/Getty Images, <http://www.theguardian.com/science/gallery/2014/aug/10/supermoon-skies-perigee-around-the-world-in-pictures>
- Full moon: image by Simon Smith, <https://apod.nasa.gov/apod/ap120901.html>
- Microcrater: from A MEETING WITH THE UNIVERSE: Science Discoveries from the Space Program <http://www.hq.nasa.gov/office/pao/History/EP-177/cover.html>, Appendix A-1
- King crater: from APOLLO OVER THE MOON: A VIEW FROM ORBIT <http://www.hq.nasa.gov/office/pao/History/SP-362/cover.htm>, fig. 149
- Gagarin crater field: from APOLLO OVER THE MOON: A VIEW FROM ORBIT, fig. 97
- Young craters: young impact crater Linne, from Apollo 15. From APOLLO OVER THE MOON: A VIEW FROM ORBIT, fig. 102
- Euler crater: taken by Apollo 17. From APOLLO OVER THE MOON: A VIEW FROM ORBIT, fig. 138
- Tycho: from the Consolidated Lunar Atlas. <http://www.lpi.usra.edu/research/cla/menu.html>
- Tycho's central peak: from LRO, on APOD 2011 July 6 <https://apod.nasa.gov/apod/ap110706.html>
- Orientale: taken Lunar Orbiter 5, <http://nssdc.gsfc.nasa.gov/planetary/lunar/lunarorb.html>
- LRO image of Orientale: from <http://roc.sese.asu.edu/posts/189>
- Galileo image of Orientale: from the Galileo Legacy Site, <http://galileo.jpl.nasa.gov/gallery/earthmoon-moon.cfm>
- Basins: from a talk by Hal Levison, "Review of Dynamic Models Associated with Late Heavy Bombardment", <http://www.boulder.swri.edu/~hal/talks/nice/Bomb/basins.html>
- Lunar topography: from Araki et al, 2009, "Lunar global shape and polar topography derived from Kaguya-LALT laser altimetry", Science 323 897
- South Pole-Aitken: Clementine image, from NASA's Solar System Exploration Gallery, [http://solarsystem.nasa.gov/multimedia/display.cfm?IM\\_ID=802](http://solarsystem.nasa.gov/multimedia/display.cfm?IM_ID=802)
- Old and young craters: from "Craters and Planetary History" by Steven Dutch, <http://www.uwgb.edu/dutchs/planets/crathist.htm>
- Crater size distribution: from "Introduction to Cratering Studies" by Greg Herres and William Hartmann, <http://www.psi.edu/projects/mgs/cratering.html>
- Chesley Bonestell painting of the lunar surface: from <https://www.airspacemag.com/daily-planet/chesley-bonestell-and-the-landscape-of-the-moon-120863737/>. Lunar mountains by James Nasmyth: from "Cosmos as Masterpiece" <https://www.nytimes.com/2014/10/14/science/space/in-cosmographics-our-changing-pictures-of-space-through-time.html>
- Lunar surface panorama: from <https://www.hq.nasa.gov/alsj/HamishALSEP.html>
- Late heavy bombardment: from "Impact Processes on the Early Earth" by Christian Koeberl Elements, vol 2 p. 211-216 (2006)
- September 2013 impact: <https://www.youtube.com/watch?v=perqv4q8Yal>
- Estimate of cratering rates: see <https://www.theguardian.com/science/2016/oct/13/face-of-the-moon-to-change-completely-in-81000-years-time>
- Maria: from <http://people.westminstercollege.edu/faculty/ccline/courses/biol102/moon.html>
- Moon rotation: from LRO <https://apod.nasa.gov/apod/ap130916.html>
- Moon interior: from Views of the Solar System by Calvin J. Hamilton <http://www.solarviews.com/eng/moon.htm>

- Hadley Rille: <http://www.nasm.si.edu/collections/imagery/apollo/AS15/a151landsite.htm> and NSSDC Image Catalog: Apollo 15 [http://nssdc.gsfc.nasa.gov/imgcat/html/mission\\_page/EM\\_Apollo\\_15\\_page1.html](http://nssdc.gsfc.nasa.gov/imgcat/html/mission_page/EM_Apollo_15_page1.html)
- Lichtenberg crater: Photo Number IV-170-H1, Digital Lunar Orbiter Photographic Atlas of the Moon [http://www.lpi.usra.edu/research/lunar\\_orbiter/index.html](http://www.lpi.usra.edu/research/lunar_orbiter/index.html)
- Second moon collision: from <http://www.theguardian.com/science/2011/aug/03/second-moon-collision>
- LRO topography: from [http://www.nature.com/nature/journal/v476/n7358/fig\\_tab/476036a\\_F1.html](http://www.nature.com/nature/journal/v476/n7358/fig_tab/476036a_F1.html)
- Evolution of the moon: from APOD 2012 Mar 20 <http://apod.nasa.gov/apod/ap120320.html>
- Spaceflight image: Ariane 6 rocket, from Spaceflight Now <https://spaceflightnow.com/2015/06/24/ariane-6-rockets-to-be-assembled-horizontally/>
- Rockets needed for Voyager round trip: from <https://what-if.xkcd.com/38/>
- Throwing balls into orbit: redrawn from "To Rise from Earth" by Wayne Lee, Fig. 1
- Image of Earth: from Visible Earth: The Blue Marble, [http://veimages.gsfc.nasa.gov/2429/globe\\_east\\_540.jpg](http://veimages.gsfc.nasa.gov/2429/globe_east_540.jpg)
- All the orbit figures are redrawn from "To Rise from Earth" by Wayne Lee, animated by HMJ
- Mars image: HST pictures of Mars at opposition, taken on February 25, 1995. Image STScI-PRC1995-17a, from the Hubble Space Telescope News Center archive, <http://hubblesite.org/newscenter/>
- Aerobraking: from Mars Reconnaissance Orbiter press release 25 August 2006, <http://mars.jpl.nasa.gov/mro/newsroom/pressreleases/20060825a.html>
- and Mars Global Surveyor MAG/ER <http://mgs-mager.gsfc.nasa.gov/overview/aerobraking.html>
- Aerobraking animation: extracted from NASA's Mars Exploration Program: Videos <http://mars.jpl.nasa.gov/gallery/video/movies/aerobraking.mov>
- Jupiter image: from StarDate Online <http://stardate.org/resources/ssguide/jupiter.html>
- Slingshot diagram: redrawn from "The Slingshot Effect" by Bob Johnson <http://www.dur.ac.uk/bob.johnson/SL/>
- Galileo's VEEGA trajectory: from [http://www2.jpl.nasa.gov/galileo/sepo/education/bulletin/launch\\_to\\_g29.html](http://www2.jpl.nasa.gov/galileo/sepo/education/bulletin/launch_to_g29.html)
- Mercury trajectory: from <http://www.mercurytoday.com/messenger/missiondesign.htm>
- Ion drive: from <https://www.nasa.gov/image-feature/development-of-high-power-solar-electric-propulsion>