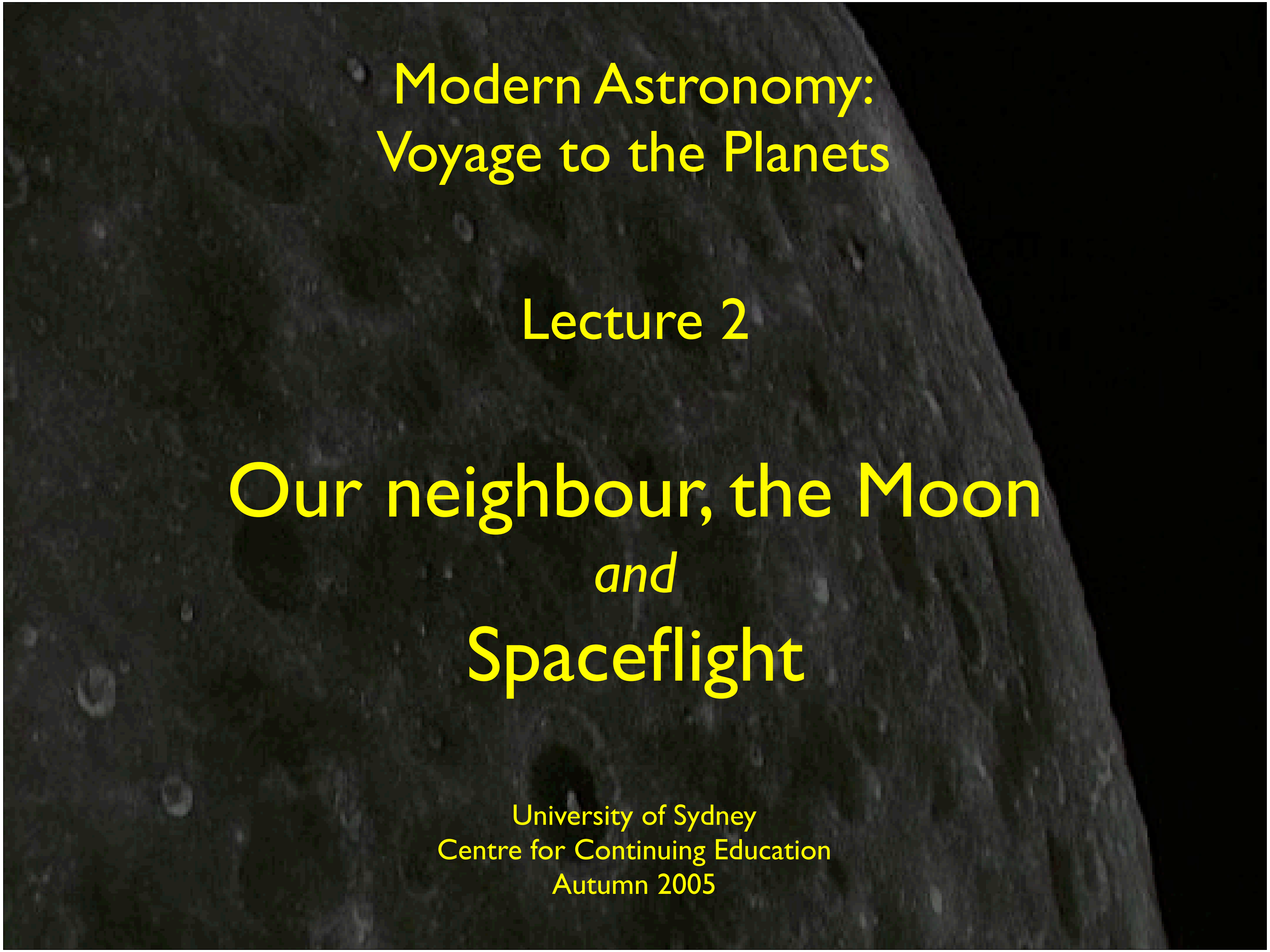

Modern Astronomy:
Voyage to the Planets
Lecture 2
Our neighbour, the Moon
and
Spaceflight
University of Sydney
Centre for Continuing Education
Autumn 2005


Tonight:
• The Moon: our nearest neighbour
• Principles of spaceflight

The Moon

Basic data

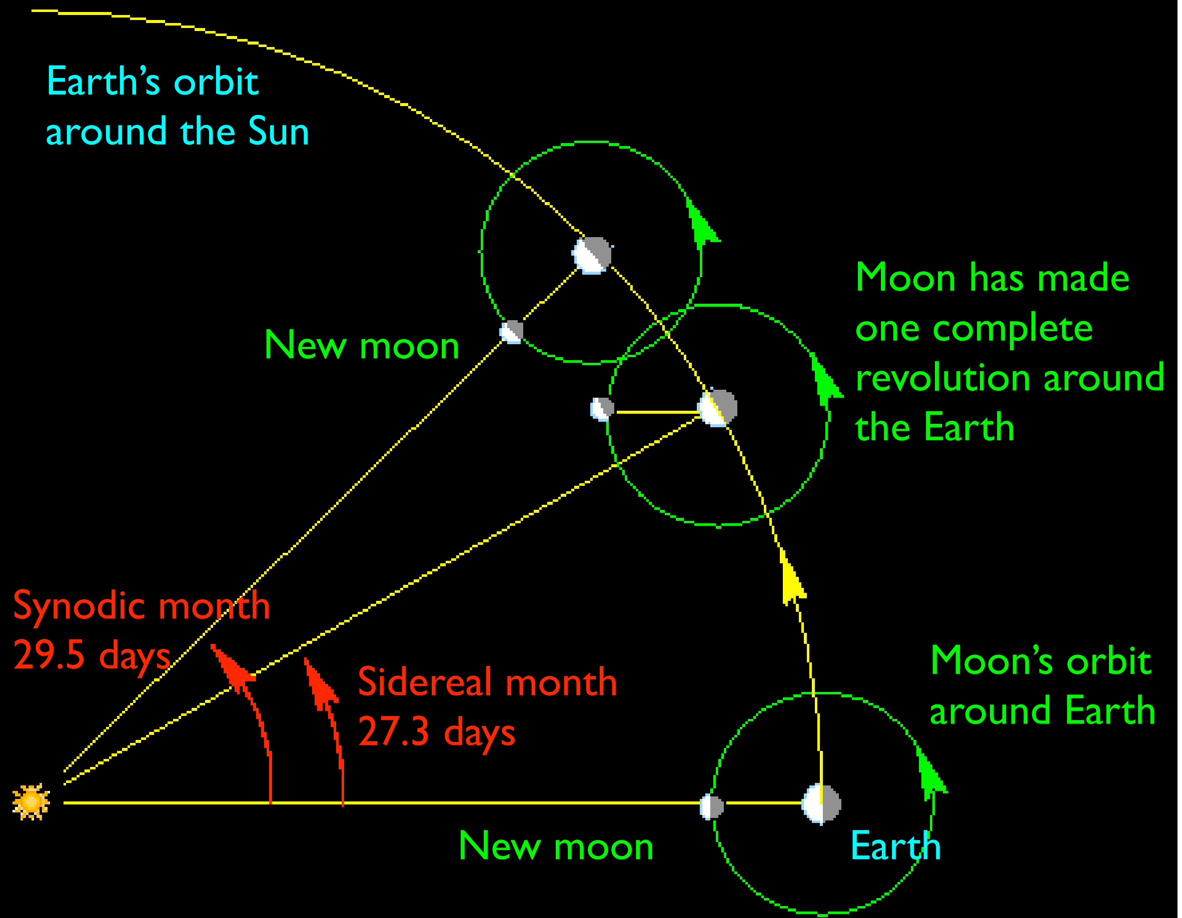
	Moon	**Moon/Earth**
Mass	0.07349×10^{24} kg	0.0123
Radius	1738.1 km	0.2725
Mean density	3.350 g/cm^3	0.607
Gravity	1.62 m/s^2	0.165
Semi-major axis	0.3844×10^6 km	
Period	27.3217 d	
Orbital inclination *(to ecliptic)*	5.145°	
Orbital eccentricity	0.0549	
Rotation period	27.3217 d	
Length of day	29.53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

The Moon has

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

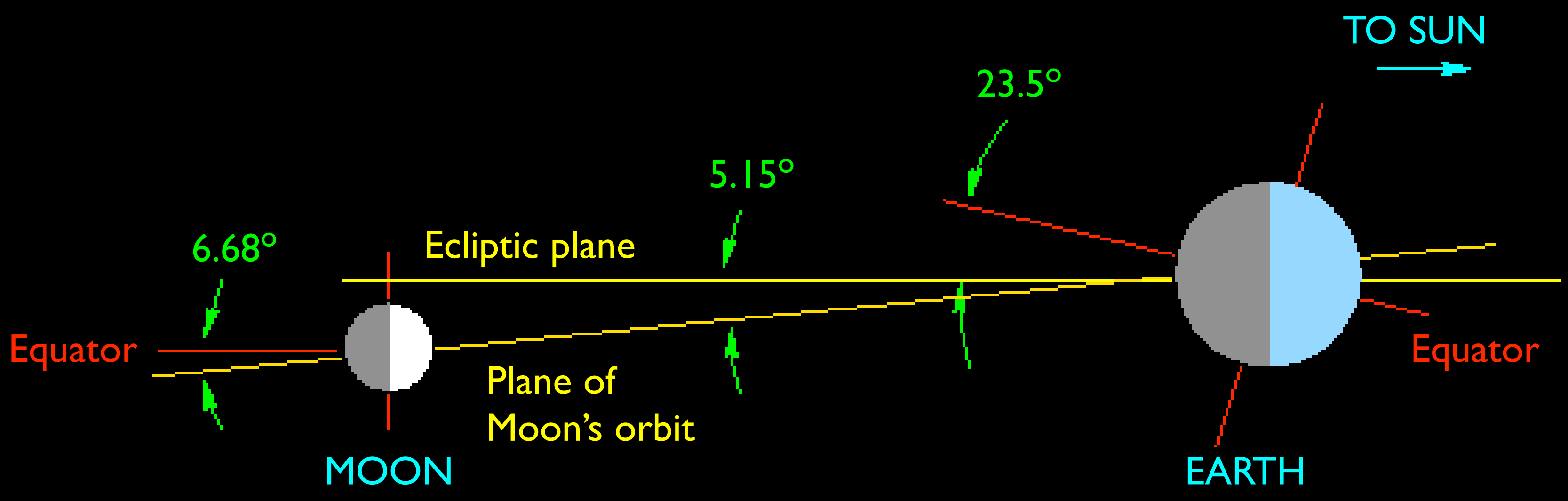
The Moon is the largest satellite in relation to its primary of any moon in the Solar System, except for Pluto/Charon.

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*. As a result of this phasing, the same side of the moon is always facing the Earth.

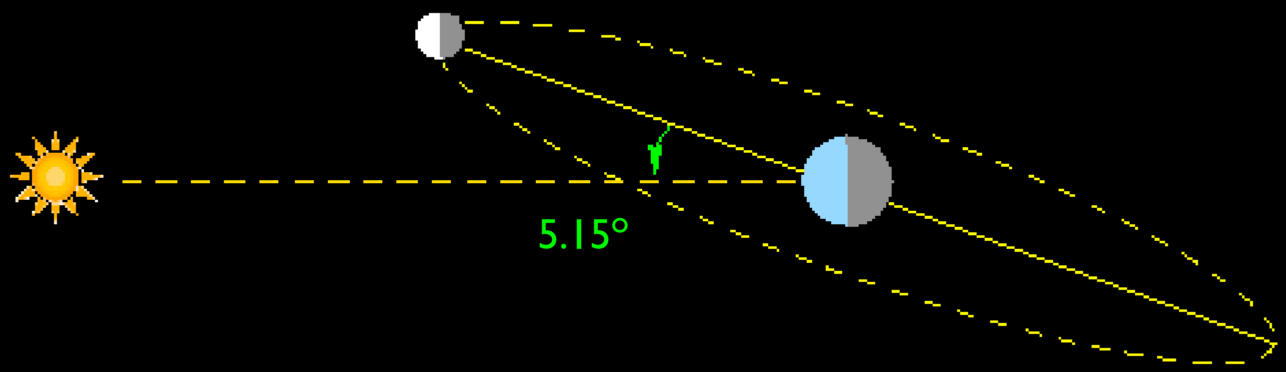


The moon always keeps the same hemisphere turned towards the Earth, so there is a side we never see: the far side. In fact, due to the 7° inclination of the moon's orbit relative to the Earth's equator, we see slightly more than one hemisphere. Over the course of time, we see about 59% of the lunar surface.

The plane of the Moon's orbit it tilted with respect to both the Earth's equator and the ecliptic. Unlike the Earth, whose axis is tilted at almost 24° to the vertical, the Moon's axis is nearly vertical (1.5°). 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).

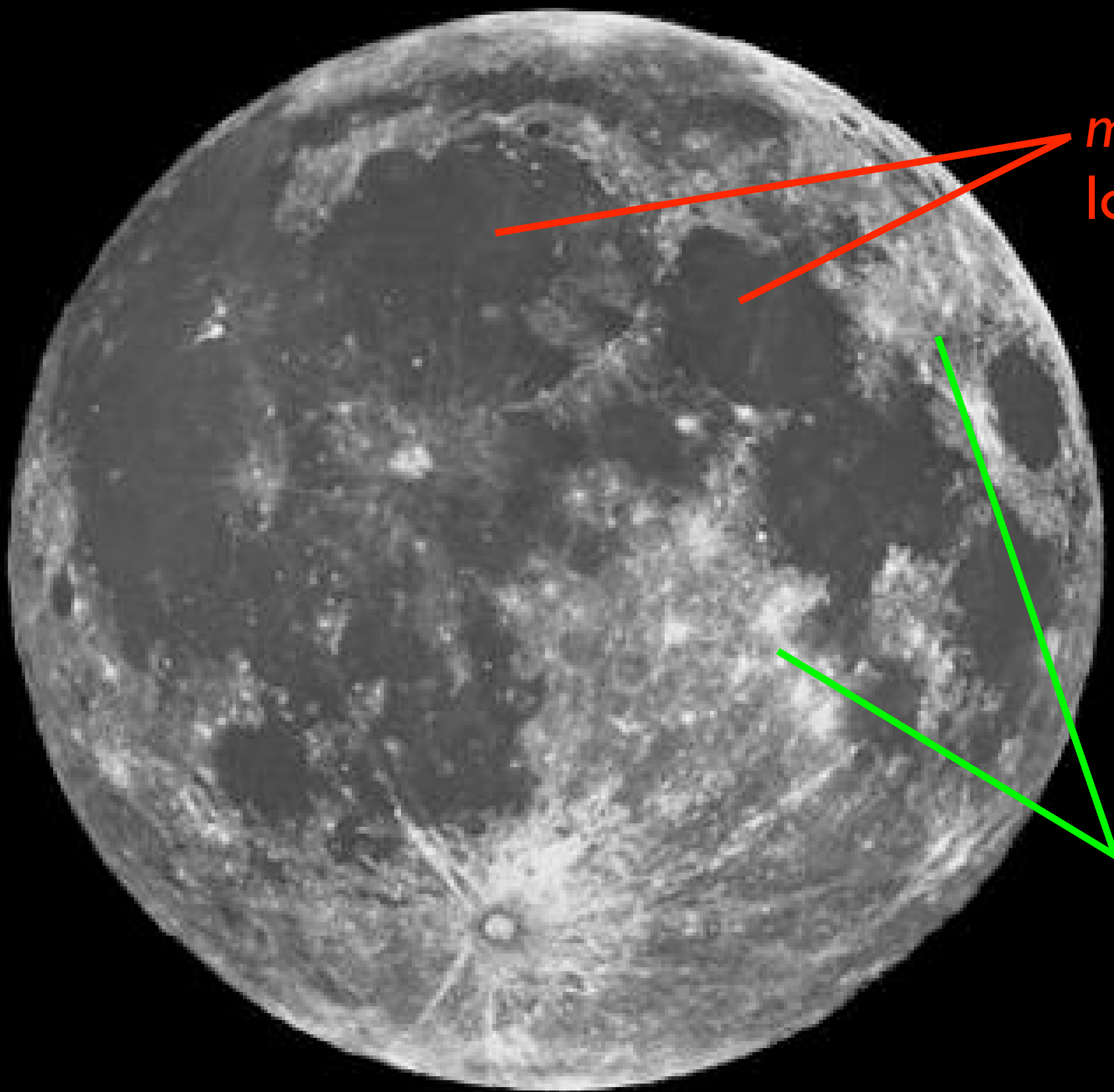


This tilt also explains why we don't get eclipses every month. The moon passes through the plane of the ecliptic twice a month. If this happens at full moon, there is the possibility of a lunar eclipse; if at new moon, there could be a solar eclipse.



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.

