Modern Astronomy:
Voyage to the Planets

Presented by
Dr Helen Johnston
School of Physics

Spring 2017

THE UNIVERSITY OF SYDNEY

There is a course web site, at

http://physics.usyd.edu.au/~helenj/VoyagetothePlanets.html

where I will put

- PDF copies of the lectures as I give them
- lecture recordings
- copies of animations
- links to useful sites

Please let me know of any problems!

This course is about the solar system as we know it in the era of planetary probes and space missions.

1. Introduction; the Earth
2. The Moon; Spaceflight
3. The inner planets: Mercury and Venus
4. Mars, the Red Planet
5. Rocks in space: asteroids, comets and meteorites
6. Jupiter
7. Saturn
8. The outer planets: Uranus, Neptune and Pluto
9. Formation of the Solar System
10. Extra-solar planets

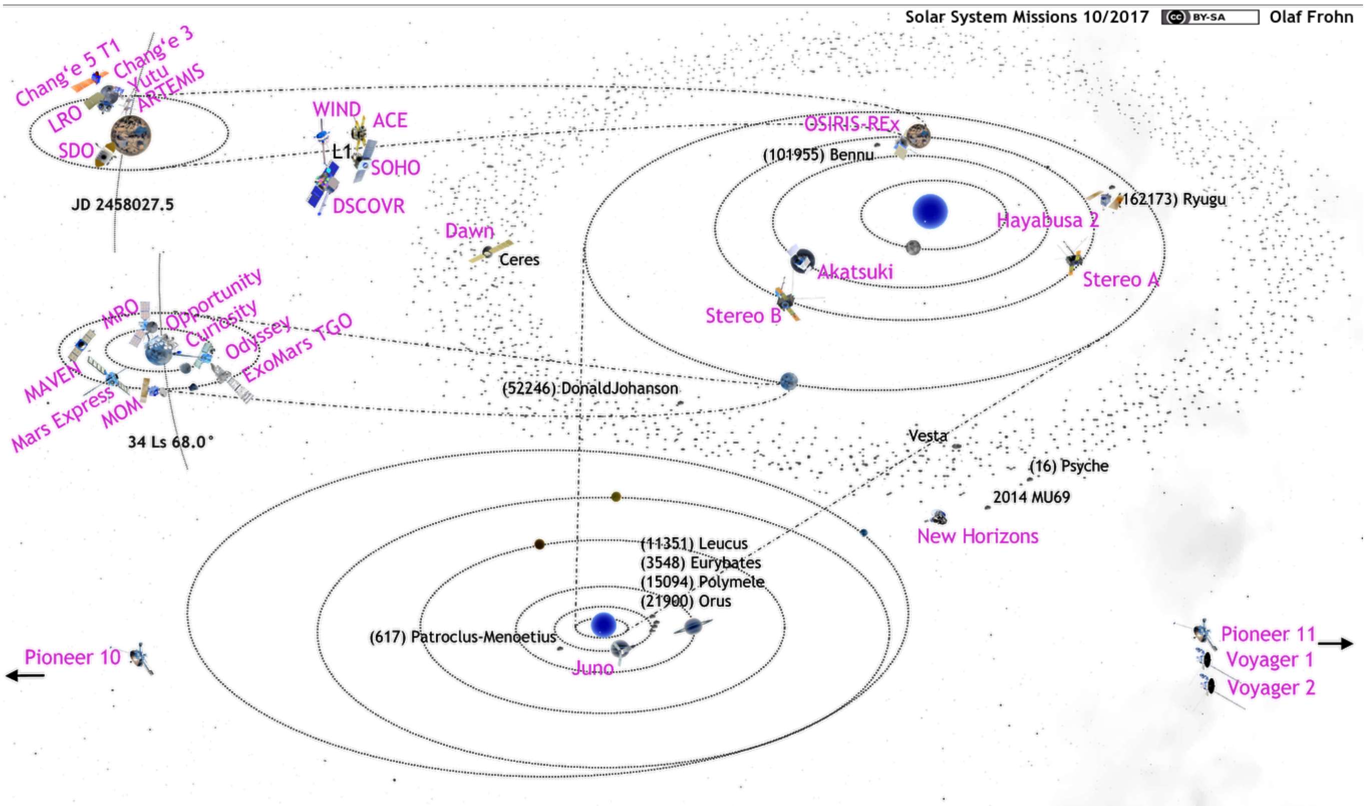
There will be an evening of star viewing in the Blue Mountains, run by A/Prof John O'Byrne on

Saturday 18 November

Details of where to go and how to get there are in a separate handout.

We live in an exciting time to be learning about the Solar System.

There have been dozens of missions in the recent past (though we've recently lost some of the best ones), orbiting Mercury, Venus, Mars, Saturn, and a couple of asteroids and comets, with many more due to be launched in the next few years.


Solar System Missions 10/2017
BY-SA
Olaf Frohn
Chang'e 5 T1
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ARTEMIS
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SOHO
DSCOVR
OSIRIS-REx
(101955) Bennu
(162173) Ryugu
Hayabusa 2
Akatsuki
Stereo A
Stereo B
Dawn
Ceres
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Opportunity
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Odyssey
ExoMars TGO
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(16) Psyche
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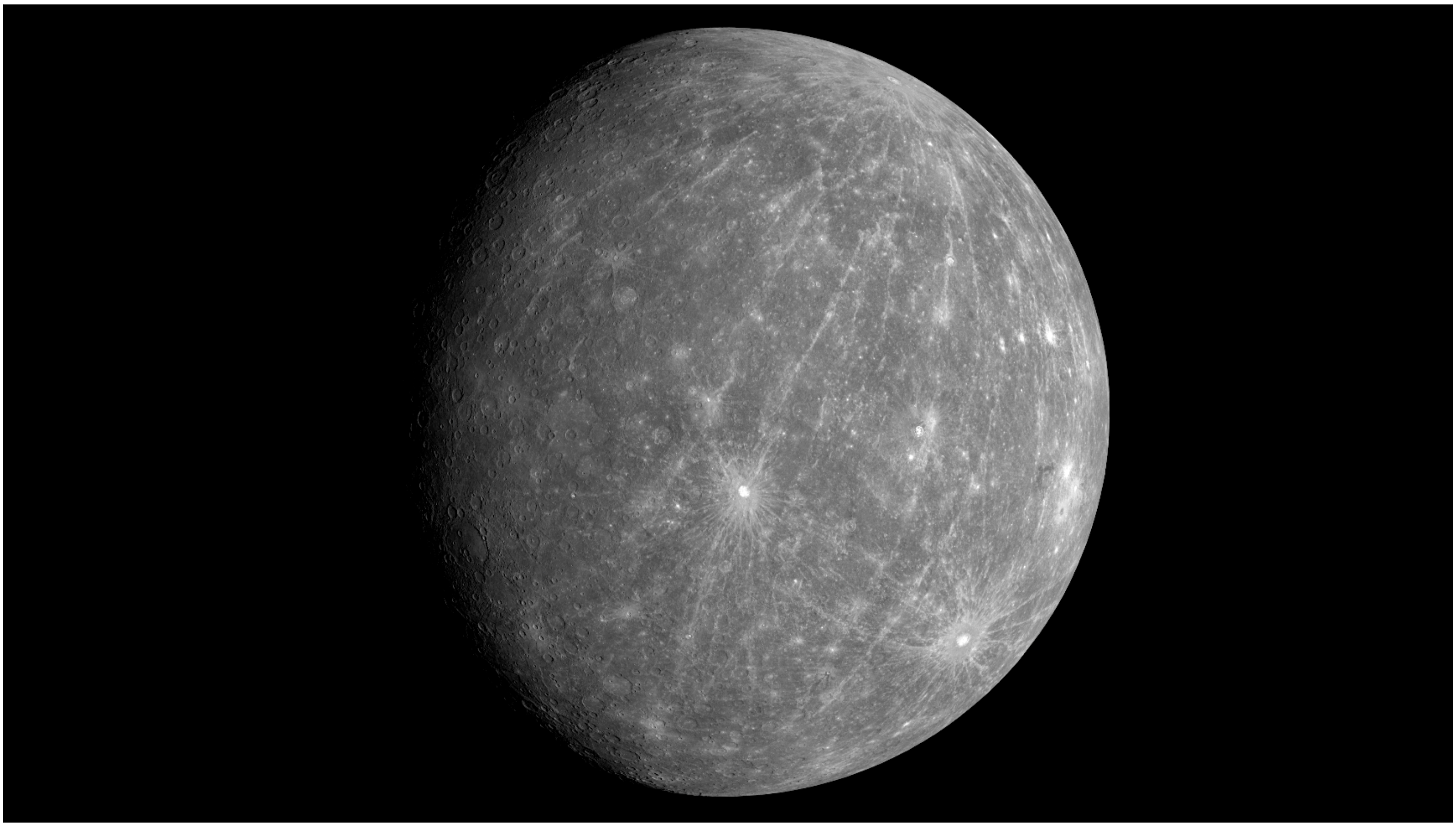
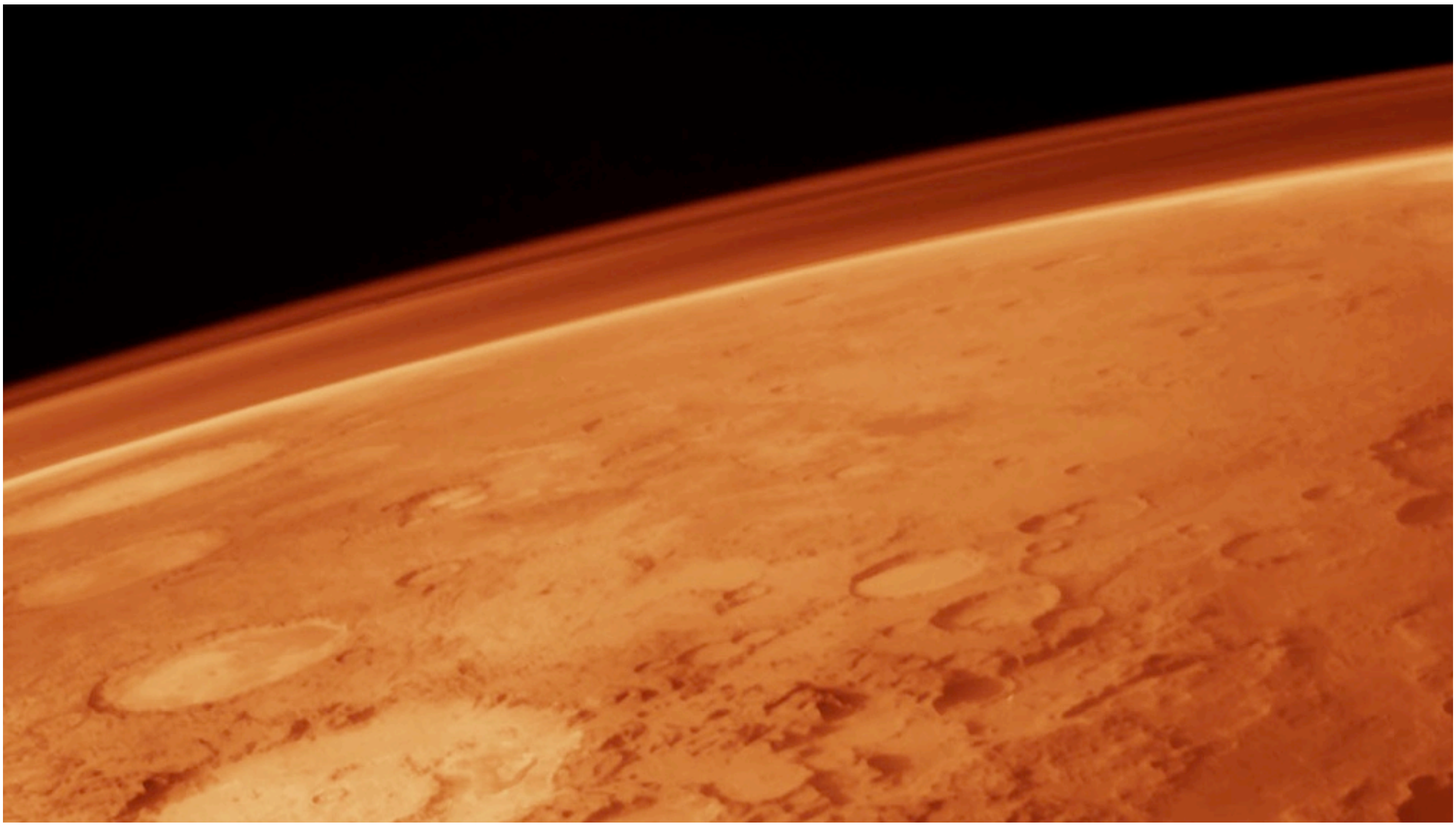
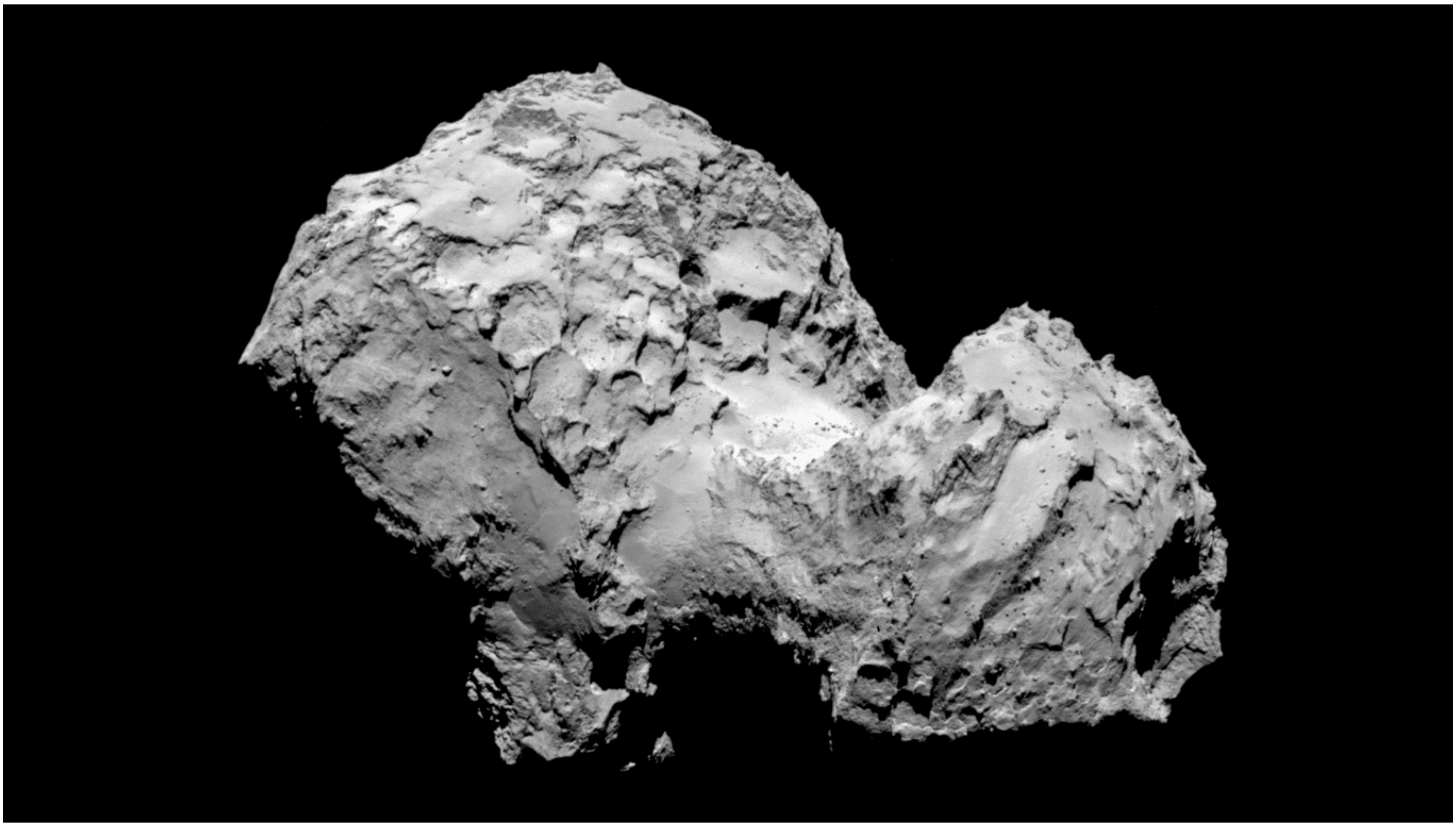
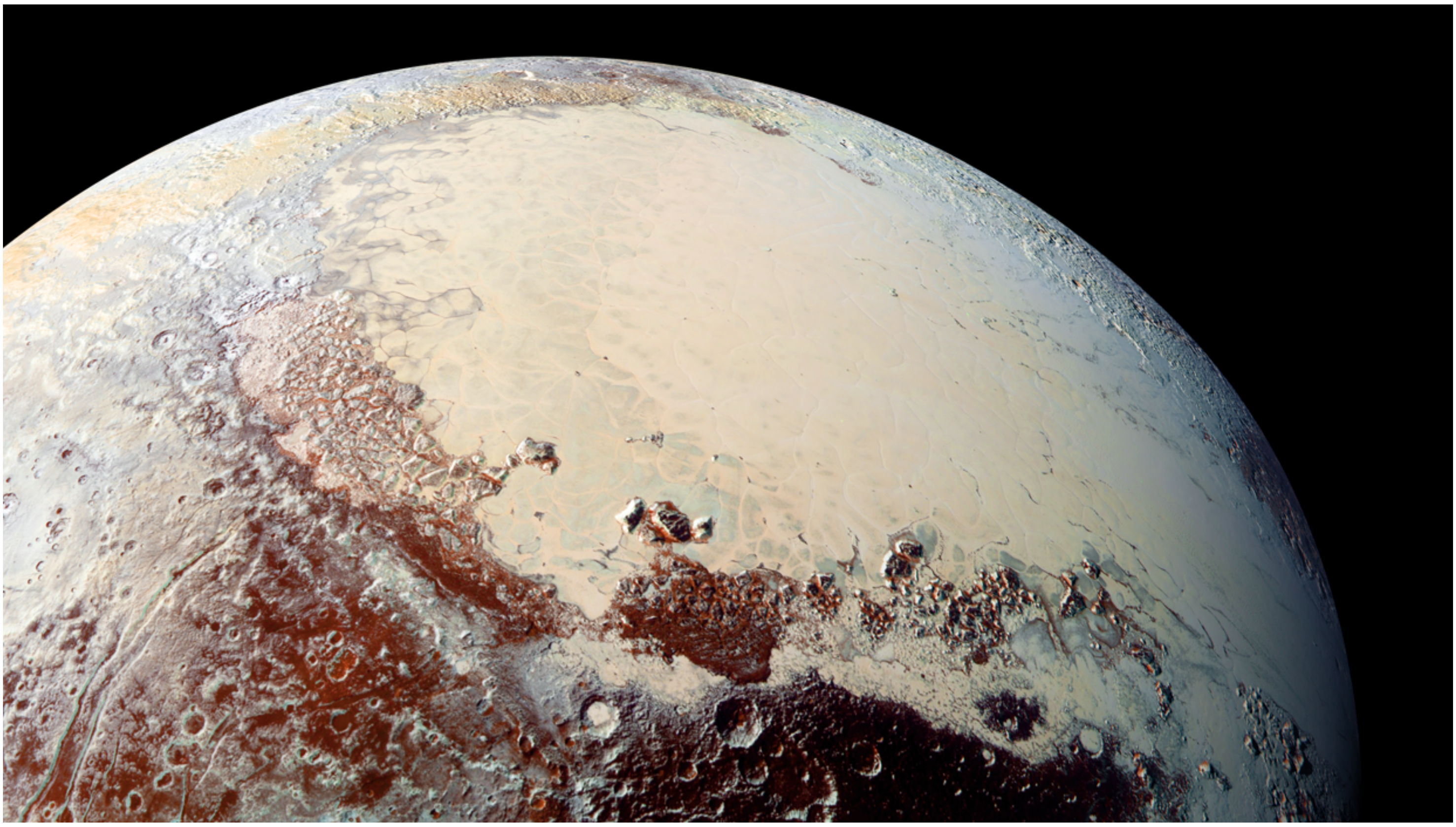
New Horizons
(11351) Leucus
(3548) Eurybates
(15094) Polymele
(21900) Orus
(617) Patroclus-Menoetius
Juno
Pioneer 10
Pioneer 11
Voyager 1
Voyager 2