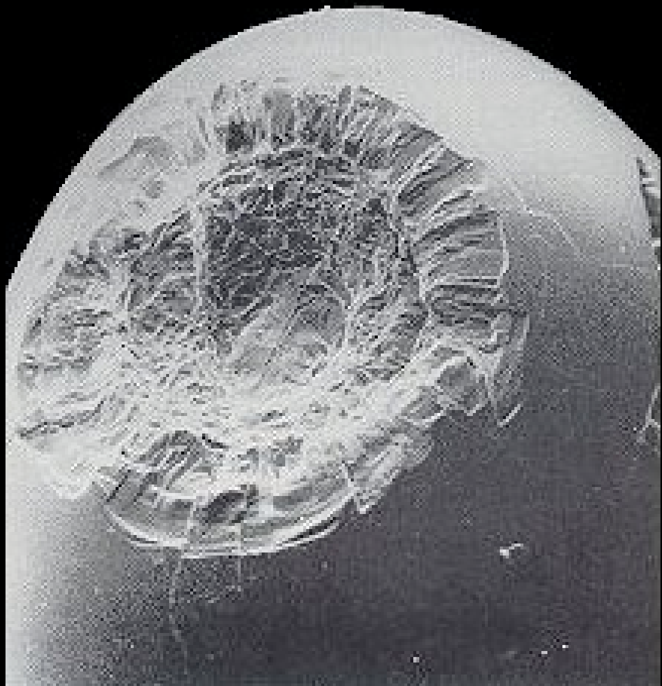
The moon's surface has two obvious terrains:



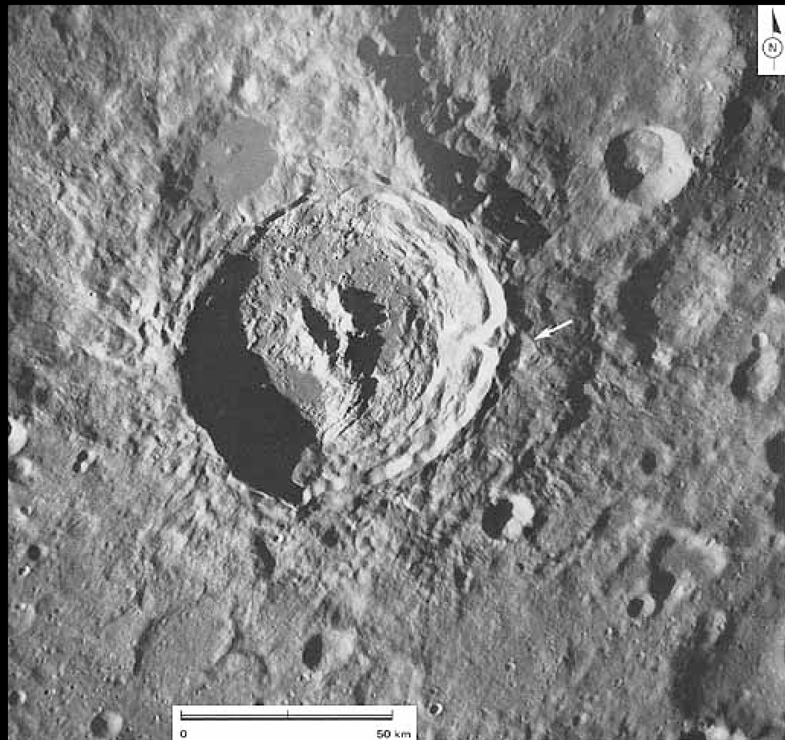
maria – smooth, dark lowlands, small craters

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

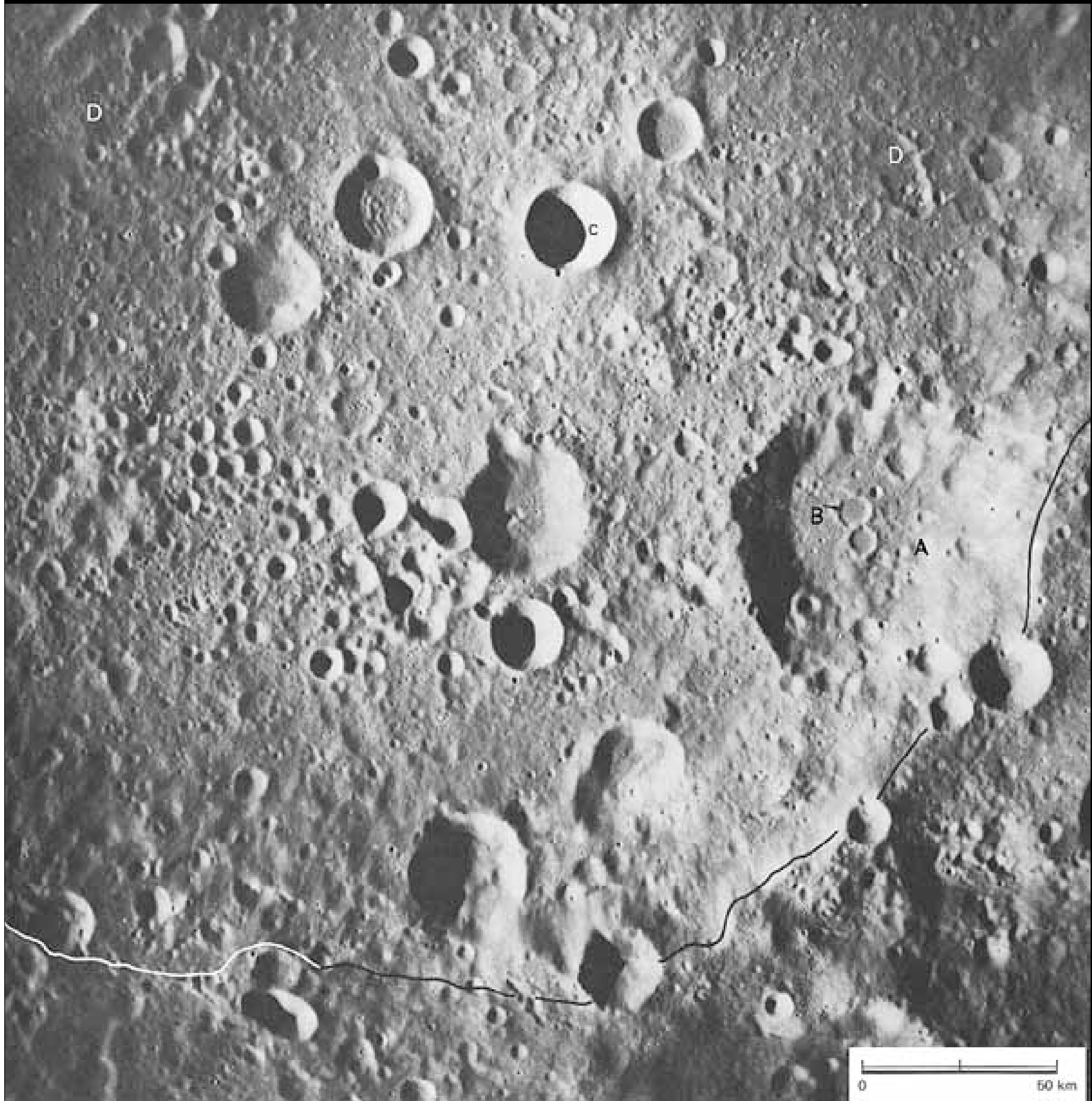
The whole lunar surface is covered with craters. Craters come in all sizes, from microscopic to planet-sized.



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



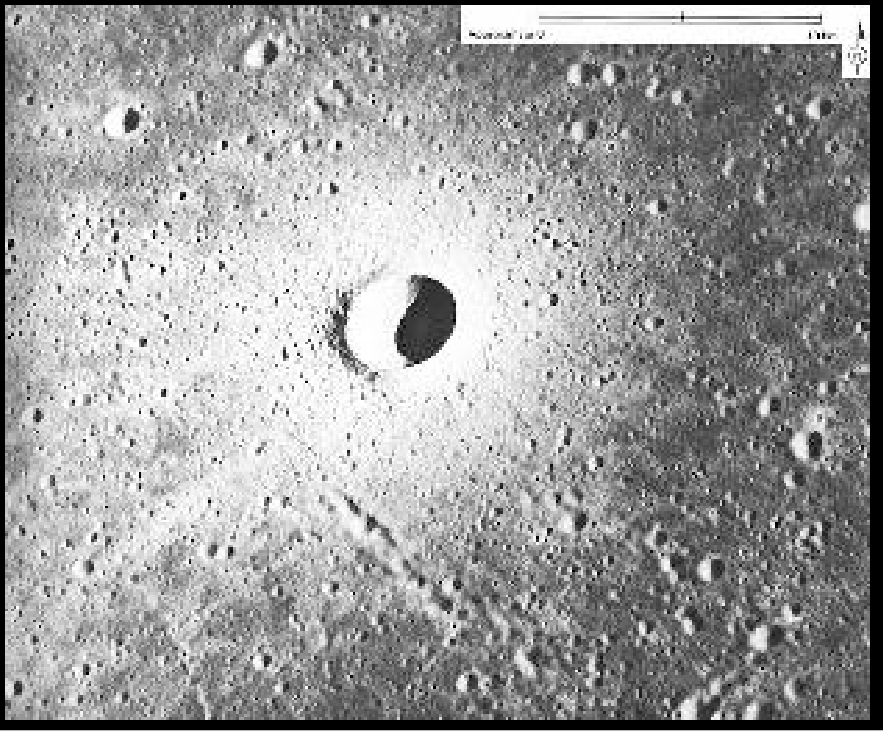
The 75-km diameter King crater on the far side, taken by Apollo 16



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.

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



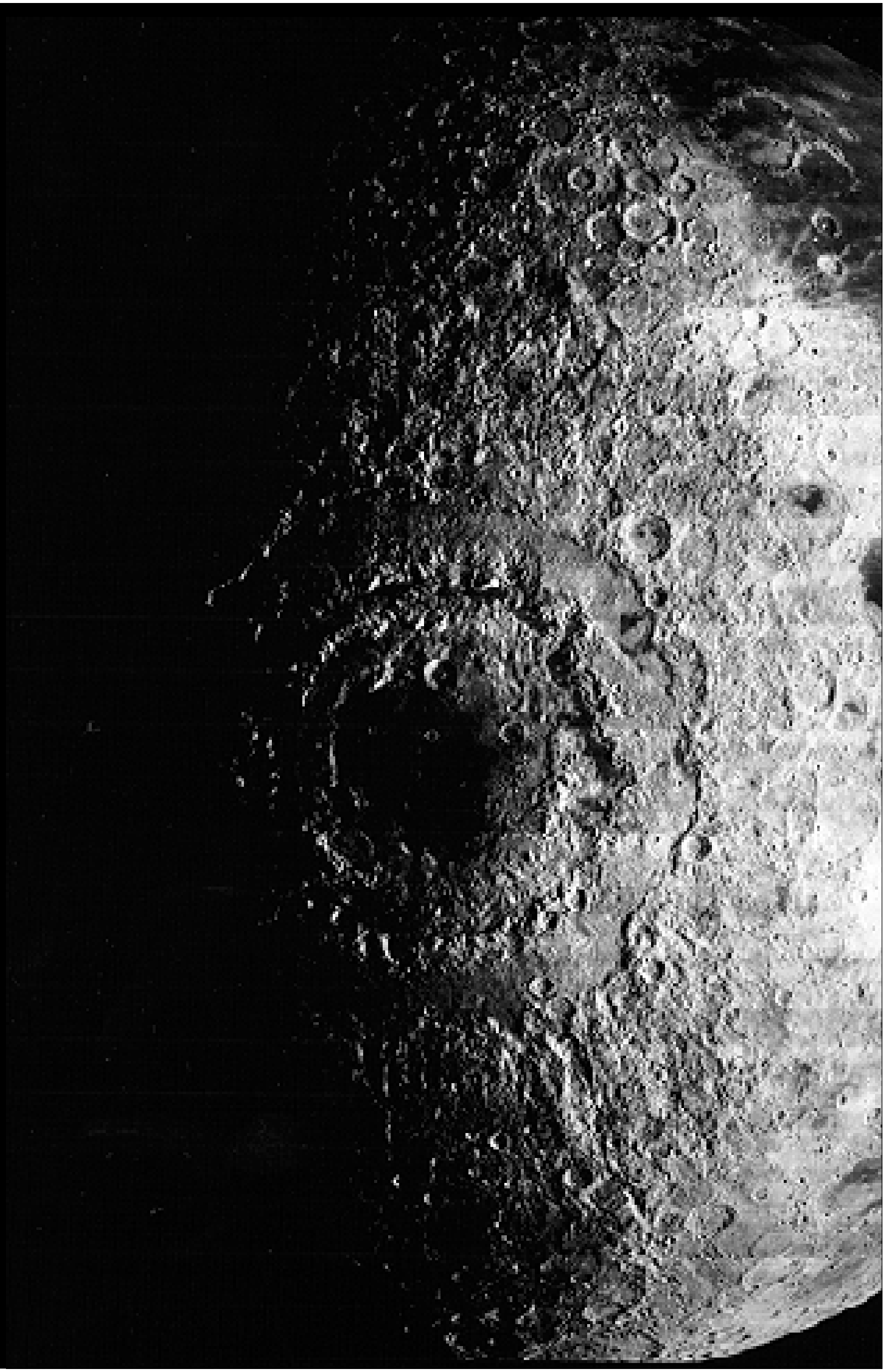
The very young crater Linne, taken by Apollo 15

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.

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

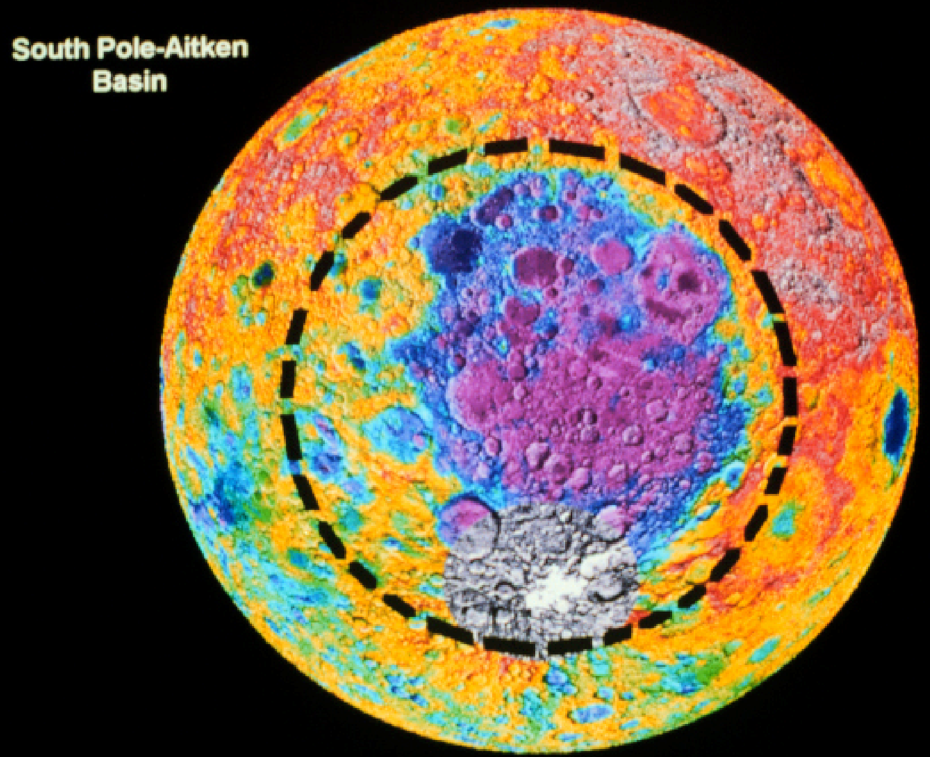
One of the youngest large craters, Tycho, is 87 km in diameter, and shows a ray system extending over 3000 km from its rim. Tycho is one of the youngest craters: 108 million years old.

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.



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 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 basin is up to 13 km in depth in some places. Its average depth is about 10 km.



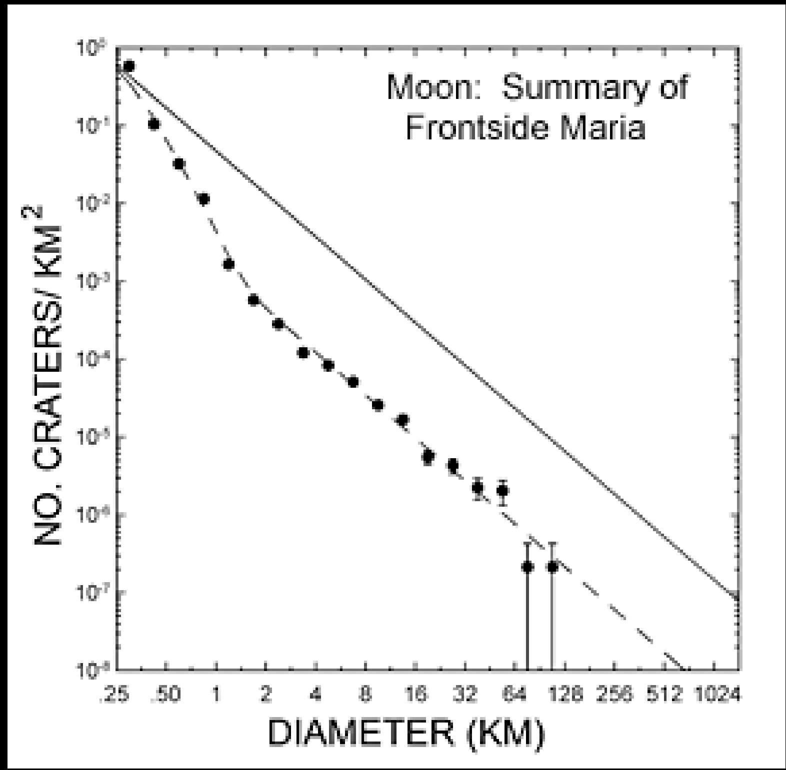
The basin floor is significantly darker than the surrounding rocks, and shows enhanced levels of iron and titanium.