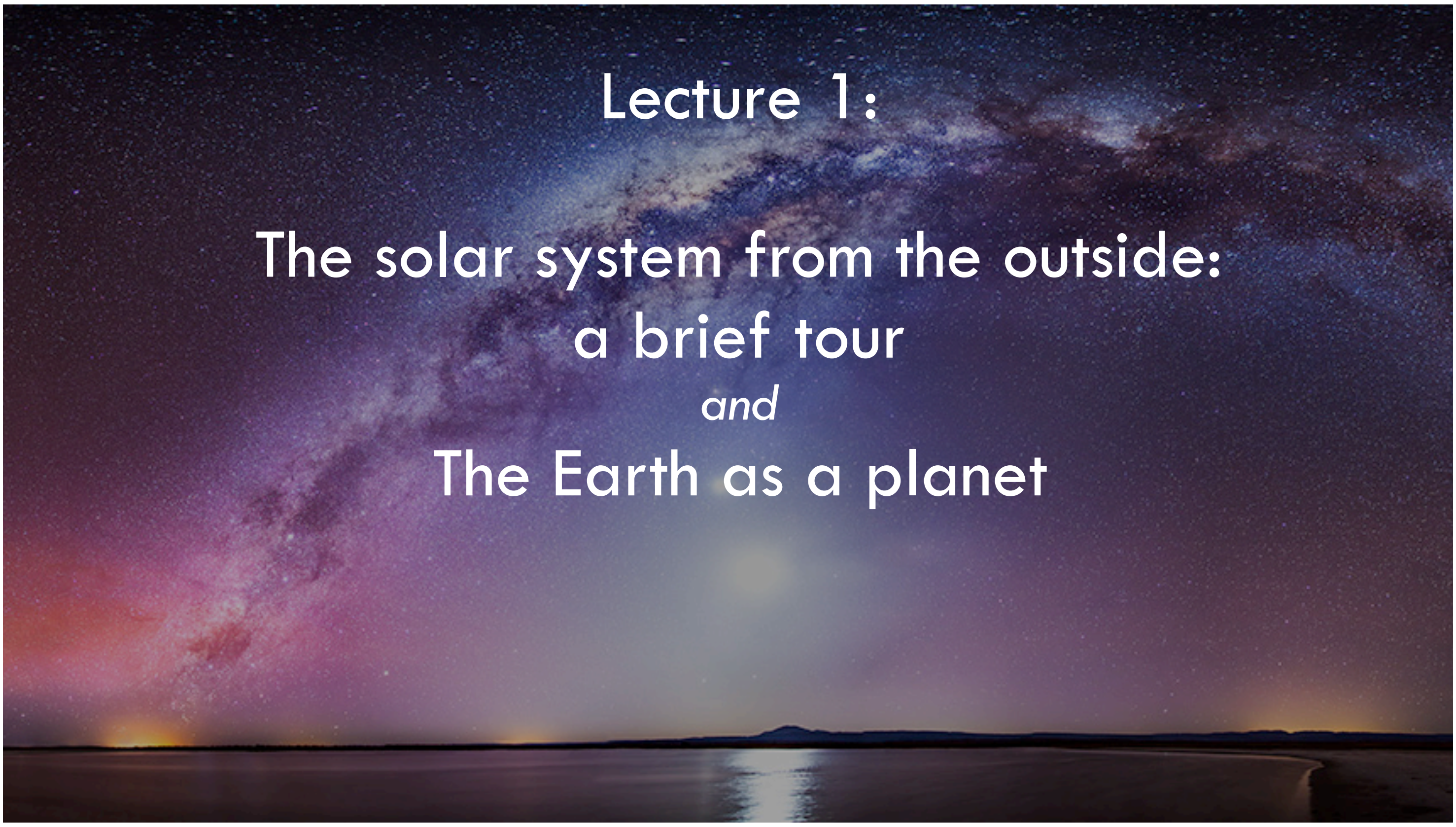


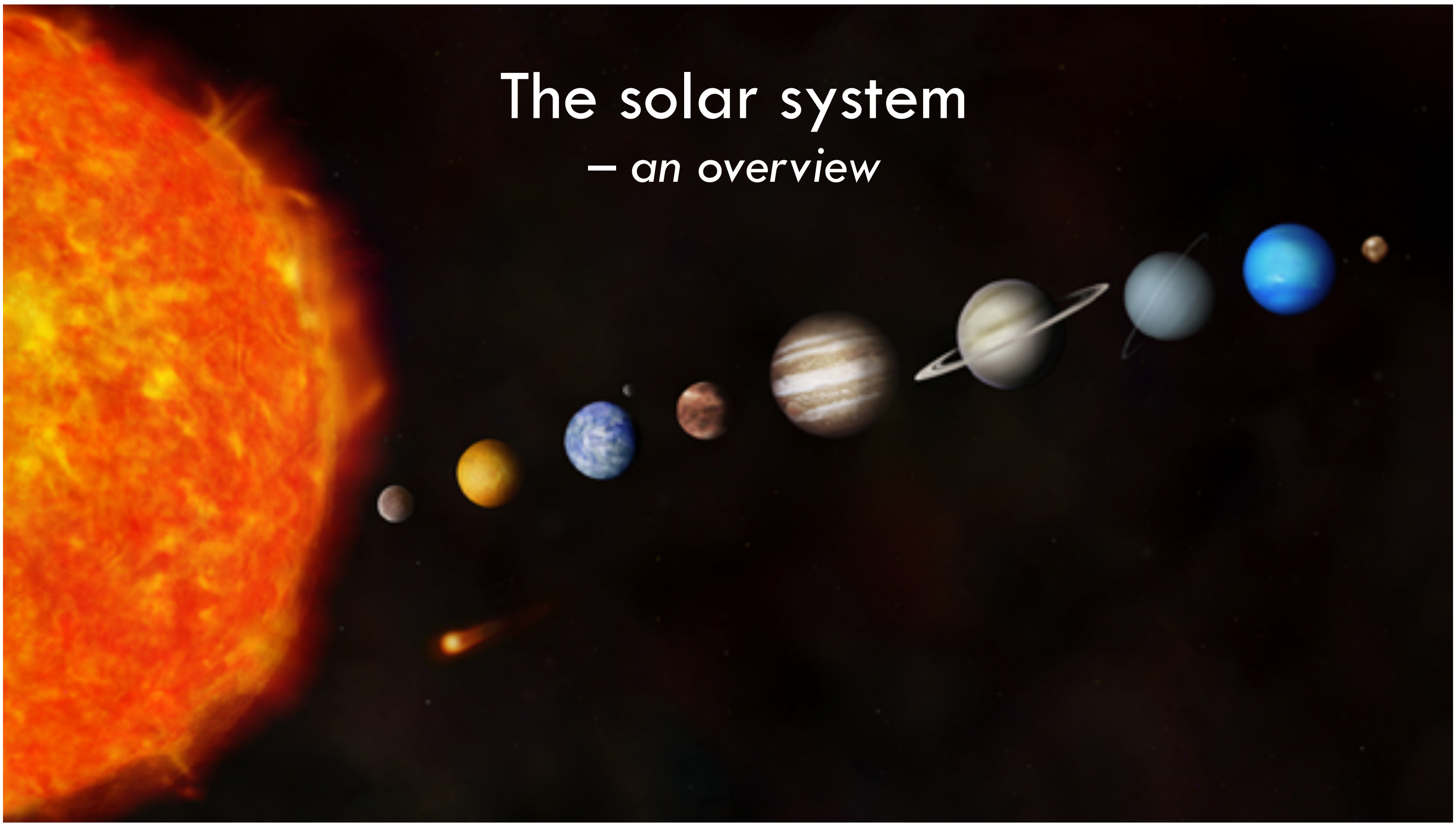
Nearly everything we know about the planets we have learned in the past four decades, in which we launched spacecraft to every planet. In this course, I want to give you some flavour of what these extraordinary expeditions have learned, how they did it, and what we might expect in the not-too-distant future.