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

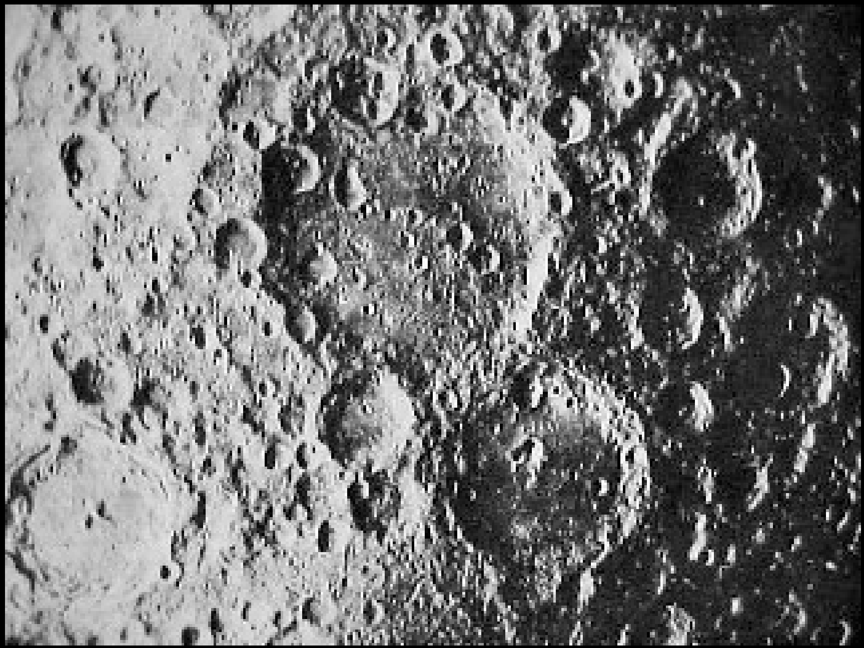
Archimedes, the large crater, must have been formed before the flooding of the Imbrium Basin, since it is partially buried and filled by basalt.

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.

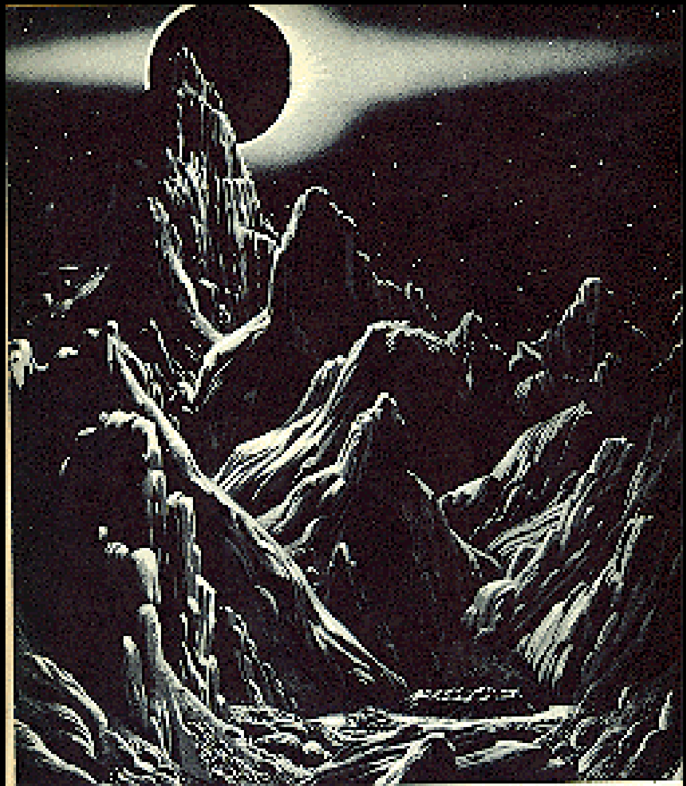
It appears the rate of bombardment tapered off about 3.9 billion years ago, and has been more or less uniform ever since. This means we can use the density of craters as a measure of the age.



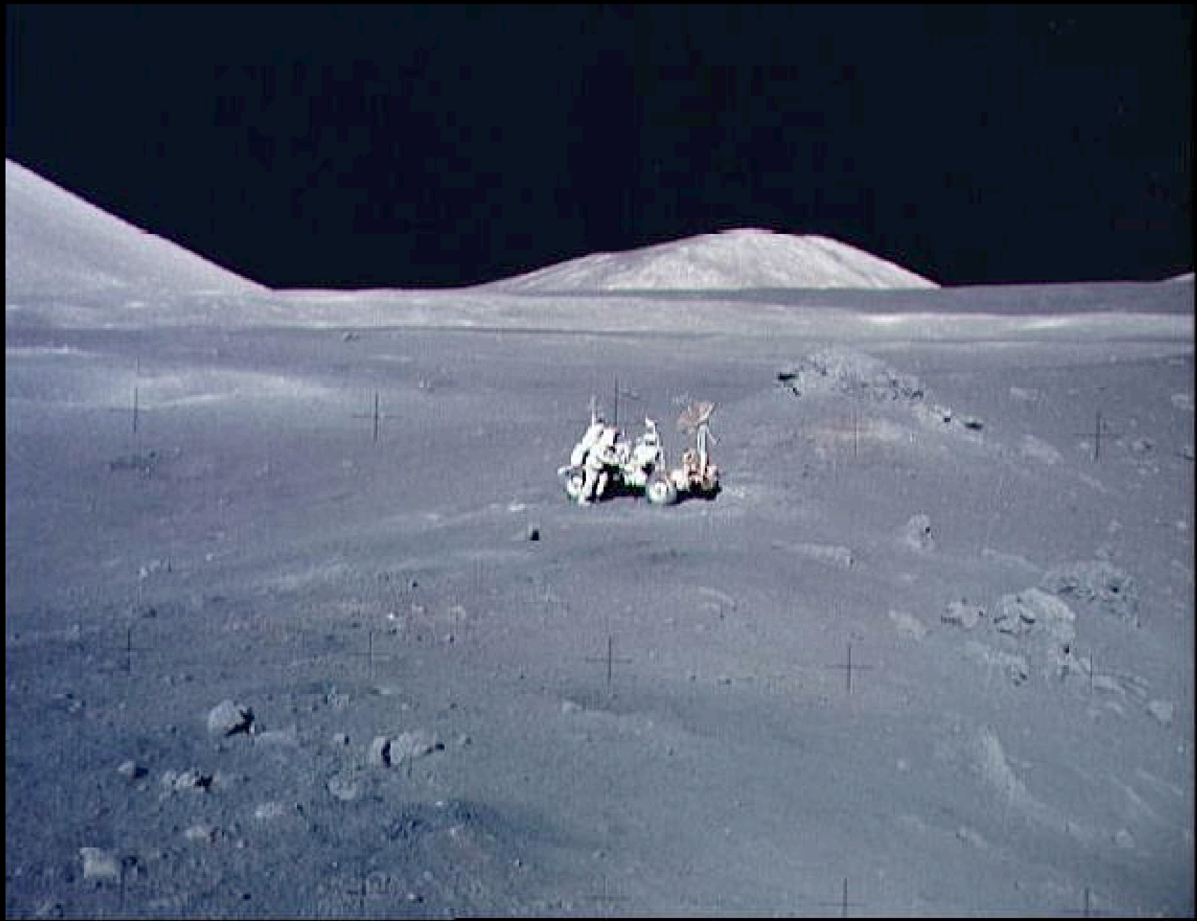
The heavily cratered highlands of the moon are much older than the maria, which have far fewer craters.



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...



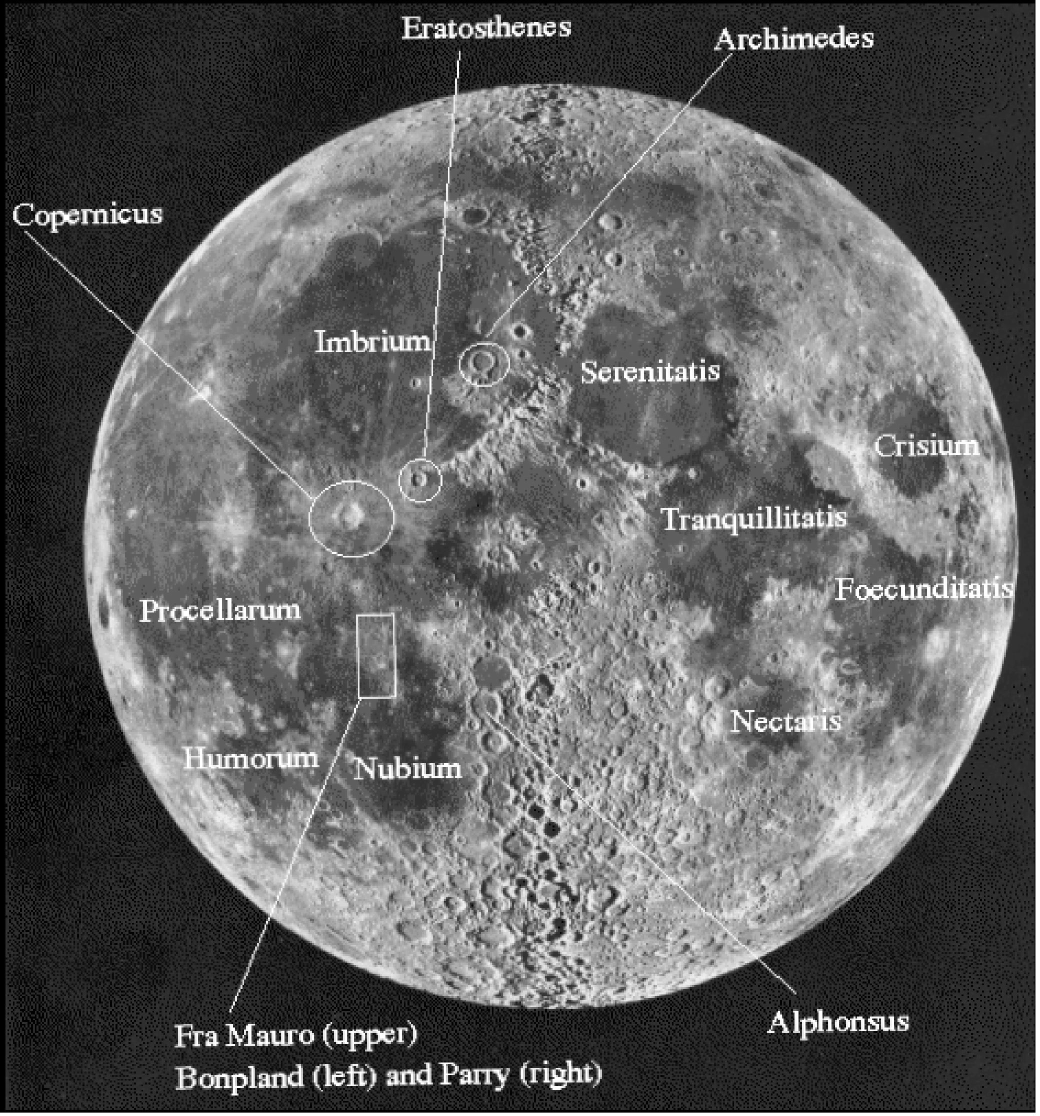
... the surface of the moon is actually remarkably smooth.



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

Maria

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



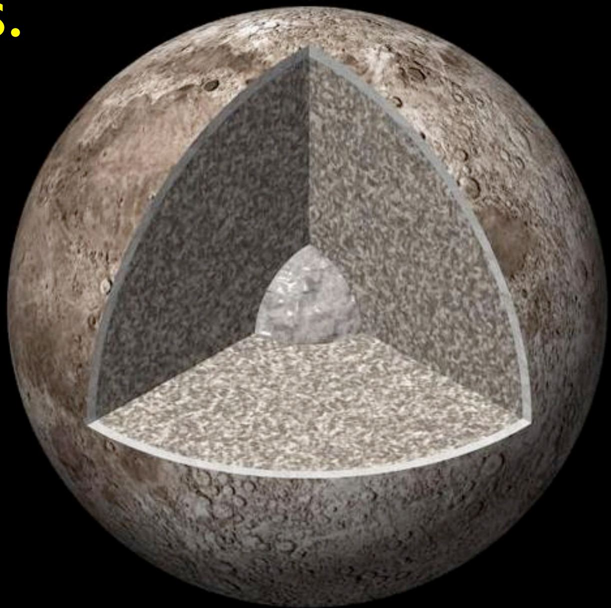
Nearly all the maria are on the near side of the moon; so although they are so obvious to the naked eye, they actually occupy only 16% of the lunar surface.

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

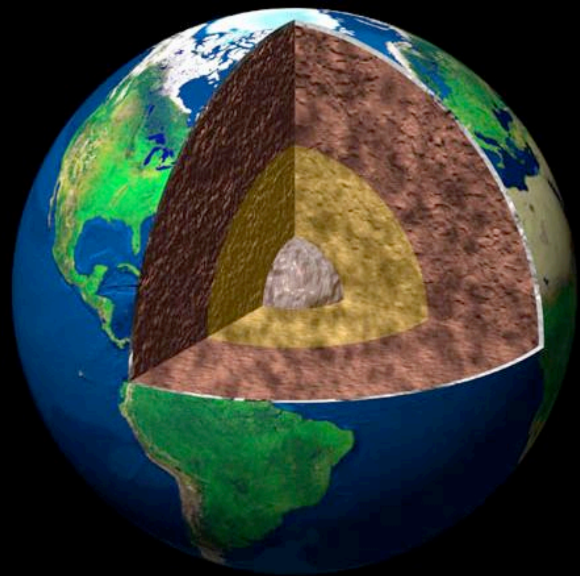
- *anorthosite*: plutonic rock (formed by slow crystallisation of magma), light-coloured, which forms the ancient highlands
- *basalt*: dark lava rocks, like those from the Hawaiian volcanoes, which fill the mare basins
- *breccia*: composite rocks formed though crushing during meteorite impacts.

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 terran rocks. The low density of the moon (3.3 g/cm^3 compared to 5.5 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.

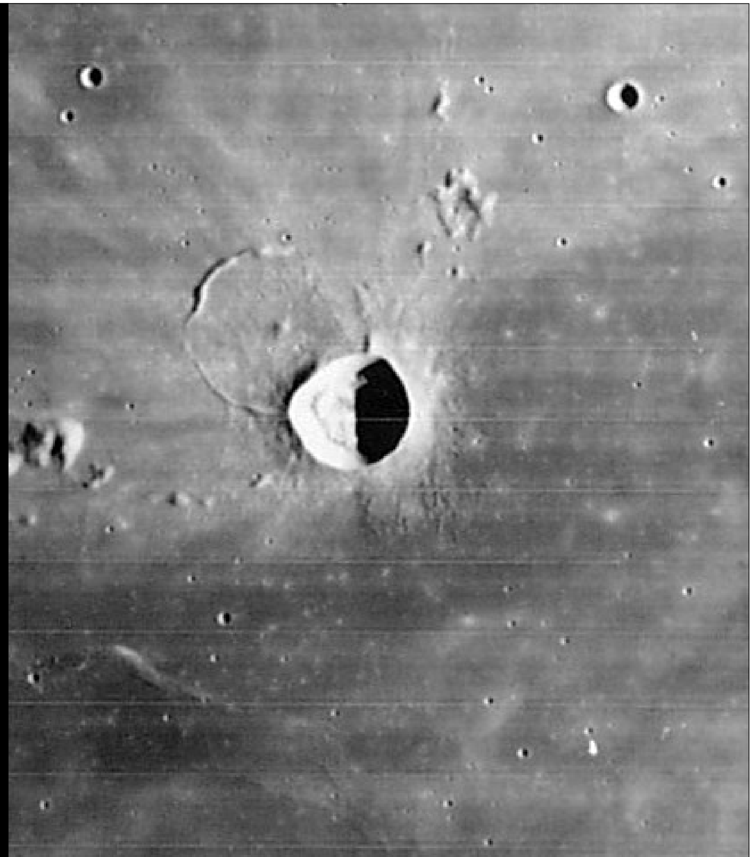


The Moon's interior, showing crust, mantle and core



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 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.

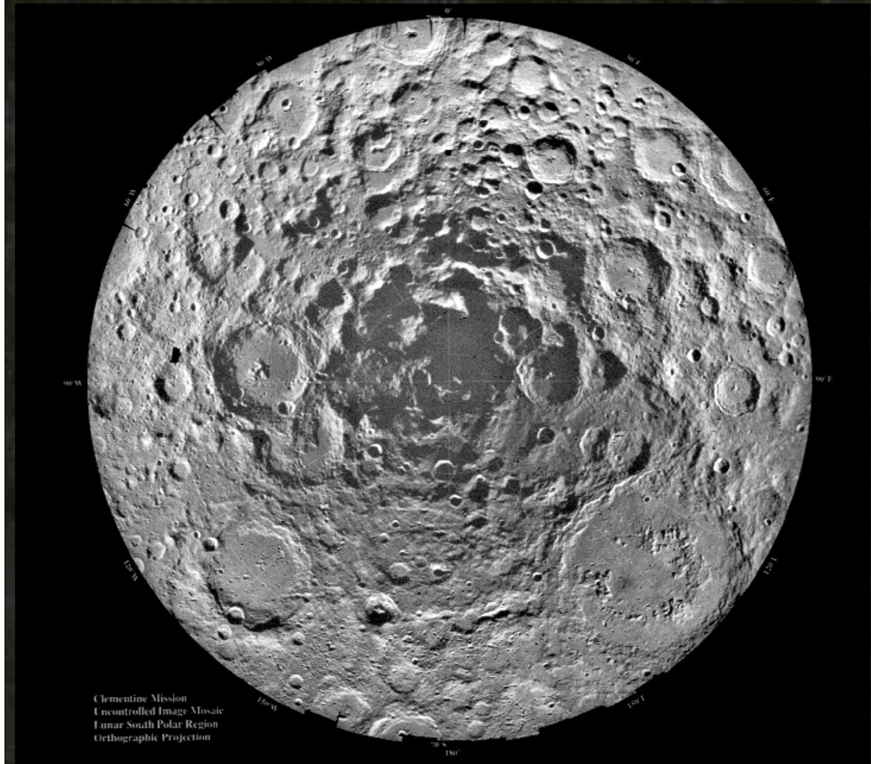
Together, these features imply that:

- 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*.