Tonight

A quick overview

- The solar system from the outside: a brief tour
- The Earth as a planet

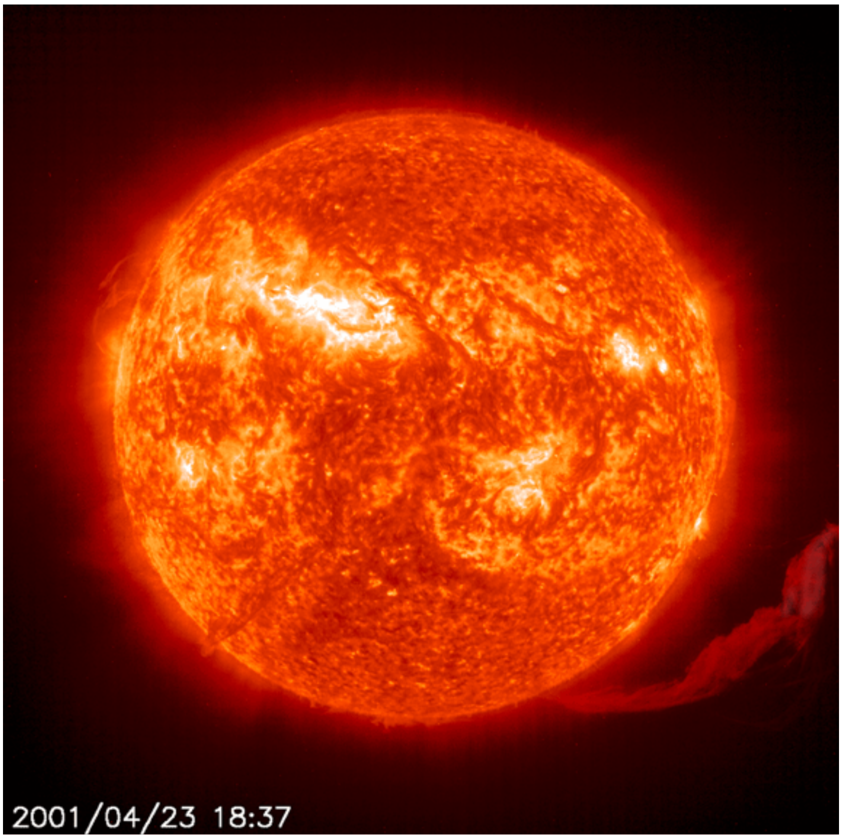


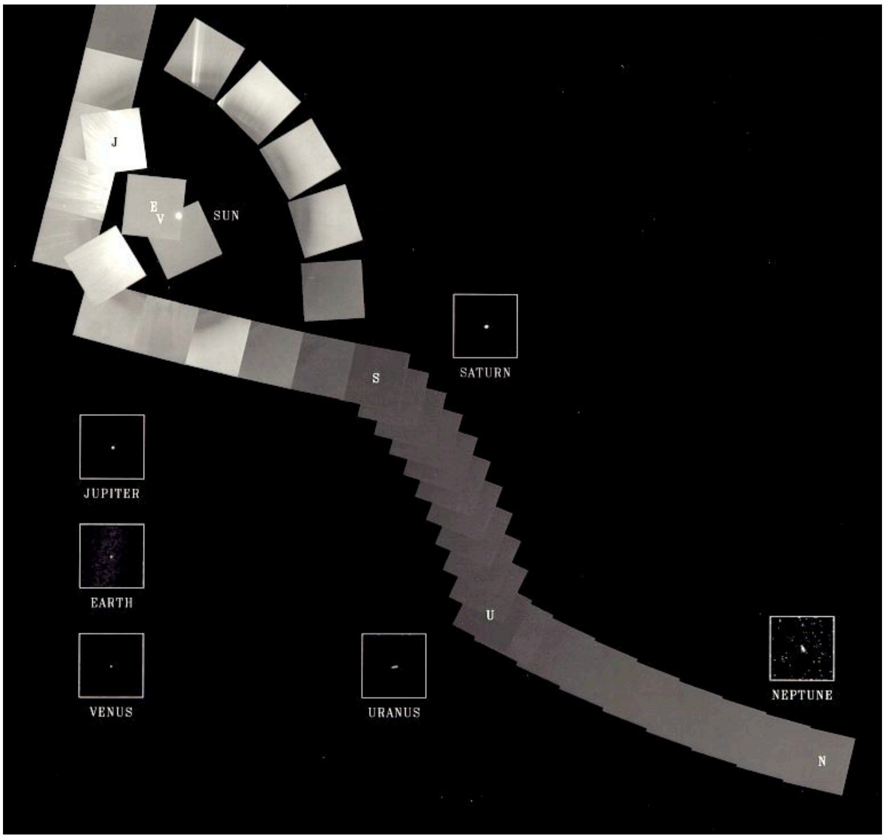


The Sun, a G2 star, contains over 99.8% of the mass of the solar system.

To very good approximation, the solar system consists of the Sun plus some debris.

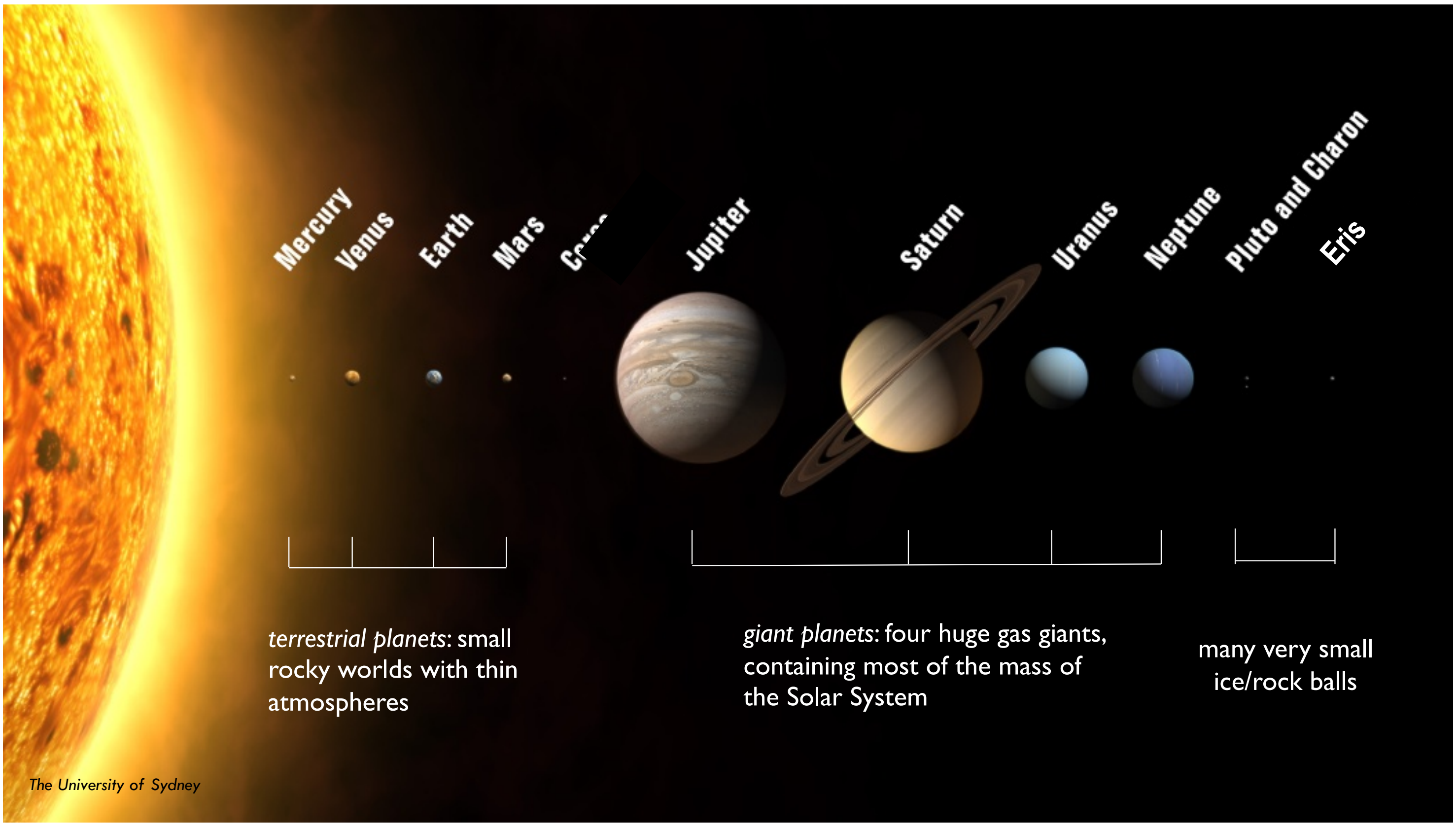
To second approximation, the solar system consists of the Sun plus Jupiter plus some debris.