We'll see later how this all comes together to a theory for the formation of the moon.

Late news: Ice on the moon?

Two recent lunar missions – Clementine (1994) and Lunar Prospector (1998) – both detected signs of water ice near the lunar poles, in permanently shadowed areas in deep craters near the poles.



Clementine image of the south pole of the Moon. Ice was detected in the dark region near the pole (centre of image).

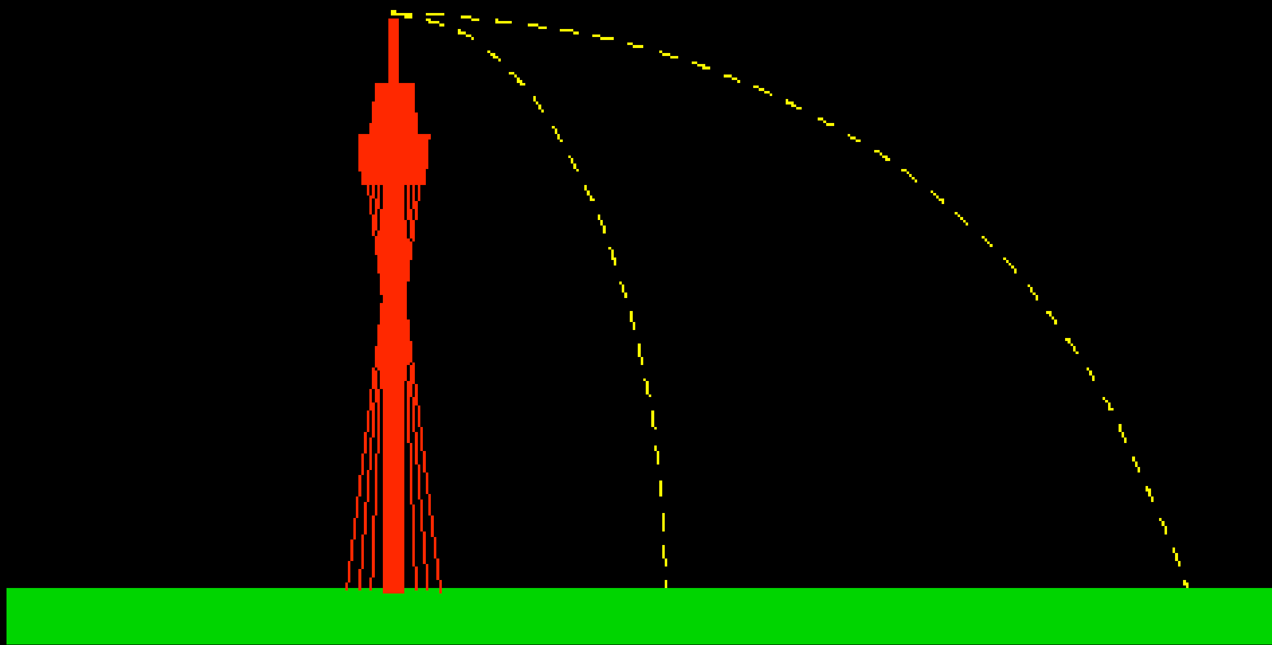
However, no sign of water was observed when Lunar Prospector crashed into a crater near the pole.


Spaceflight
or, how to get where we want to go

What is an orbit?

Consider throwing an 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.

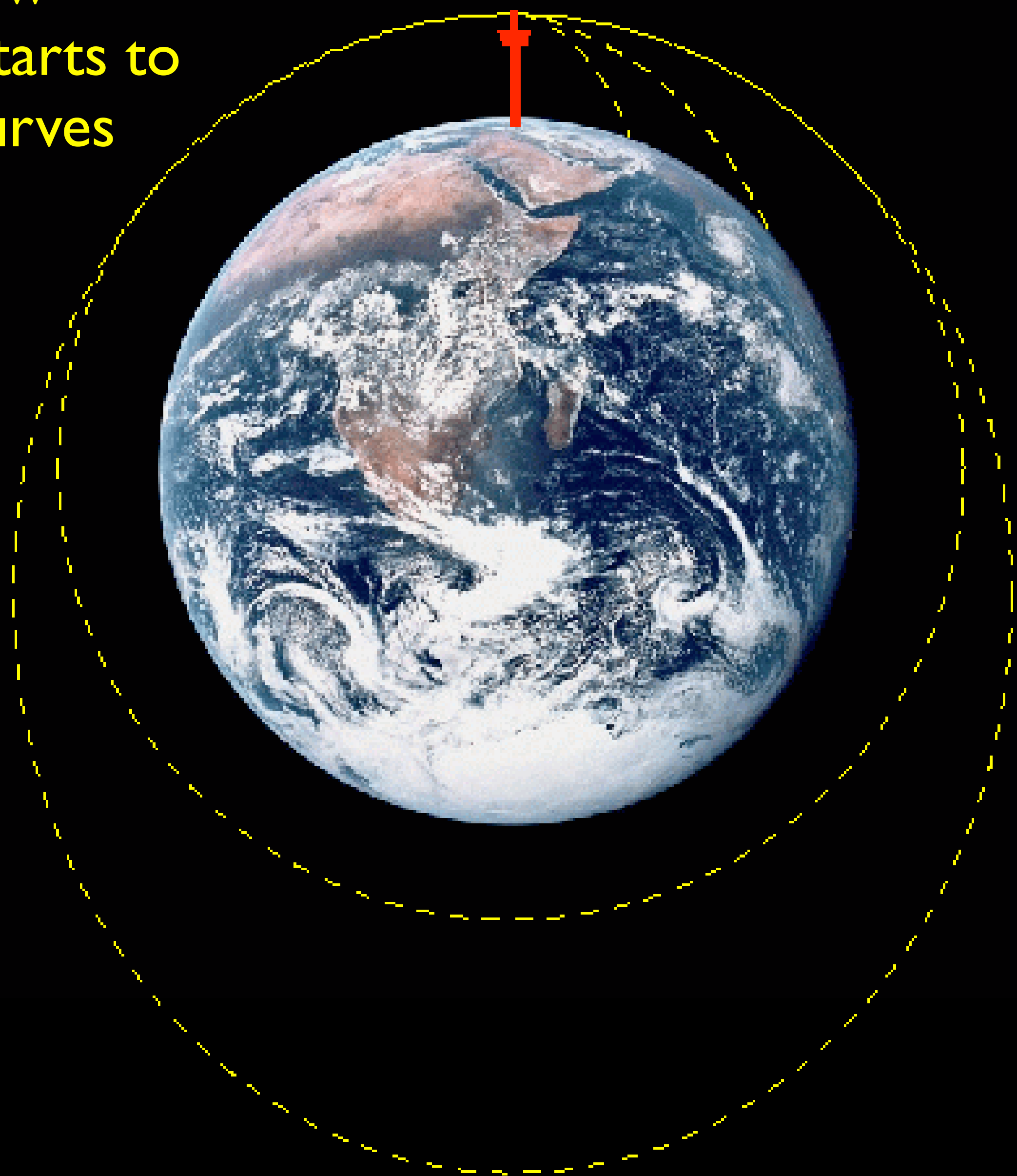
What happens if you throw it faster? It falls at the same rate (and in the same time!), but travels further forward before it hits the ground.



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

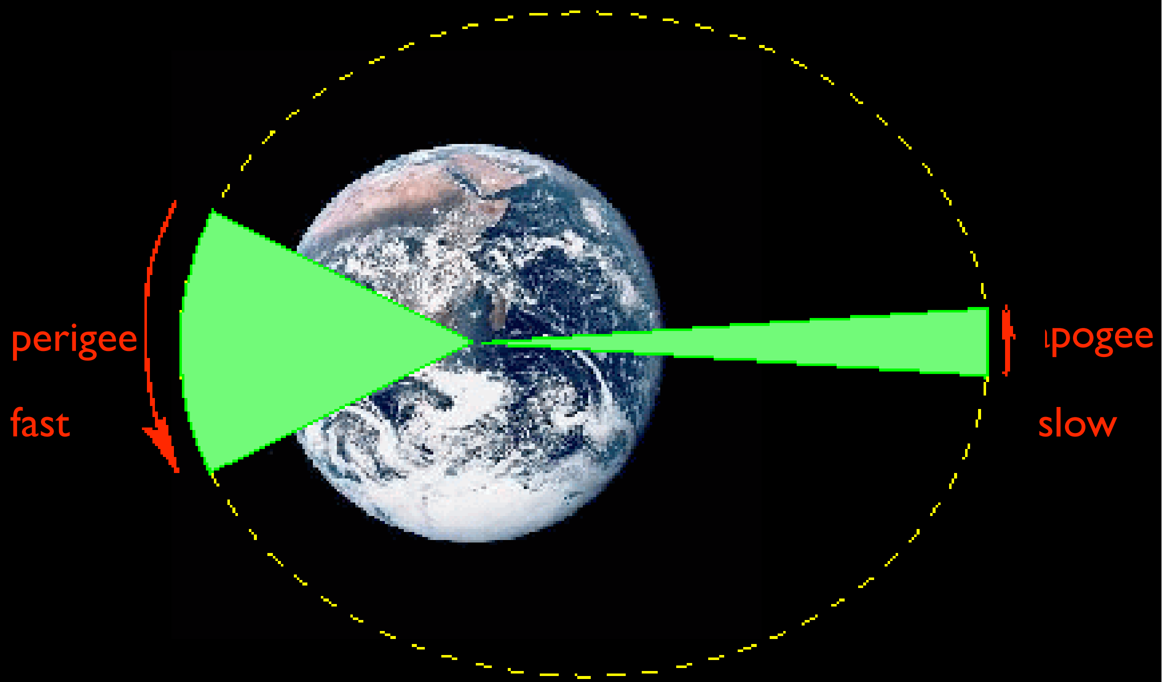
Because the spacecraft is falling around the Earth, objects (and astronauts) experience weightlessness. The astronaut and the floor are falling at the same rate, so there is no force counteracting the pull of gravity.

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.



Kepler's third law

Kepler's third law states that the period of an orbit (the time taken to complete it) depends on the altitude: the higher the orbit, the longer the period, and the slower the spacecraft travels.

Thus, for example:

- a satellite in low Earth orbit (altitude 300 km) takes 90 minutes to orbit the Earth
- a satellite in geo-synchronous orbit (altitude 35,000 km) takes 24 hours to orbit;
- the moon, altitude (distance) 380,000 km, takes 28 days to orbit.

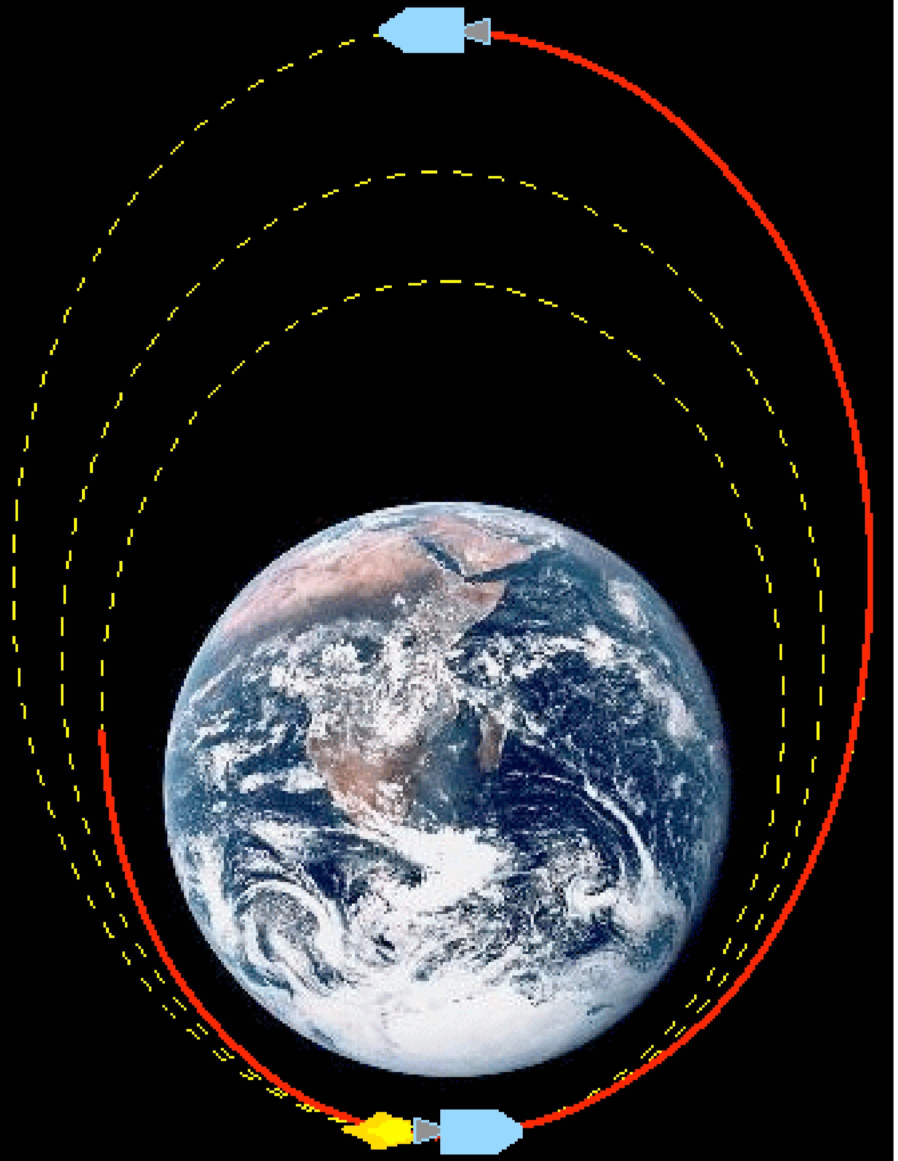
Changing orbits

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.

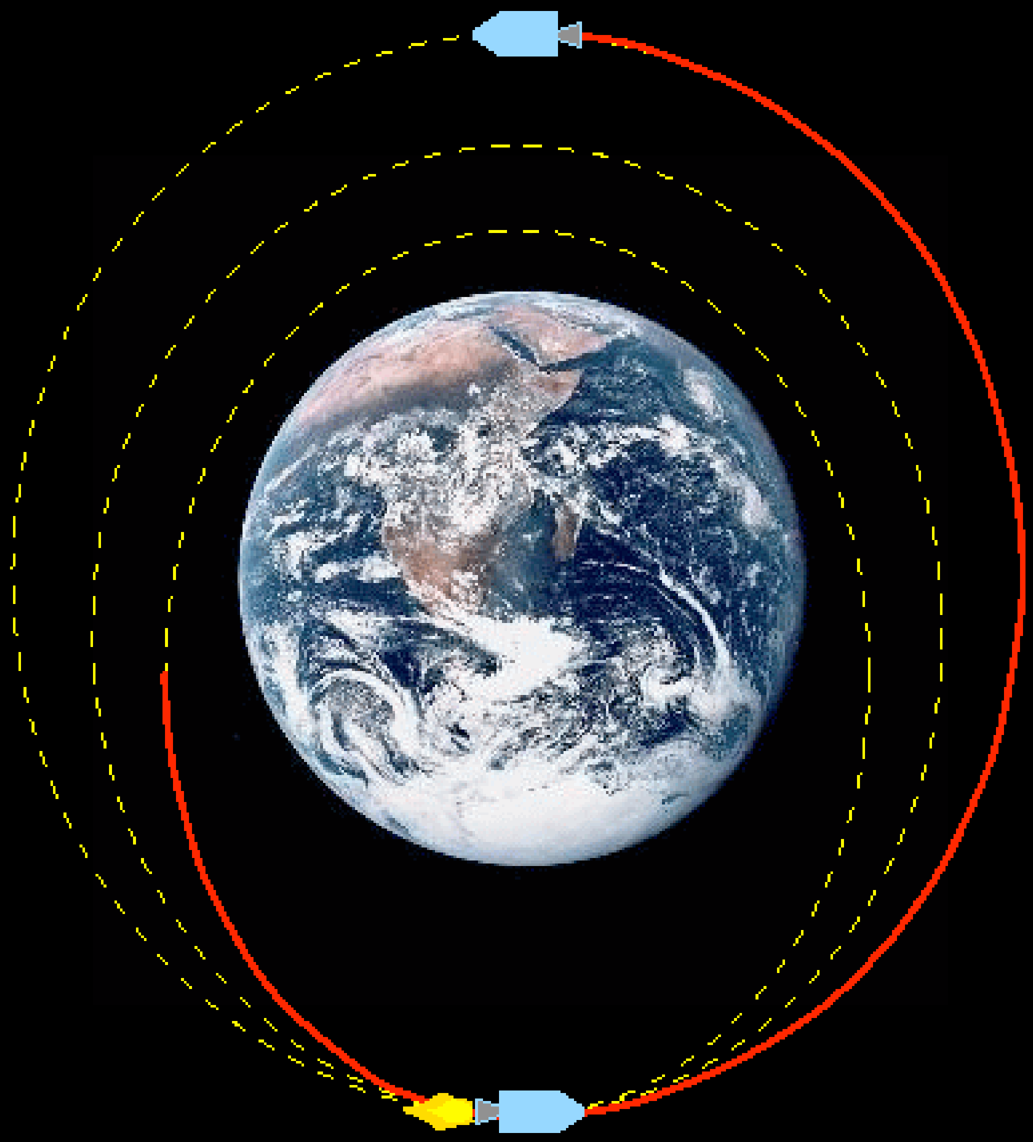
A burn at perigee *increases* the ellipticity of the orbit. The harder the burn, the more elliptical the final orbit.



What if we burn at apogee?

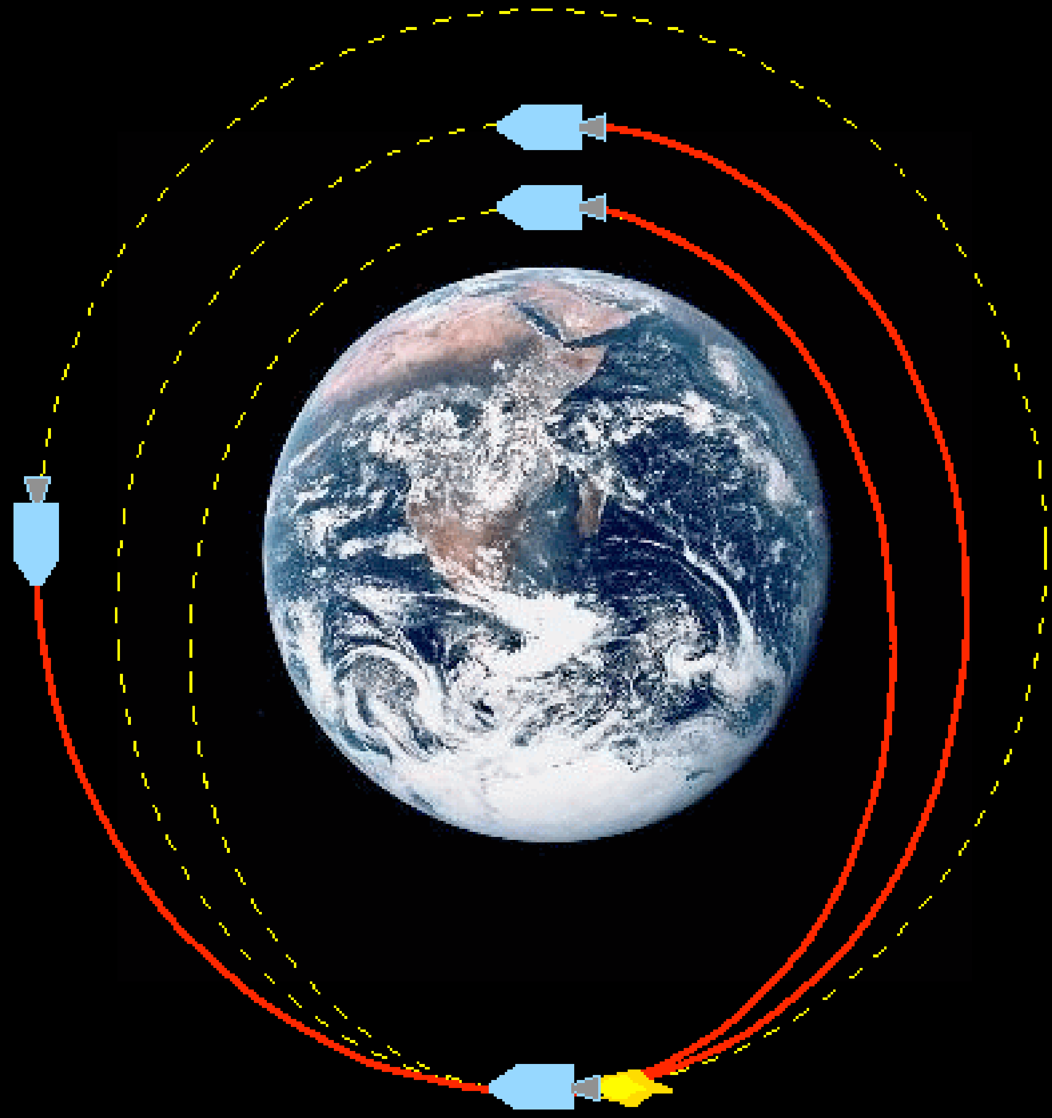
The burn lowers the altitude of every point on the orbit except the burn point, so a burn at apogee *decreases* the ellipticity of the orbit.

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

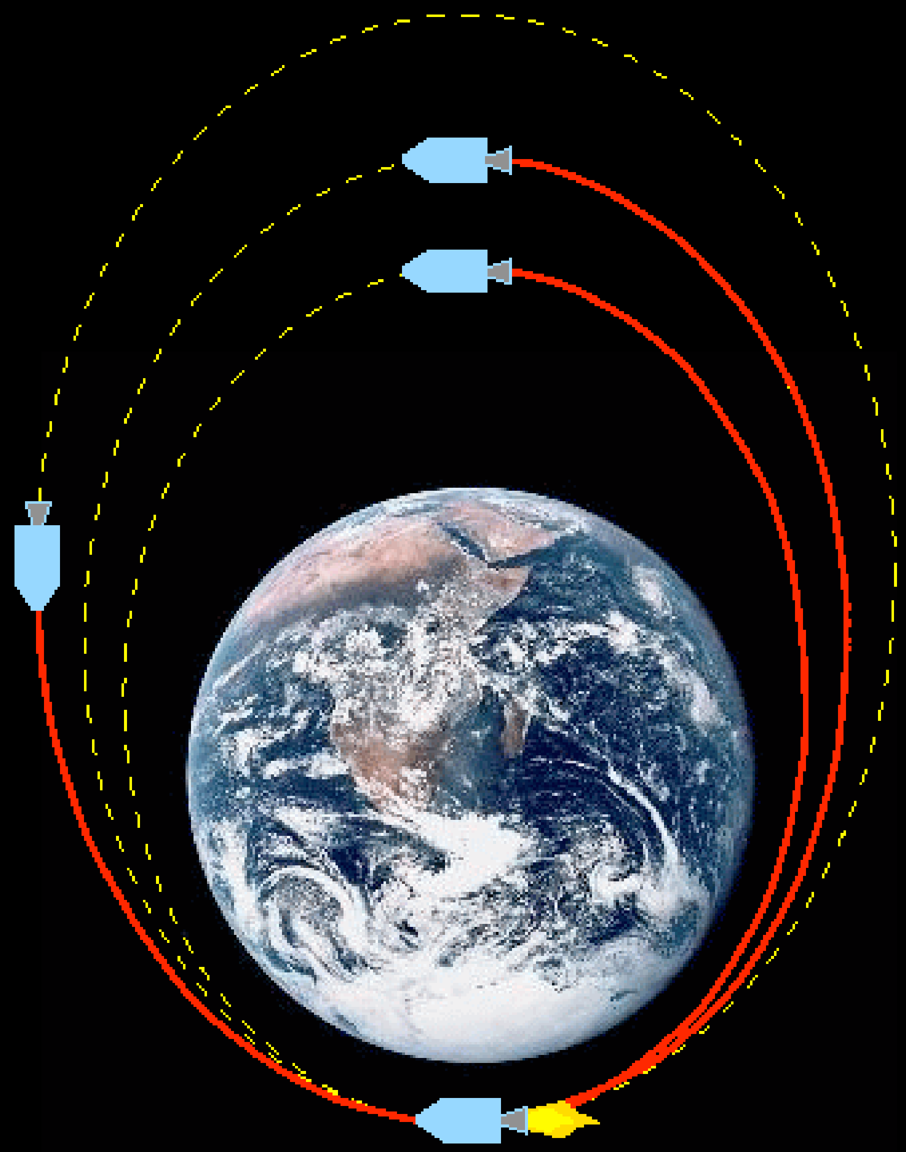


A *retrograde burn* has the opposite effect: it lowers the altitude of every point on the orbit except the burn point, so the orbit gets smaller. A burn at apogee *increases* the ellipticity of the orbit.

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



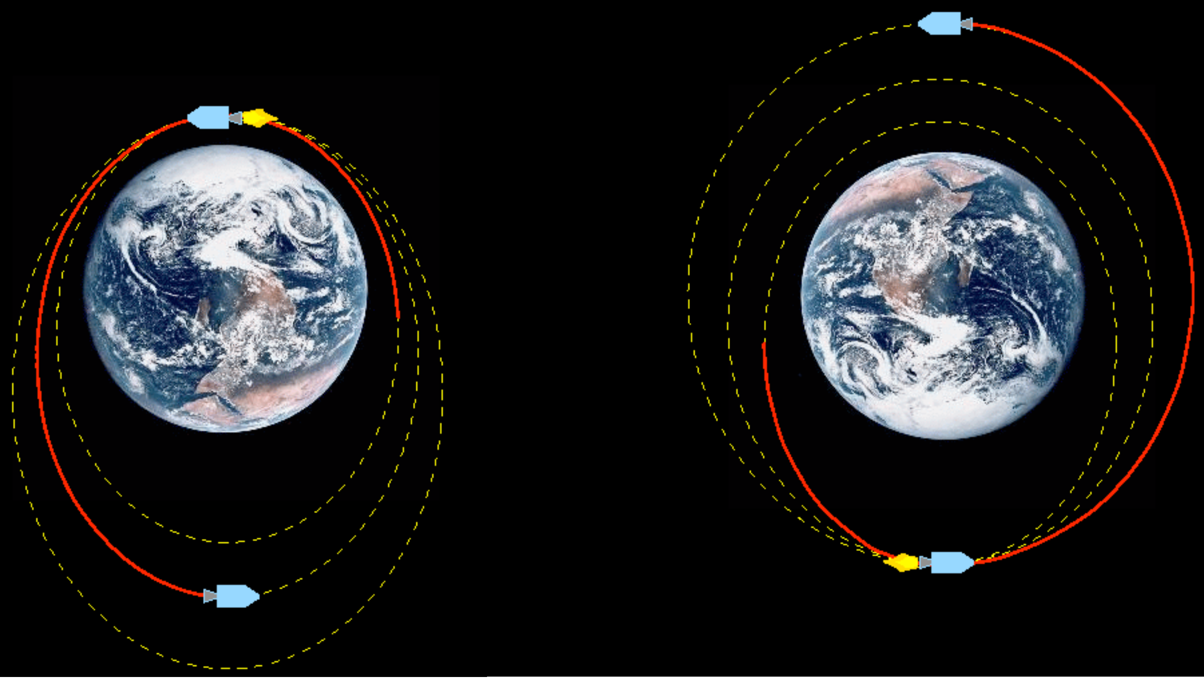
You can probably work out by now what a retrograde burn at perigee does: by decreasing the altitude of apogee, it makes the orbit more circular. Note that, in order to do a retrograde burn, the spacecraft has to turn around so its rocket fires the other way.



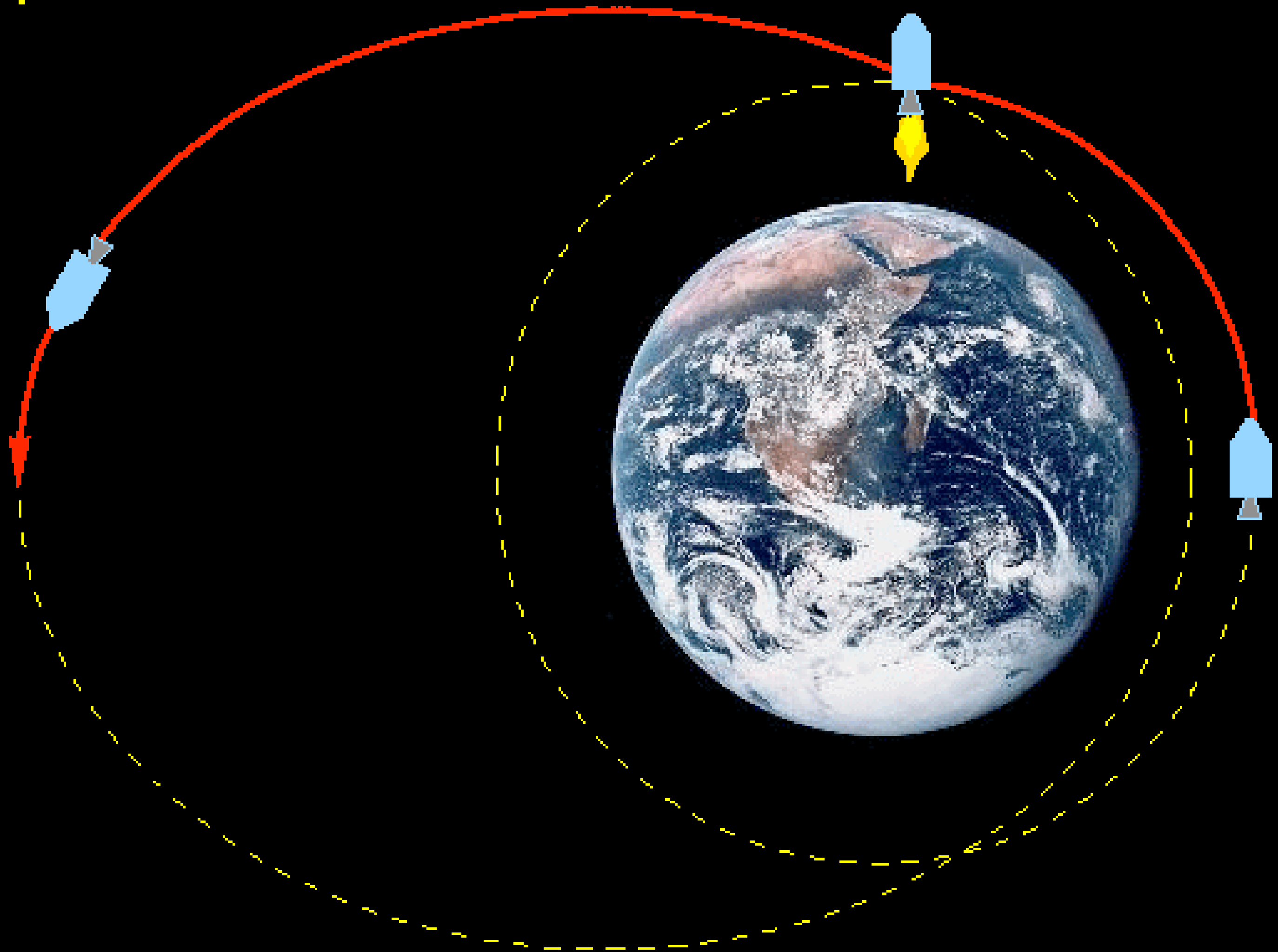
We can re-state all of the above as follows:

- 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", ΔV, 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

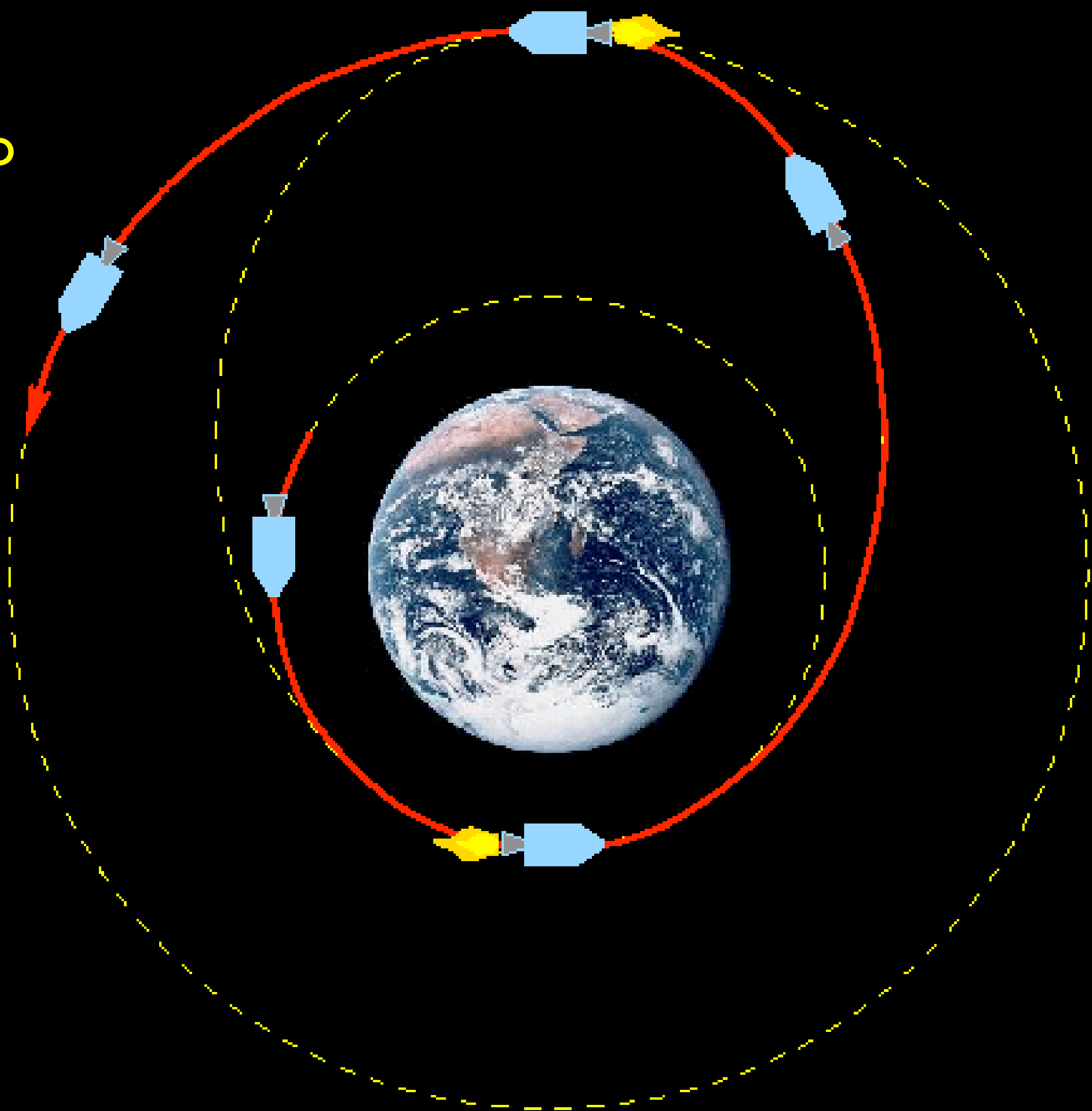
Now let's use all of this for something interesting: getting where we want to go. Let's consider the problem of getting from one (circular) orbit to another. This requires two burns, one to get to get from the initial orbit to an intermediate orbit, and one from the intermediate orbit to the final orbit.