There are eight planets orbiting the Sun, plus a multitude of smaller worlds.

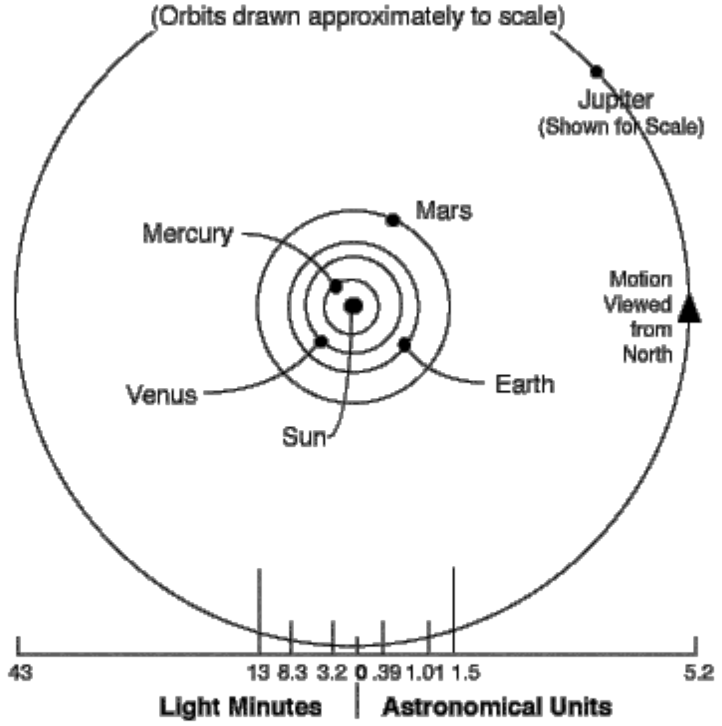
Portrait of the Solar System taken by Voyager 1 on 14 February 1990

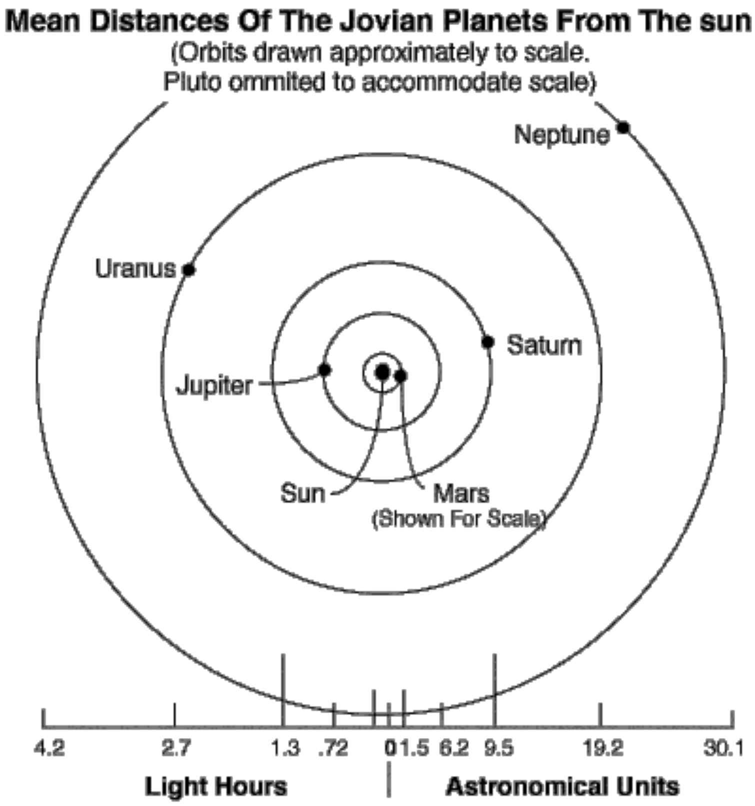


	Mercury	Venus	Earth	Mars	Jupiter	Saturn	Uranus	Neptune	Pluto
Mean distance (AU)	0.387	0.723	1	1.52	5.2	9.58	19.2	30.05	39.24
Orbital inclination (°)	7	3.4	0	1.9	1.3	2.5	0.8	1.8	17.2
Orbital eccentricity	0.205	0.007	0.017	0.094	0.049	0.057	0.046	0.011	0.244
Diameter (km)	4,879	12,104	12,756	6,794	142,984	120,536	51,118	49,528	2,390
Mass (Earth=1)	0.0553	0.815	1	0.107	317.8	95.2	14.5	17.1	0.0021
Density (g/cm3)	5.43	5.24	5.52	3.93	1.33	0.69	1.27	1.64	1.75
Surface gravity	0.378g	0.907g	1g	0.377g	2.36g	0.916g	0.889g	1.12g	0.059g
Rotation period	58.65 d	–243 d	23h 56m	24h 37m	9h 56m	10h 40m	17h 14m	16h 6m	6d 9h
Length of day	175.9d	116.8d	24h	24h 42m	9h 56 m	10h 40m	17h 14m	16h 6m	6d 9h
Length of year	88.0 d	224.7 d	365.2 d	687.0 d	11.9 y	29.4 y	83.7 y	163.7 y	248.0 y
Number of moons	0	0	1	2	63	33	27	13	4
Atmosphere	Almost none	CO_2	Nitrogen Oxygen	CO_2	Hydrogen Helium	Hydrogen Helium	Hydrogen Helium Methane	Hydrogen Helium Methane	None (?)
Space missions	Mariner 10	Mariner 2,5 Mariner 10 Venera Vega 1 Vega 2 Pioneer Venus Magellan		Mariner 4,6 Mars 2,3 Mariner 7,9 Mars 5,6 Viking 1,2 Phobos Pathfinder Global Surveyor Mars Express	Pioneer 10 Pioneer 11 Voyager 1 Voyager 2 Galileo	Pioneer 11 Voyager 1 Voyager 2 Cassini	Voyager 2	Voyager 2	New Horizons

Mean Distances Of The Terrestrial Planets From The Sun

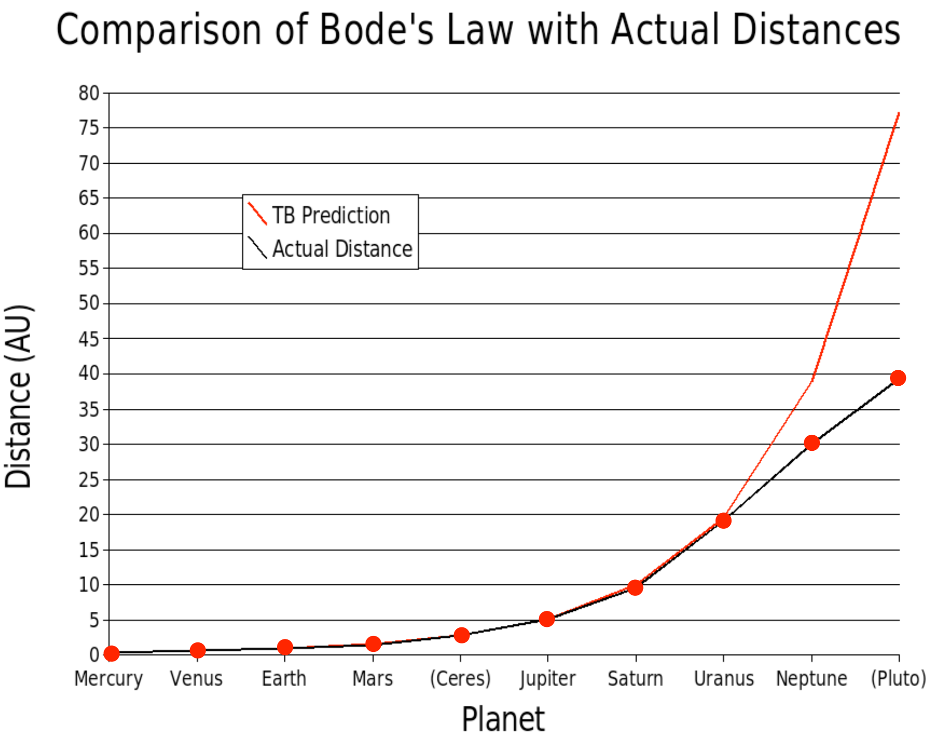
(Orbits drawn approximately to scale)



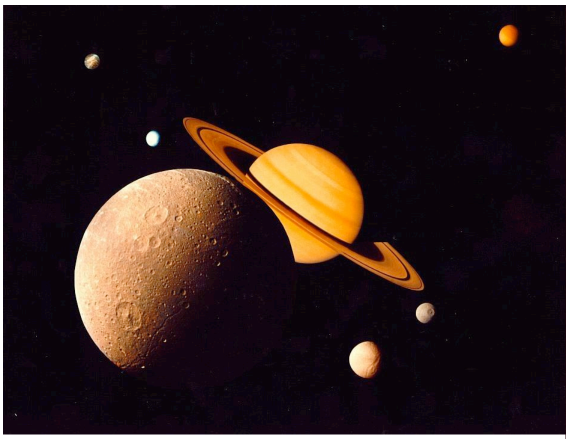


In 1766, Johann Titius proposed an empirical rule for the distances of the planets from the Sun, popularised by Johann Bode. Take the series 0, 3, 6, 12, 24, 48... then add 4 and divide by 10. The answers approximate rather well most of the distances of planets in AU from the Sun:

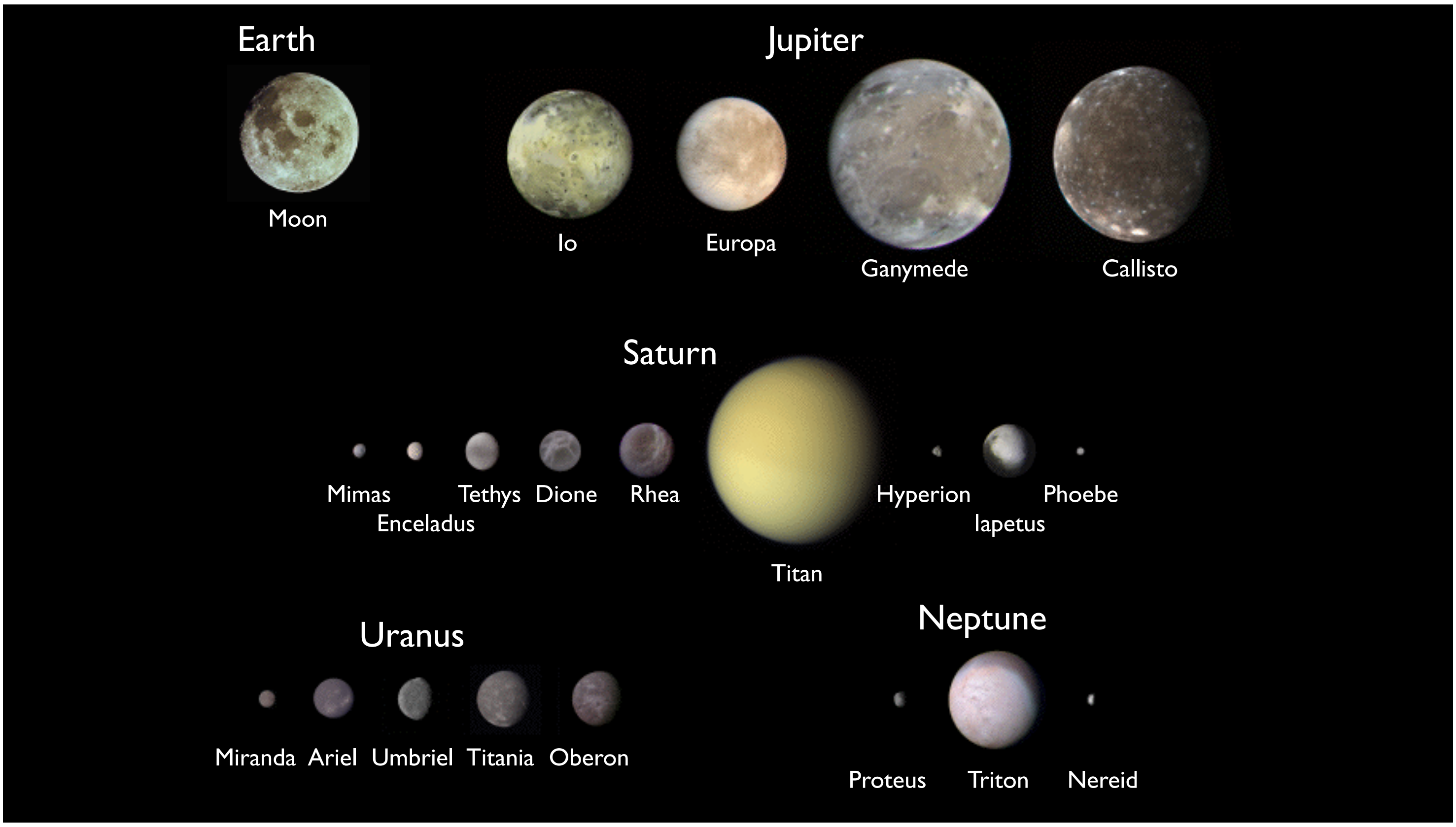
	Distance (AU)	Bode-Titius rule	
Mercury	0.39	0.3	
Venus	0.72	0.7	
Earth	1	1	
Mars	1.52	1.6	
(Ceres)	(2.77)	2.8	1801
Jupiter	5.2	5.2	
Saturn	9.54	10	
Uranus	19.2	19.6	1781
Neptune	30.1	38.8	1834
Pluto	39.5	77.2	1930



Moons



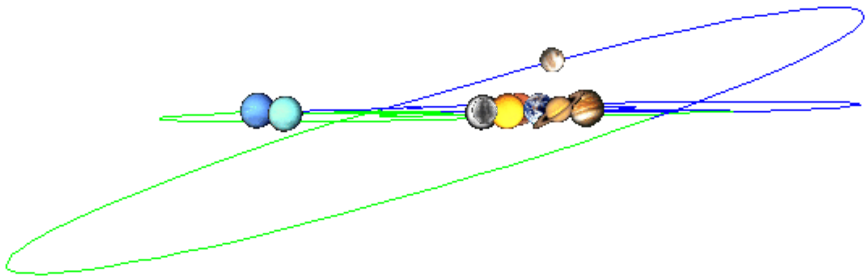
Most of the planets (all except Mercury and Venus) have moons in orbit around them. The giant planets all have large satellite systems, consisting of several large- and medium-size moons, as well as many smaller moons and rings.



The largest of these satellites are larger than some of the planets.

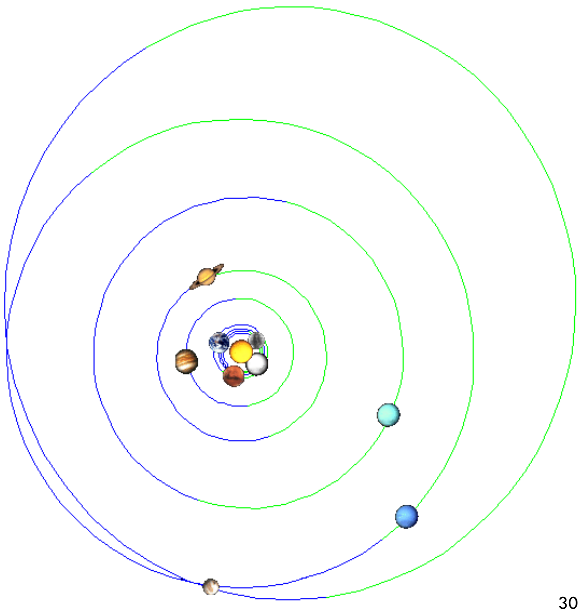
Co-planar orbits

All the planets (except Pluto) orbit in the same direction and in the same plane (the *ecliptic*), to within 6°.