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.

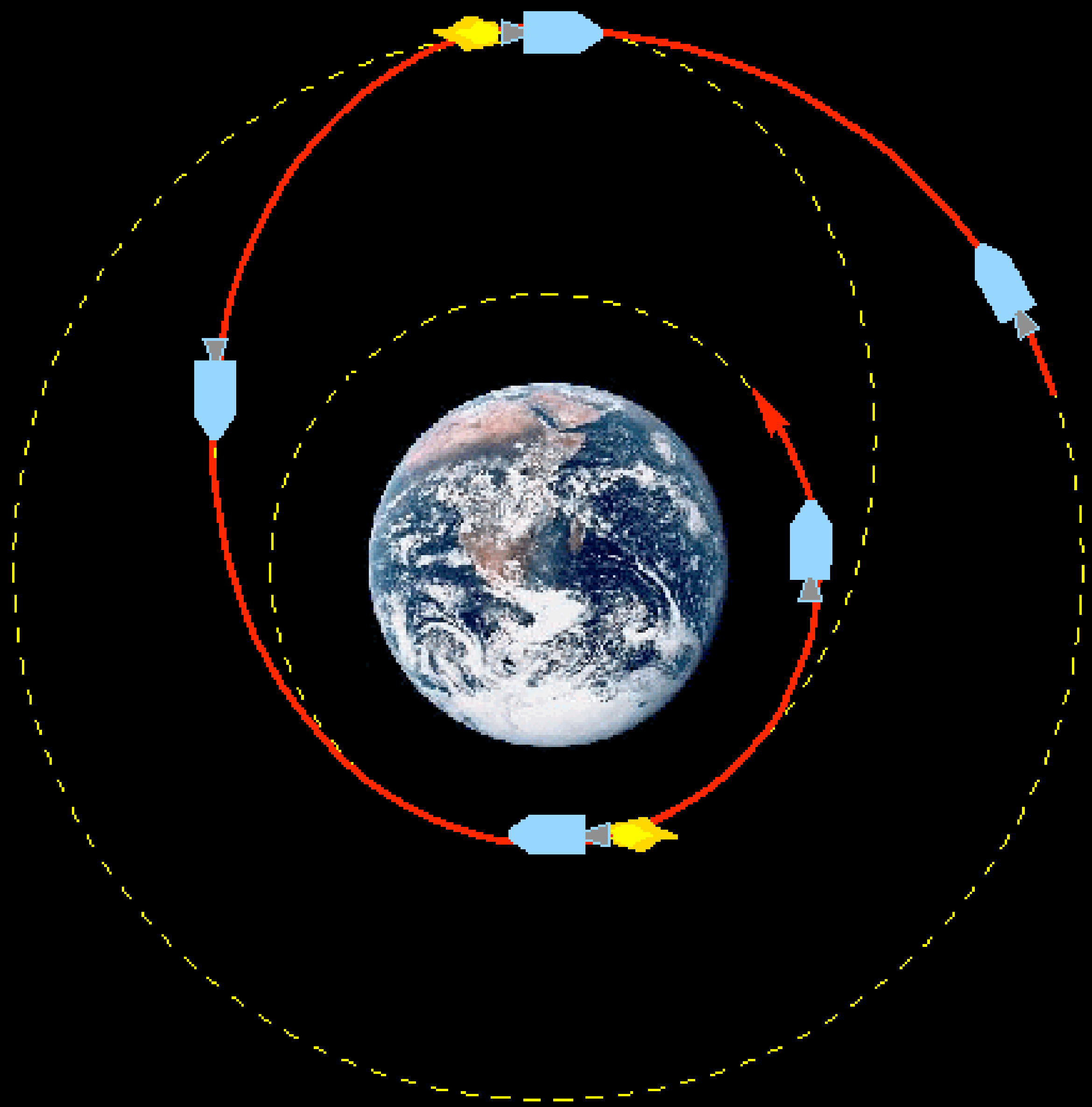
Suppose we want to get our space-craft from the inner orbit to the outer.

Do a forward burn into an orbit with apogee at the outer orbit. The burn point becomes the perigee of the transfer orbit.

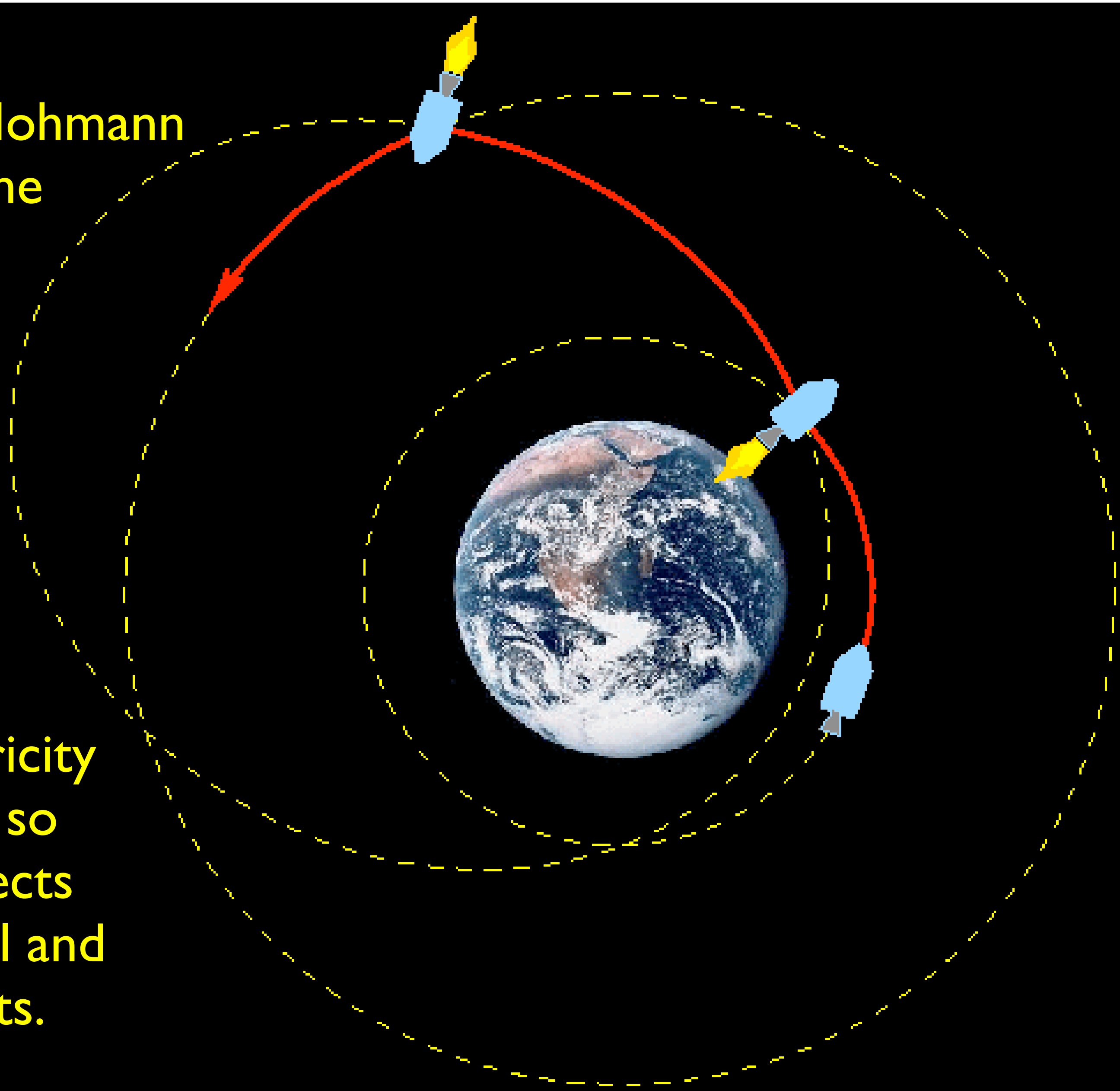
At apogee, do another forward burn to circularise the orbit.



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.



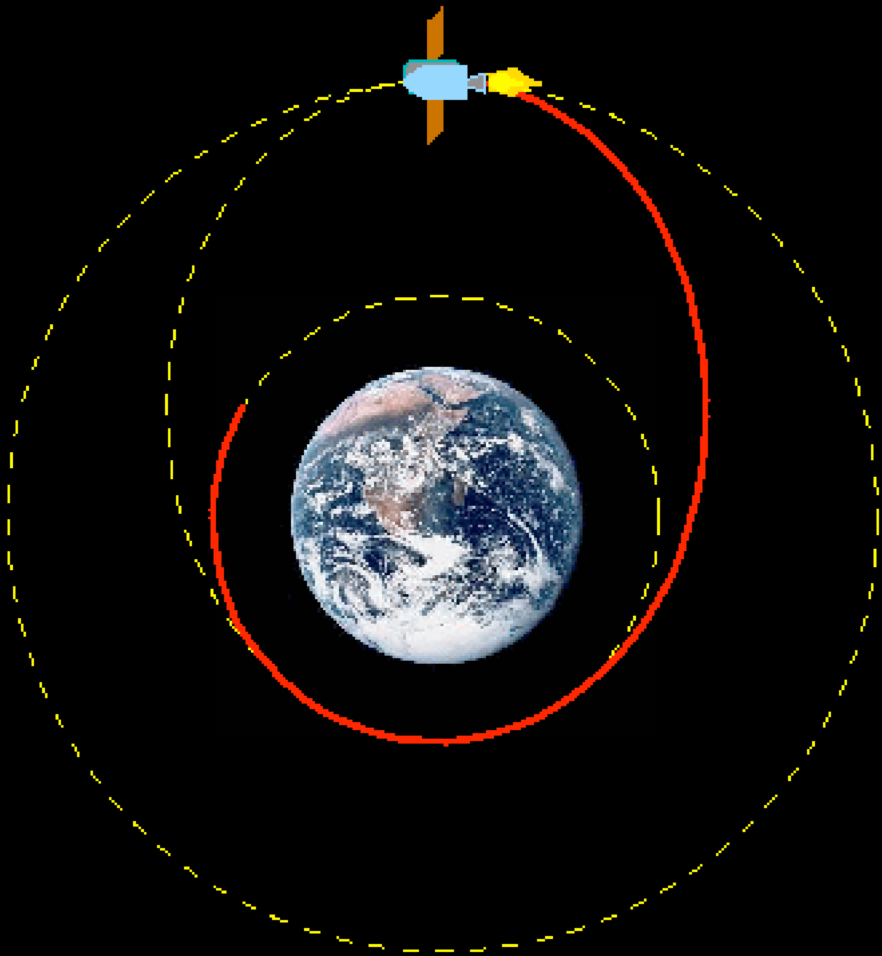
Note that the Hohmann transfer is not the only way to get from one orbit to another: it is merely the most fuel-efficient way. The transfer orbit can be of any size, eccentricity and orientation, so long as it intersects both the original and destination orbits.



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, it must start off ahead of the spacecraft in order to reach the rendezvous point at the same moment.

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

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

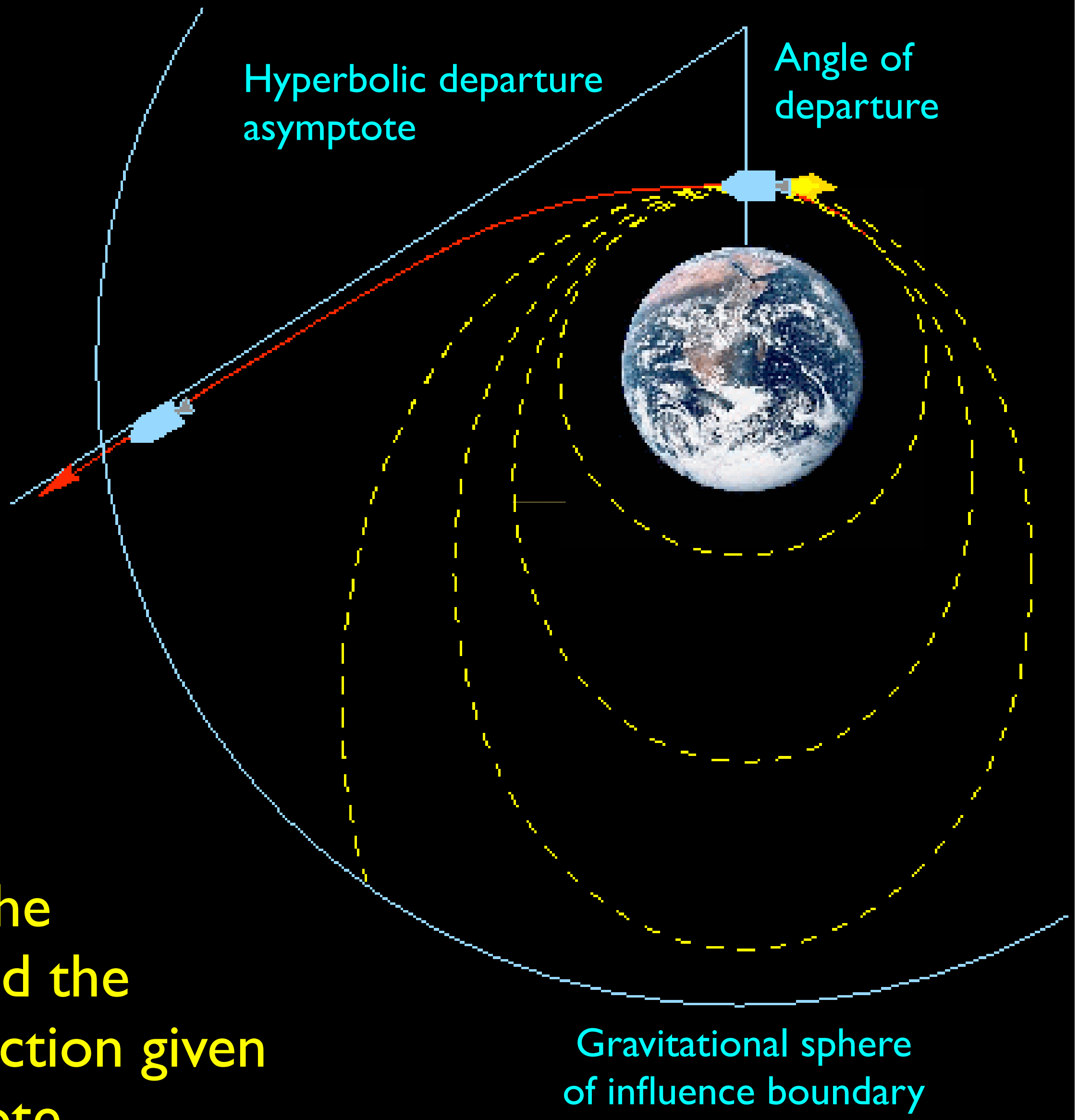
Leaving Earth

Now let's consider how to reach other planets. First, we have to leave the Earth. Recall that a forward burn raises the altitude of the apogee, and that the harder the burn, the higher the apogee, and the longer the spacecraft can coast before gravity slows it down and turns it back towards Earth. A hard enough burn can give the spacecraft enough ΔV 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 starts on a low-Earth circular orbit. A forward burn increases the altitude of apogee.

If the burn is strong enough (141% of the circular orbit velocity) the trajectory becomes a parabola, and the spacecraft never returns to Earth.

Higher velocities makes the trajectory a hyperbola, and the spacecraft leaves in a direction given by the departure asymptote.