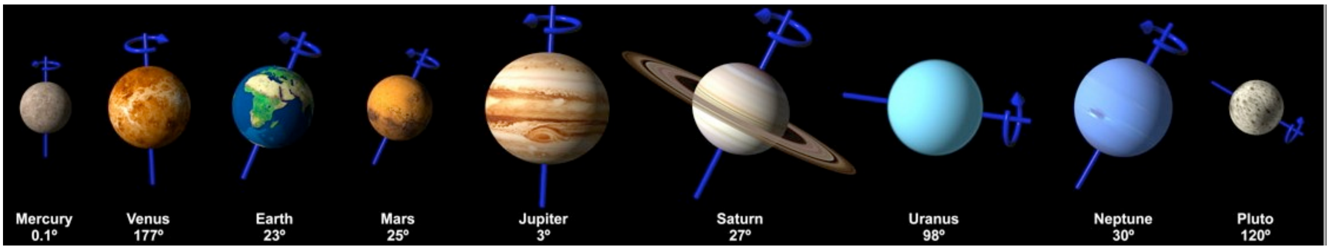
Circular orbits

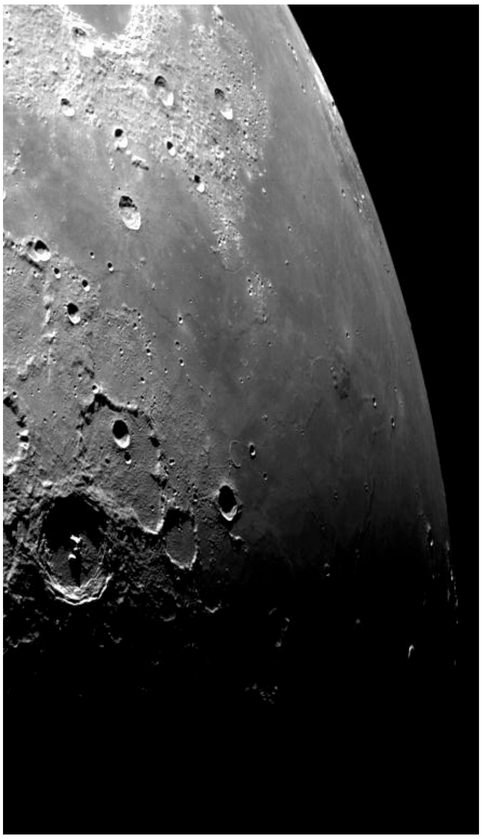
All the planets (except Pluto) have almost circular orbits.



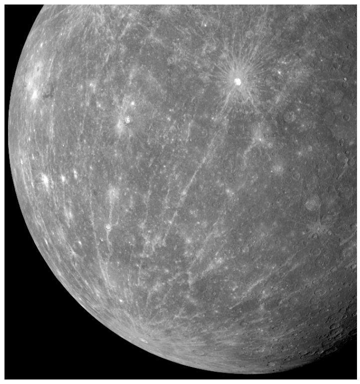
Prograde orbits

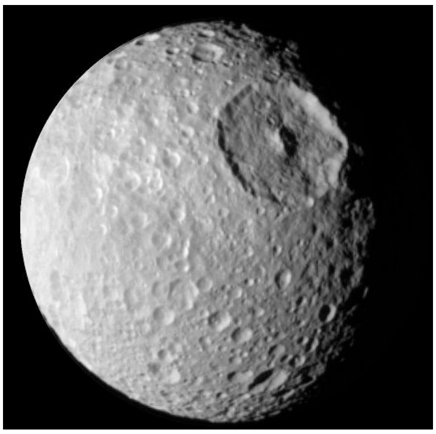
All the planets go around the Sun in the same direction. Most moons go around their primaries in the same direction, and most (but not all) of the planets spin in the same direction as well.

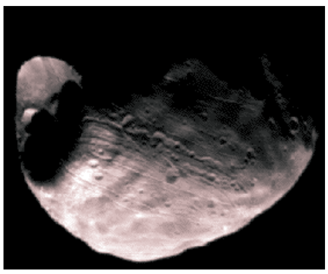




Most planets and satellites show large numbers of impact craters, far more than could be produced over the age of the Solar System at current impact rates.







The Moon, Mercury, Phobos and Mimas

We'll revisit these facts later, when we look at how the Solar System formed: they are important clues for theories of its formation.

In the meantime, let's take a look at the very nearest member of the Solar System.

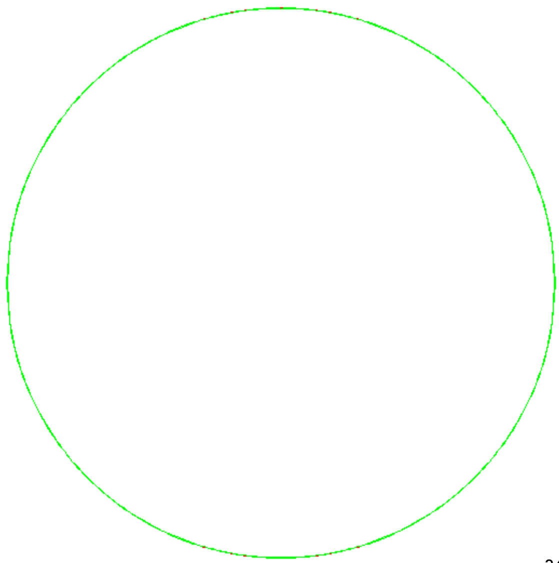
The Earth as a planet

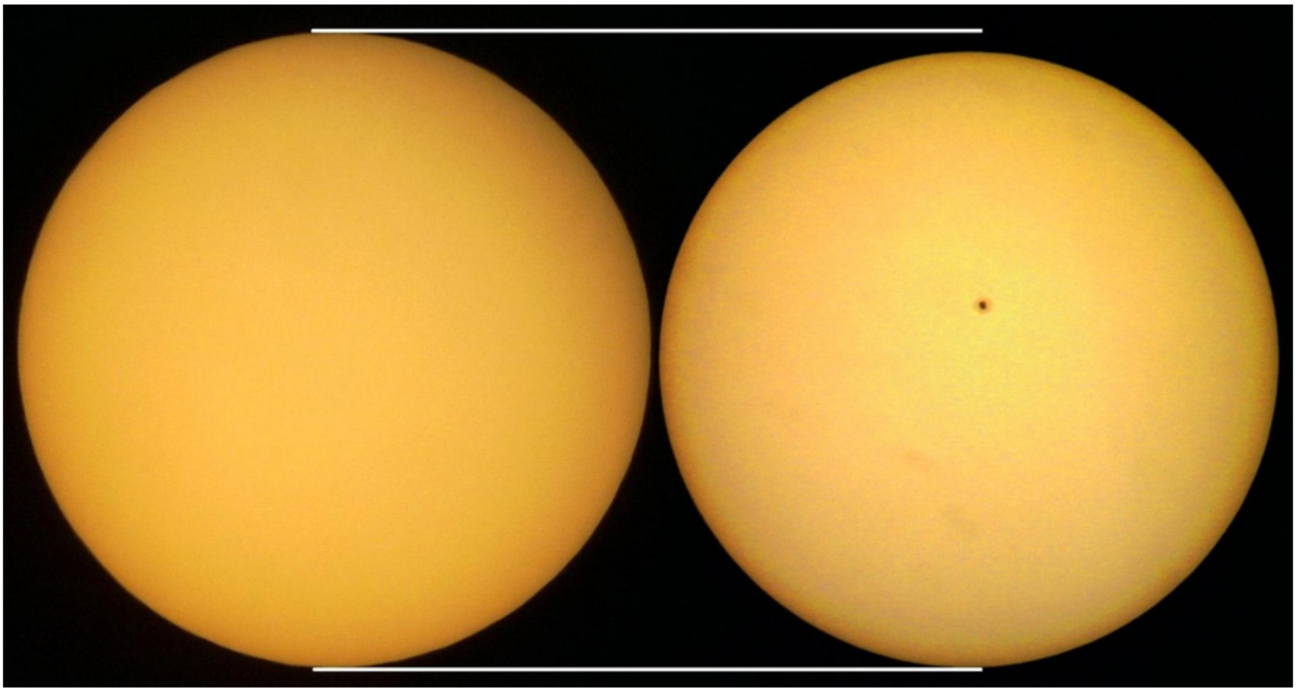
Basic data

	Earth
Mass	5.9736×10^{24} kg
Radius	6378.1 km
Mean density	5.515 g/cm^3
Gravity	9.798 m/s^2
Semi-major axis	149.60×10^6 km
Period	365.256 d
Orbital inclination	0.0^{o}
Orbital eccentricity	0.0167
Rotation period	23.9345 h
Length of day	24.0000 h

The Earth's orbit is nearly but not quite circular: the eccentricity is 1.67%, which is essentially indistinguishable from a circle.

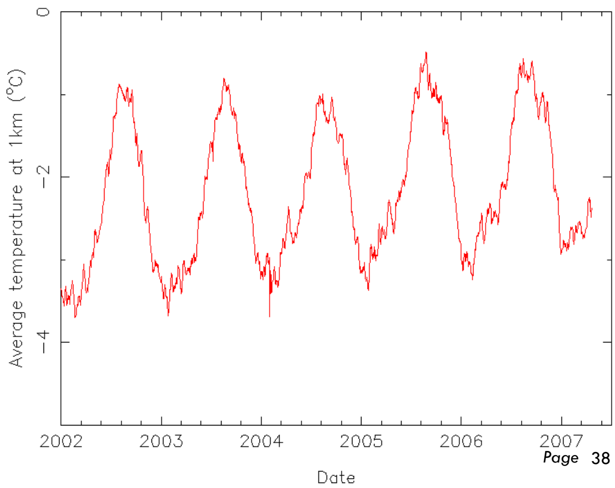
At closest approach (*perihelion*) the Earth–Sun distance is 147.5 million km; at furthest approach (*aphelion*) the distance is 152.6 million km.