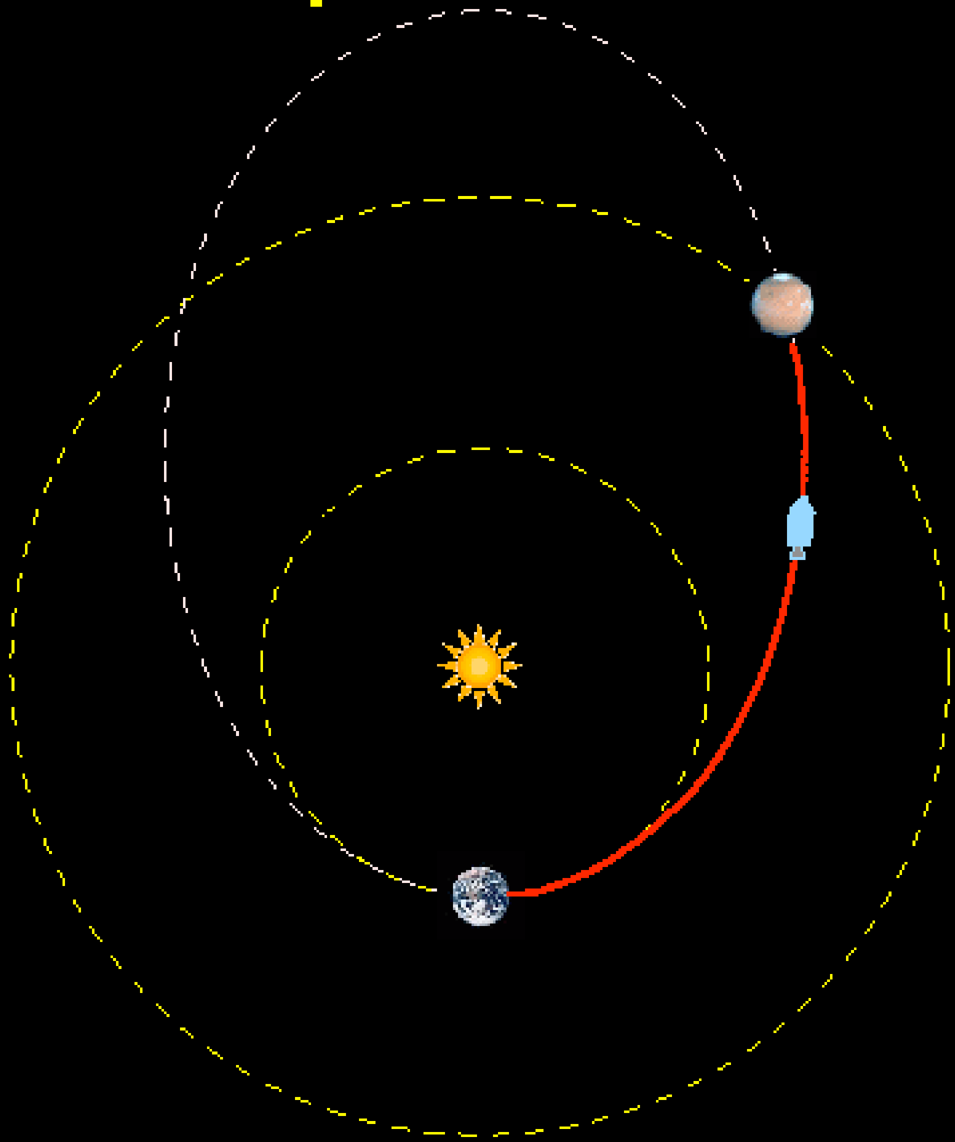


Reaching other planets

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

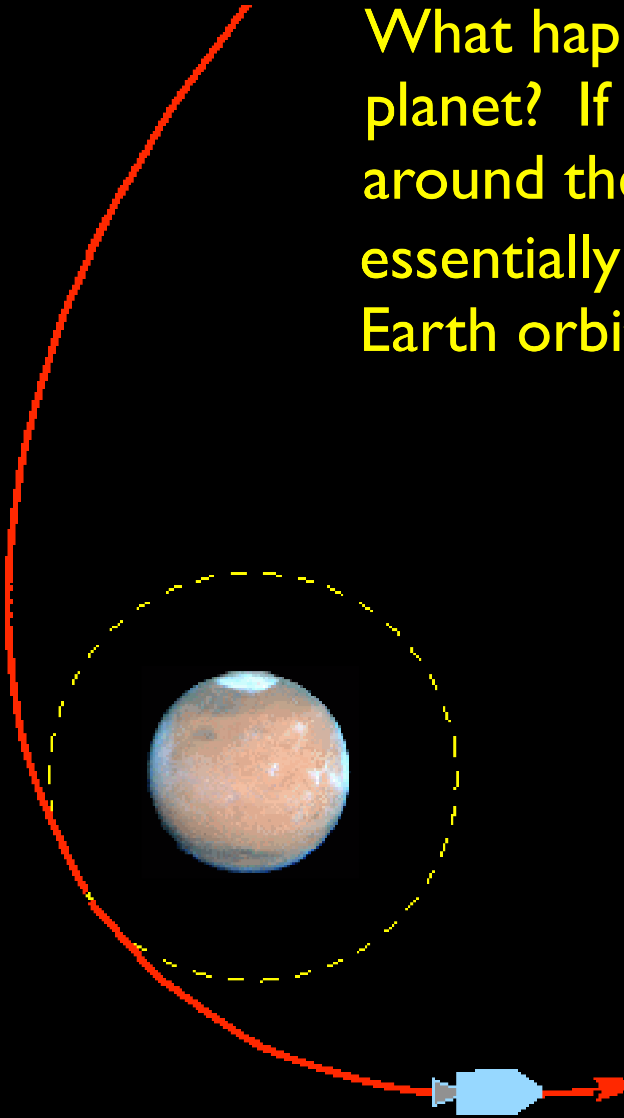
This is just the orbital rendezvous problem: we have to perform an orbital transfer, timing arrival to meet Mars.

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.



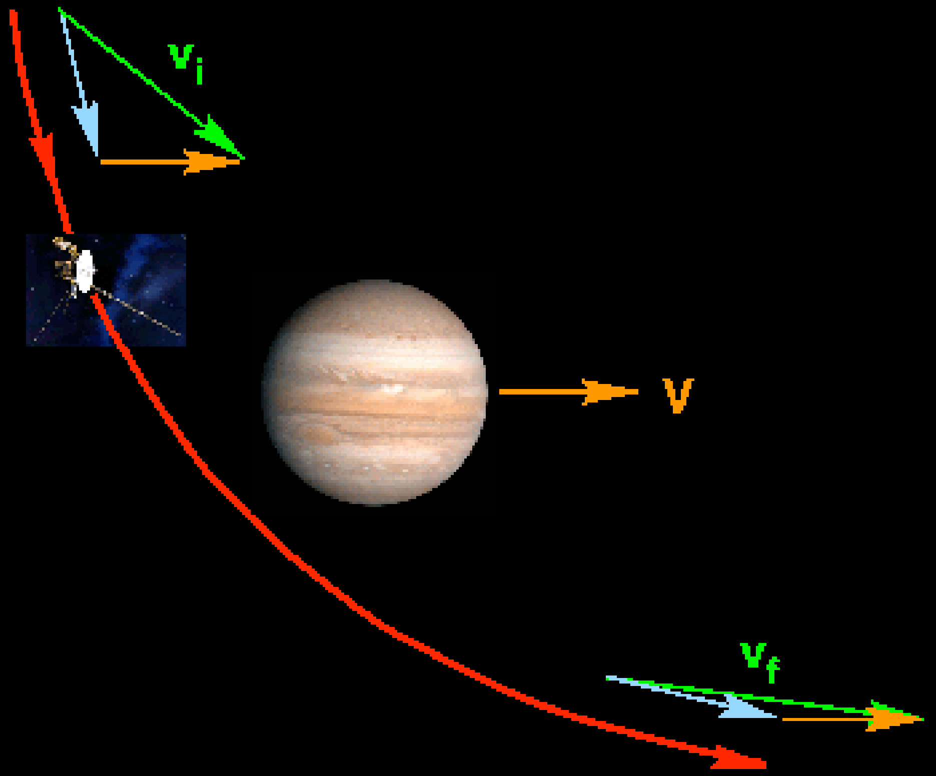
Arrival at the planet

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.



The other option is 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.

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*.

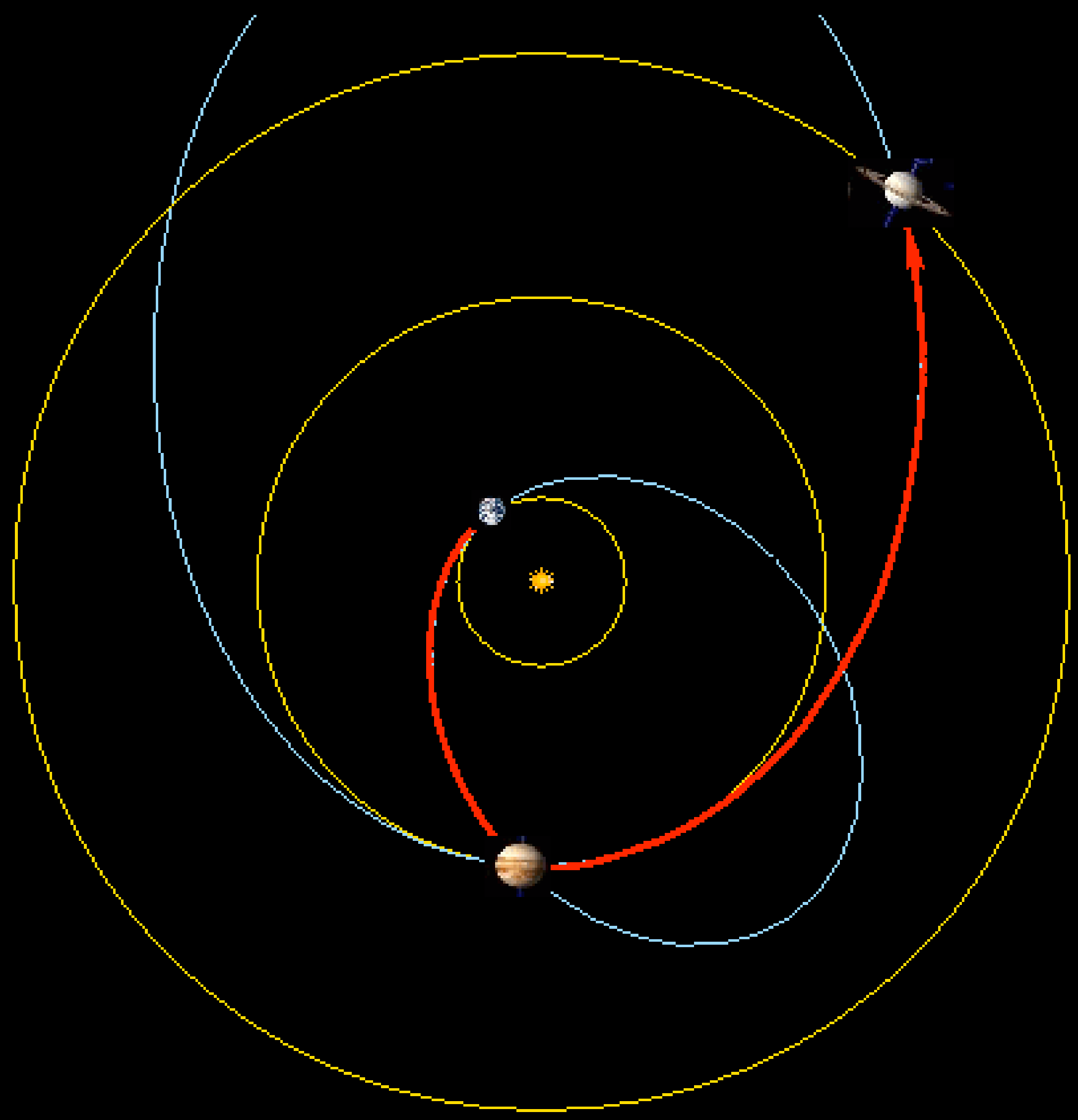


In the frame of the planet, the spacecraft's speed is the same before and after the encounter, but the direction has changed.

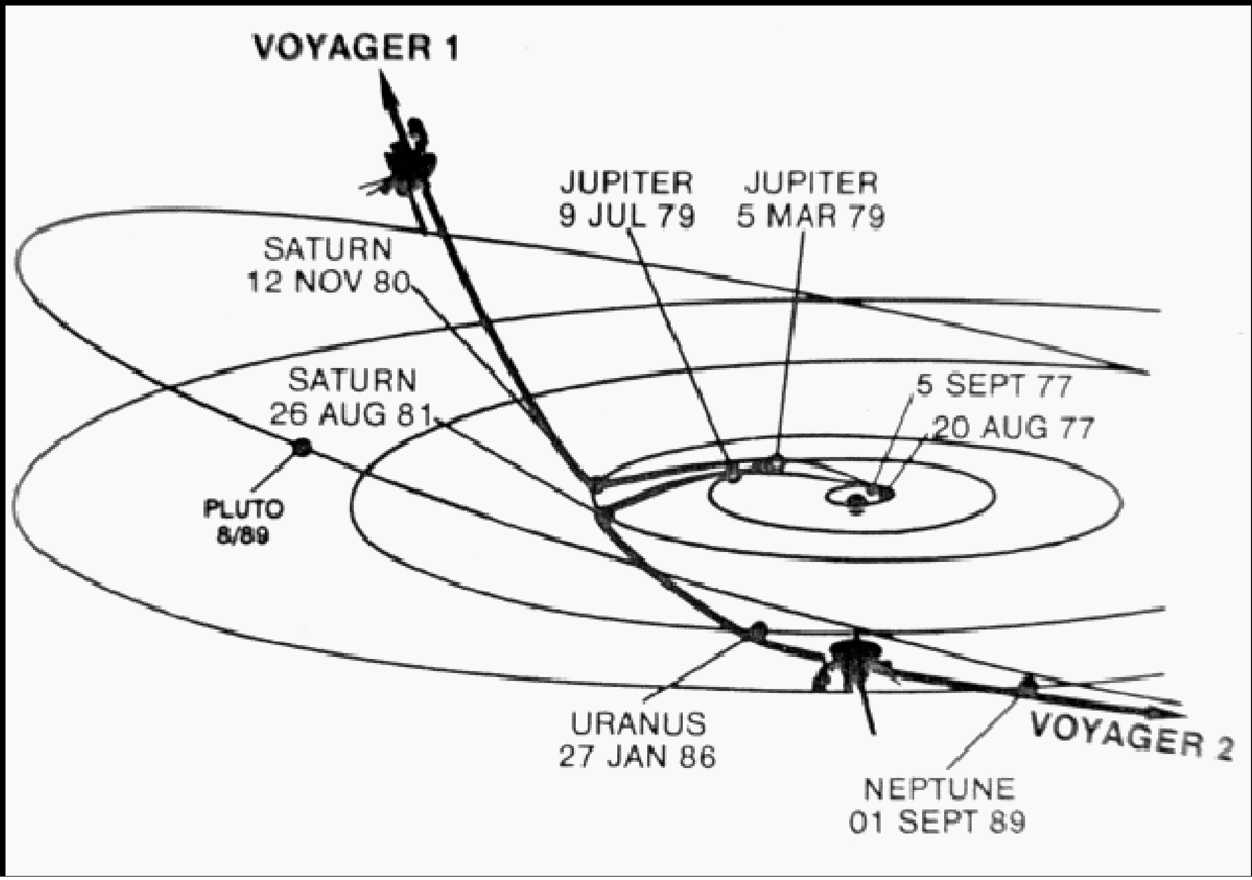
However, since the planet is also moving, then relative to the Sun the spacecraft has gained speed.

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

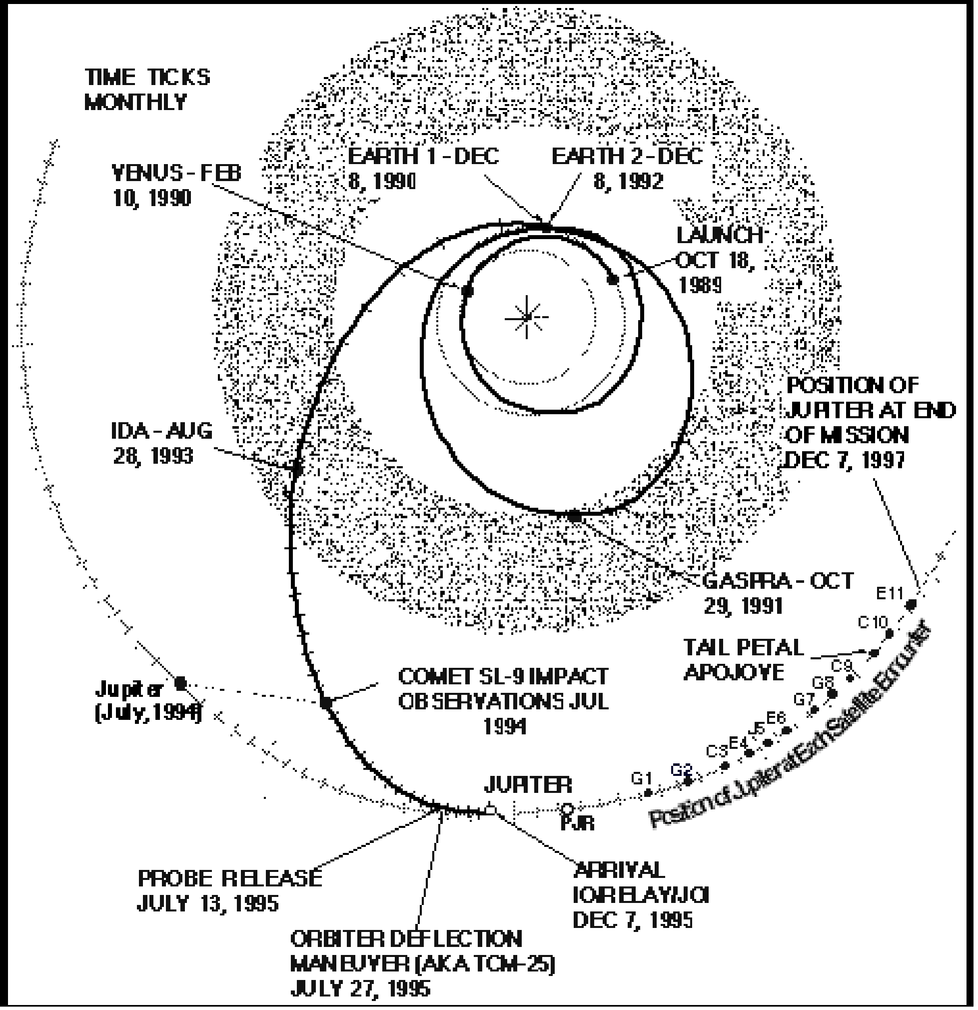
Jupiter slings the spacecraft into a new, larger orbit which intersects Saturn's orbit. All three planets must be in the right position or the manoeuvre will not work.

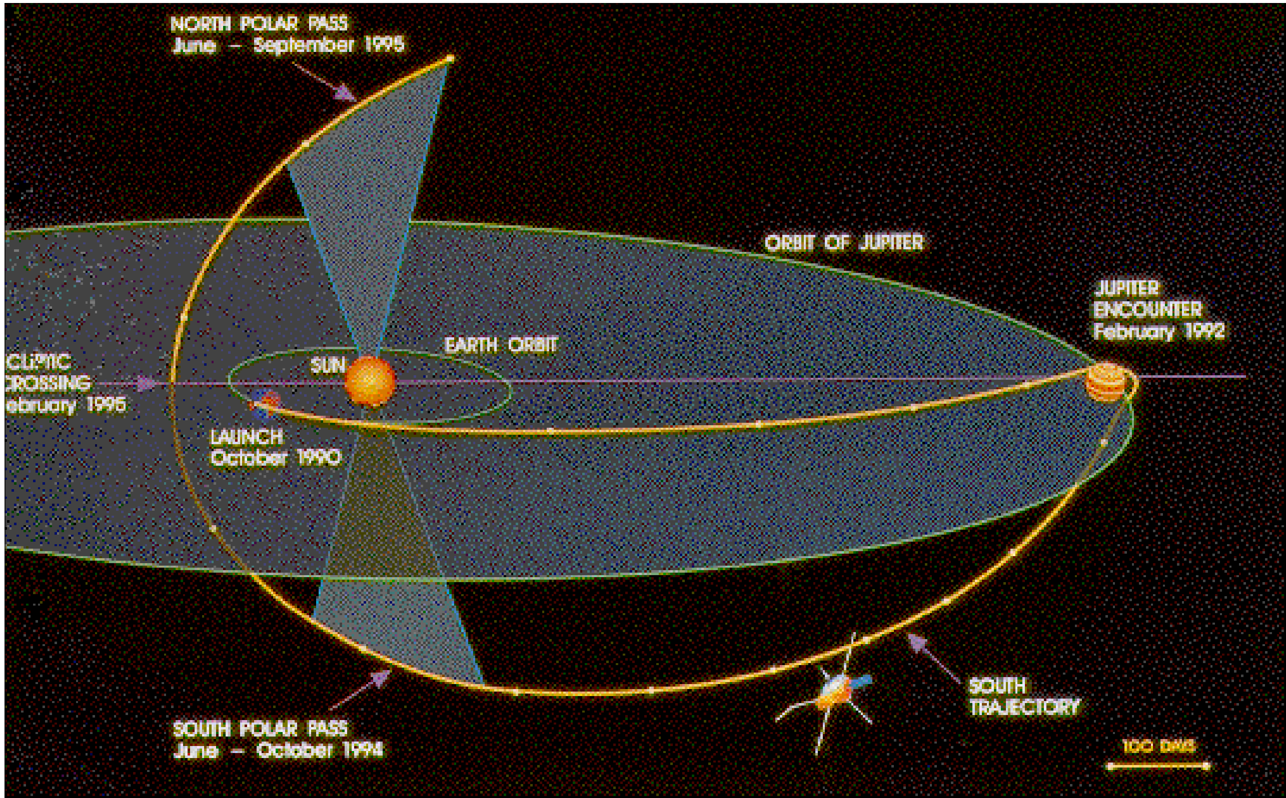


The Voyager missions used multiple gravity assists to visit nearly all the outer planets, which would not have been possible using the on-board propellant alone.

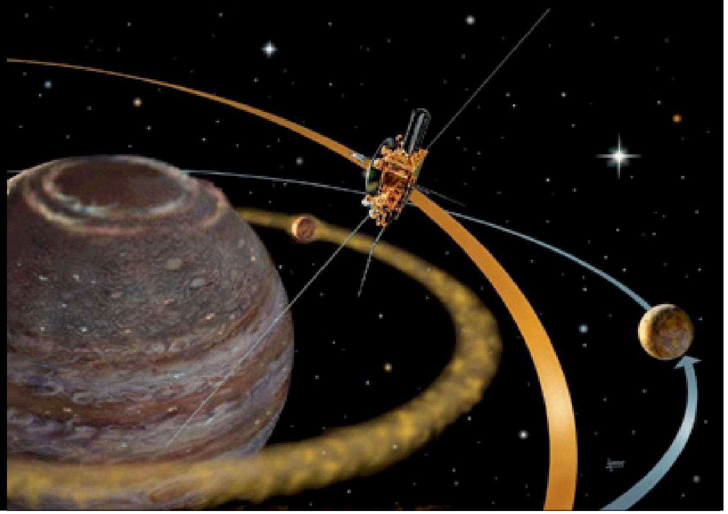


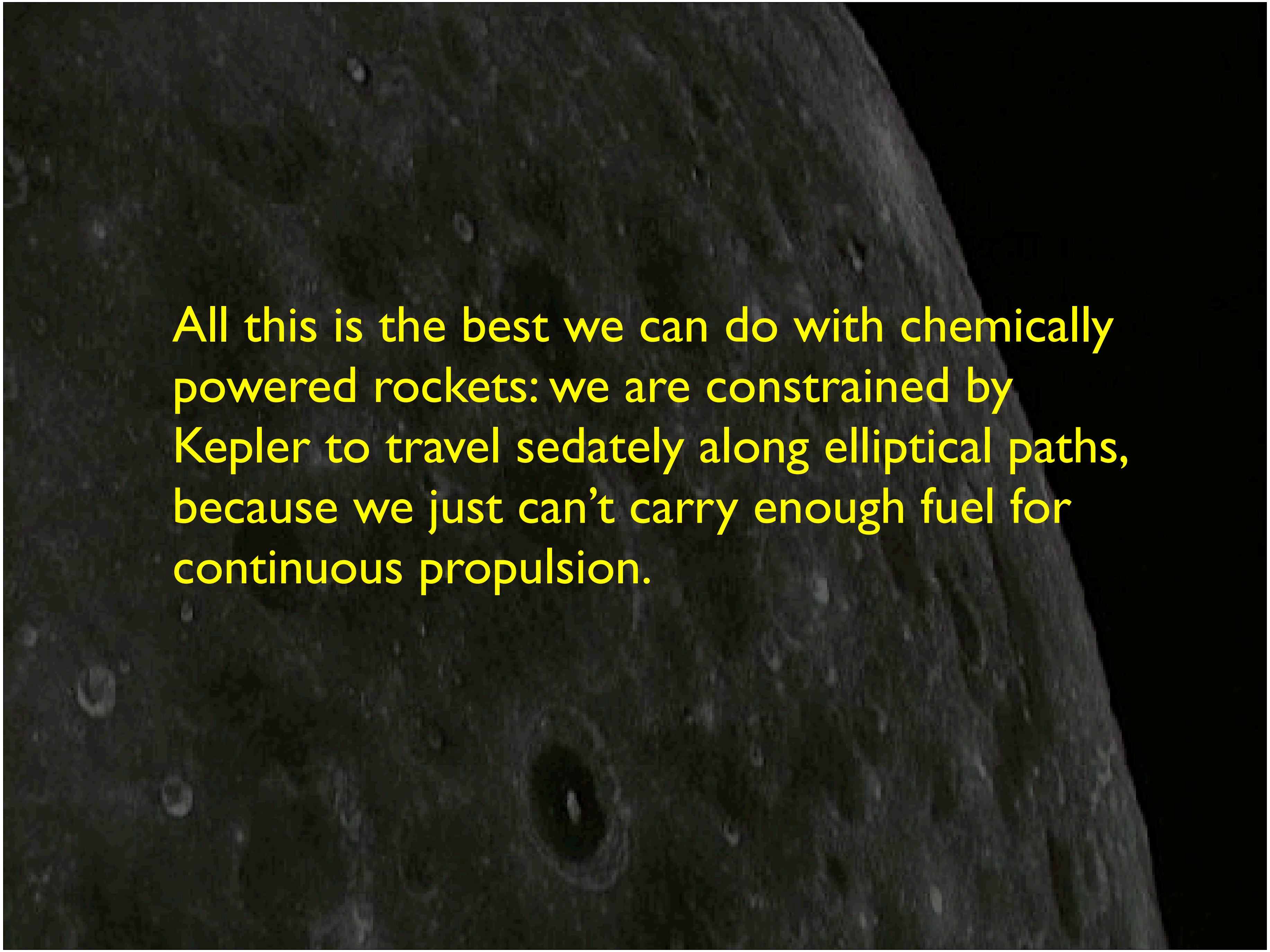
Many other spacecraft have used gravity assists. *Galileo* used a VEEGA trajectory (Venus–Earth–Earth Gravitational Assist) to get to Jupiter.



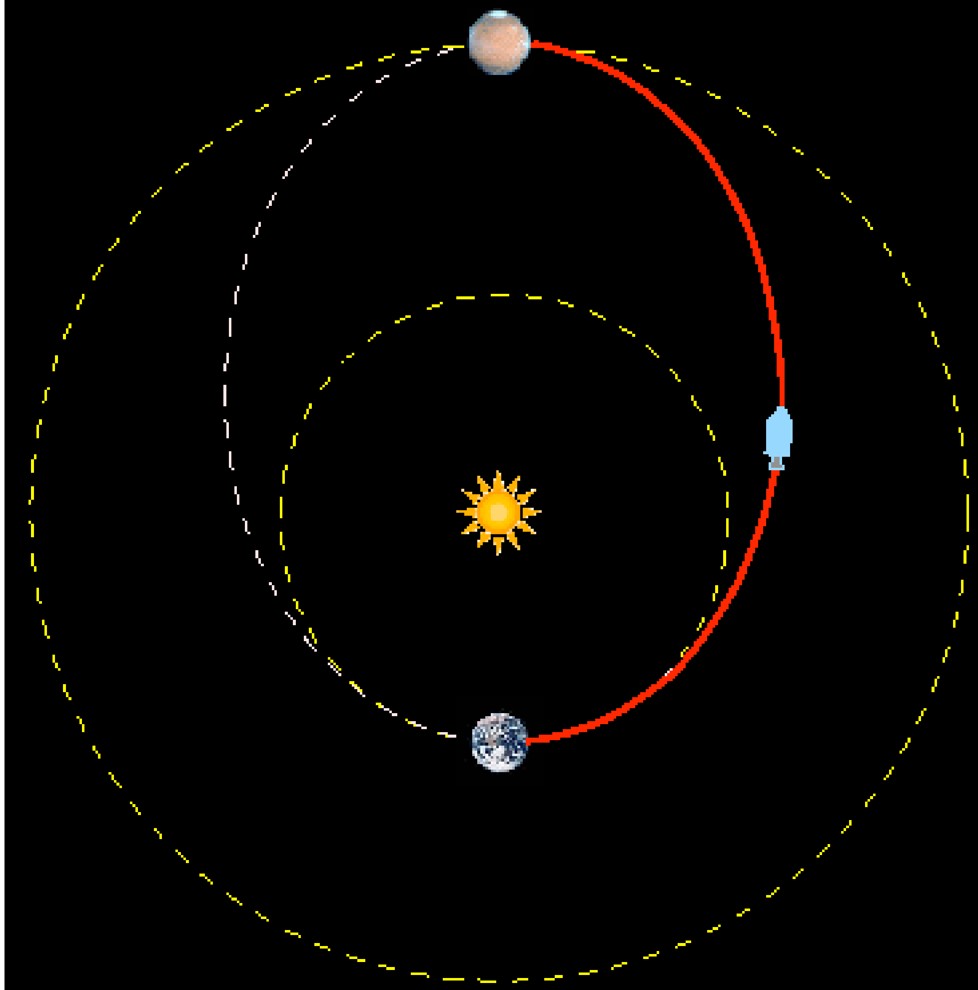


Ulysses used an encounter with Jupiter to swing its orbit out of the ecliptic, thus becoming the first spacecraft to be able to see the poles of the Sun.




All this is the best we can do with chemically powered rockets: we are constrained by Kepler 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.

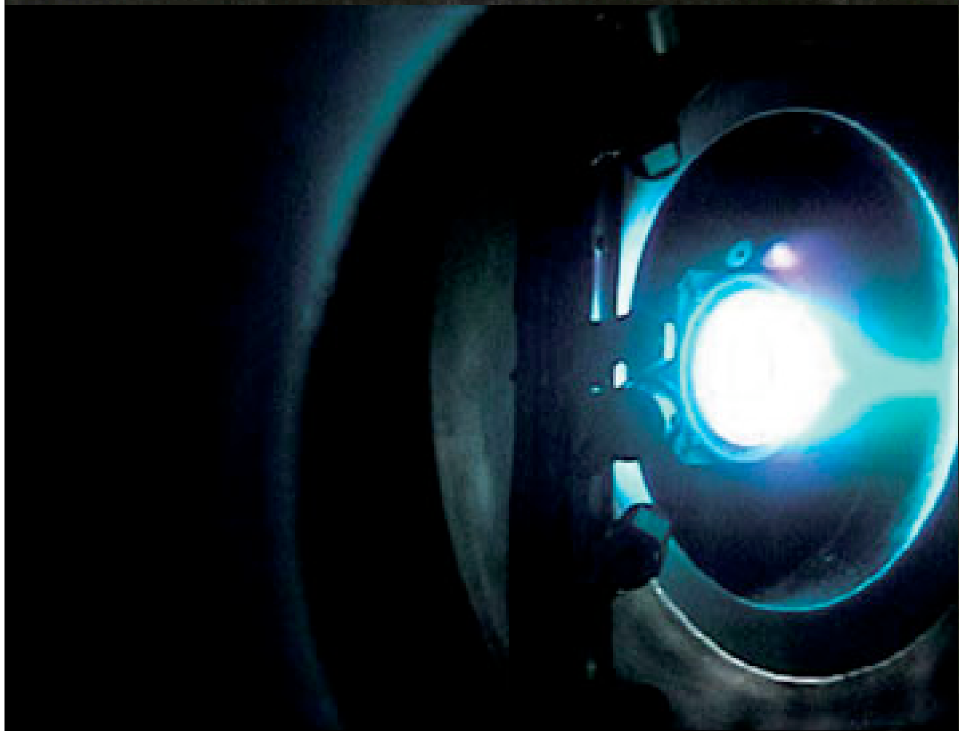


If we could accelerate at just 0.01g, then since we can travel a distance $d = \frac{1}{2}at^2$, we can reach Mars near conjunction in

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

Which is much better than 8 months!

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



The SMART-1 ion engine being test fired.

Next week...

we'll look at the inner planets, Mercury and Venus.

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.
- 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.

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.
- 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.
- **"The Slingshot Effect"** by Bob Johnson has a very thorough discussion of gravity assist techniques: http://www.dur.ac.uk/bob.johnson/SL/

Sources for images used:

- Background image: View of the lunar surface taken from Apollo 8, looking southward from high altitude across the Southern Sea. NASA Photo ID: AS08-12-2192. http://images.jsc.nasa.gov
- 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: from "Inconstant Moon The Moon at Perigee and Apogee" by John Walker http://www.fourmilab.ch/earthview/moon_ap_per.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: the young impact crater Linne, taken by 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
- Orientale: taken Lunar Orbiter 5, http://nssdc.gsfc.nasa.gov/planetary/lunar/lunarorb.html
- Galileo image of Orientale: from the Galileo Legacy Site, http://galileo.jpl.nasa.gov/gallery/earthmoon-moon.cfm
- South Pole-Aitken: Clementine image, from NASA's Solar System Exploration Gallery, 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
- Pre-space flight depictions of the lunar surface: from a 1955 book "Exploring the Moon" by Roy Gallant, illustrated by Lowell Hess. From "Dreams of Space" by John Sisson http://sun3.lib.uci.edu/~jsisson/john.htm
- Lunar surface: AS17-137-21011, from http://images.jsc.nasa.gov/iams/html/pao/as17.htm

- Maria: from an essay on The Grand Canyon and the Moon by Charles R. Cowley http://www.astro.lsa.umich.edu/users/cowley/
- Rotating moon, moon interior: from Views of the Solar System by Calvin J. Hamilton http://www.solarviews.com/eng/moon.htm
- 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
- Throwing balls into orbit: redrawn from "To Rise from Earth" by Wayne Lee, Fig. 1
- Image of Earth: taken by the Apollo 17 crew on the way to the Moon. AS17-148-22727, from NASA Human Spaceflight, http://spaceflight.nasa.gov/gallery/
- All the orbit figures are redrawn from "To Rise from Earth" by Wayne Lee.
- 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/
- 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://btc.montana.edu/ceres/dc/galileo/html/navigate1.html
- Ulysses trajectory: from Ulysses COSPIN home page, http://ulysses.sr.unh.edu/WWW/Simpson/Ulysses.html. Artist's impression of Ulysses at Jupiter: from Ulysses Science: Jupiter Distant Encounter http://ulysses.jpl.nasa.gov/science/jupiter_two.html
- SMART-1 ion engine: from SMART-1: The magic of ion engines, http://www.esa.int/SPECIALS/SMART-1/SEMLB6XO4HD_0.html