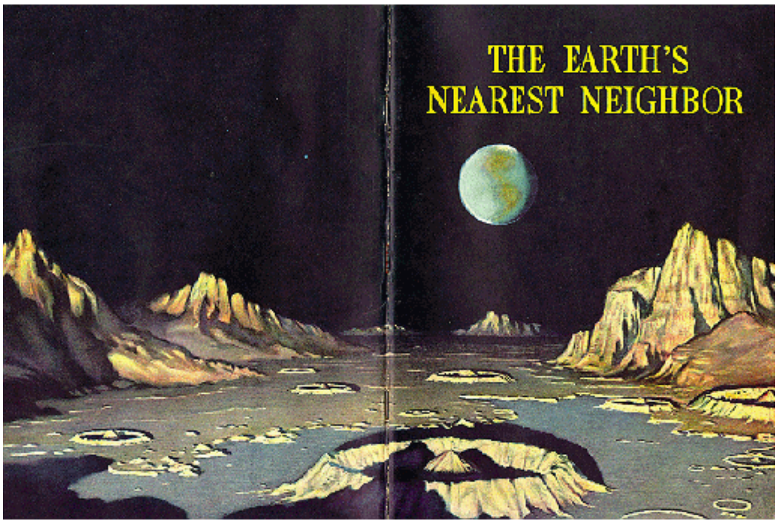


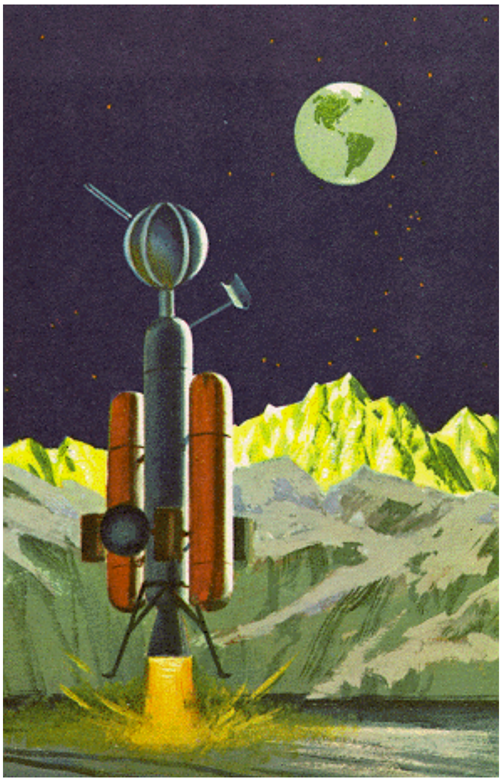
Size of the Sun at perihelion (January) and aphelion (July)

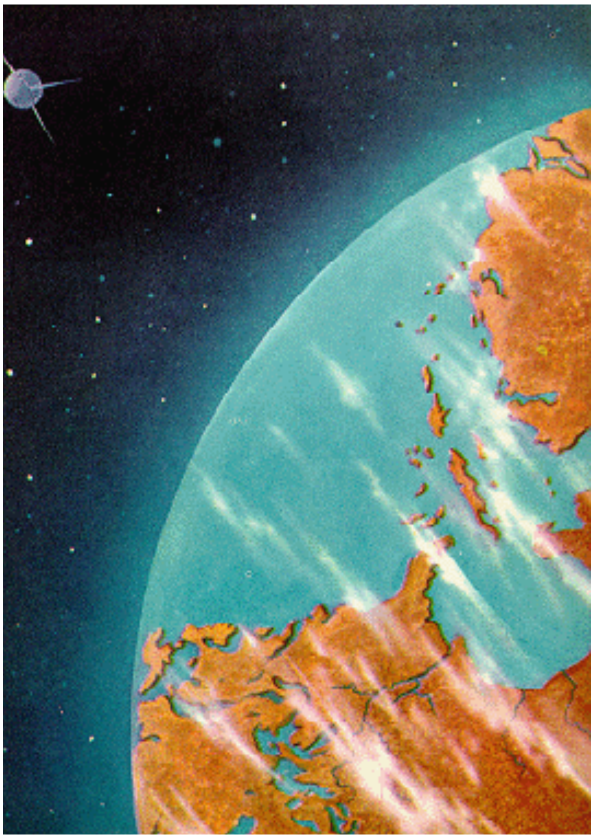
Perihelion occurs in Southern hemisphere summer. The amount of sunlight received is 7% less at aphelion than perihelion.
But the average temperature of the whole Earth at aphelion is about 2.3° C higher than it is at perihelion. Because of the difference in speed, northern summers are 2–3 days longer than southern ones.



Pre-space age depictions of Earth invariably described or depicted the planet as "blue-green".

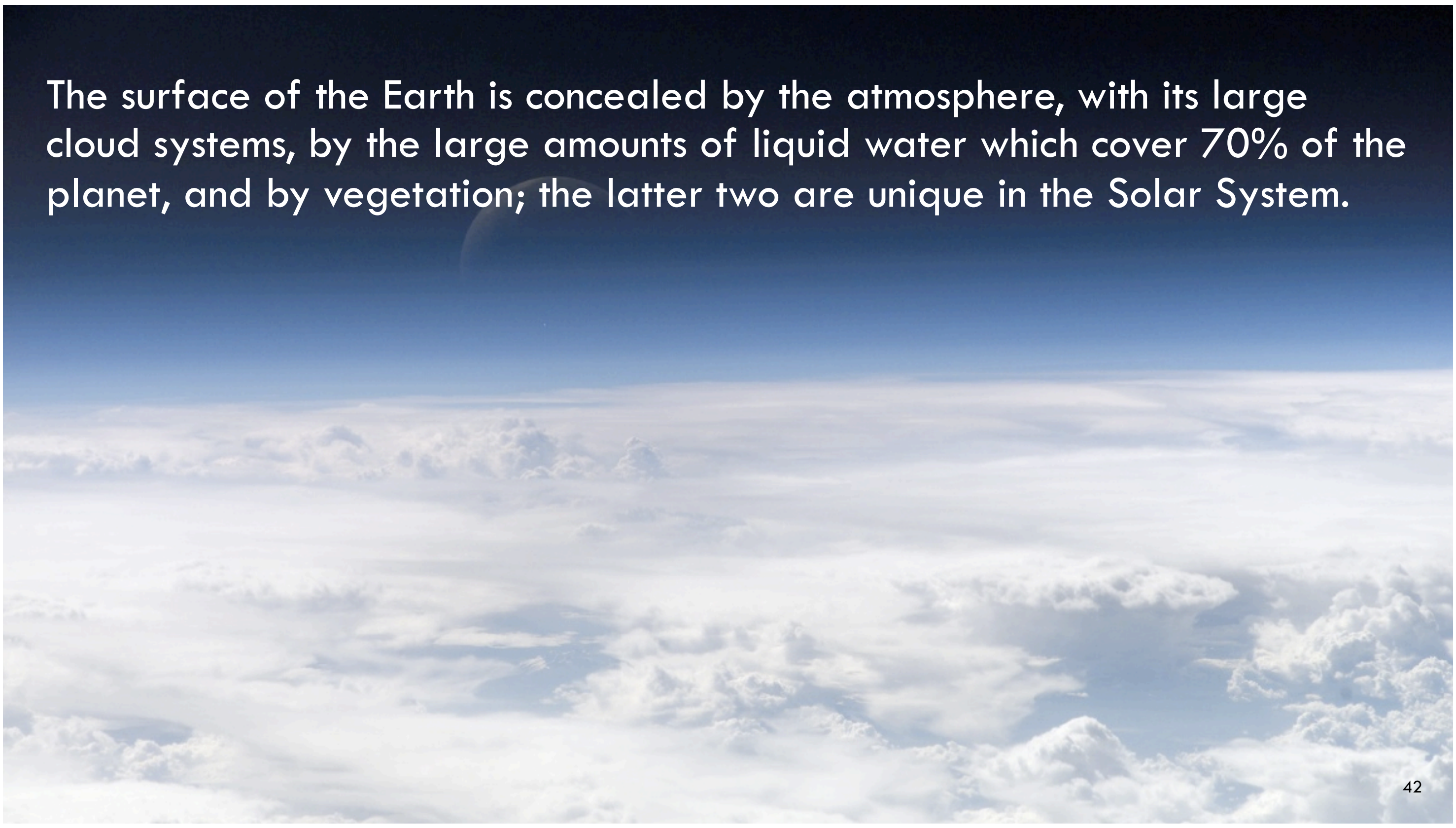




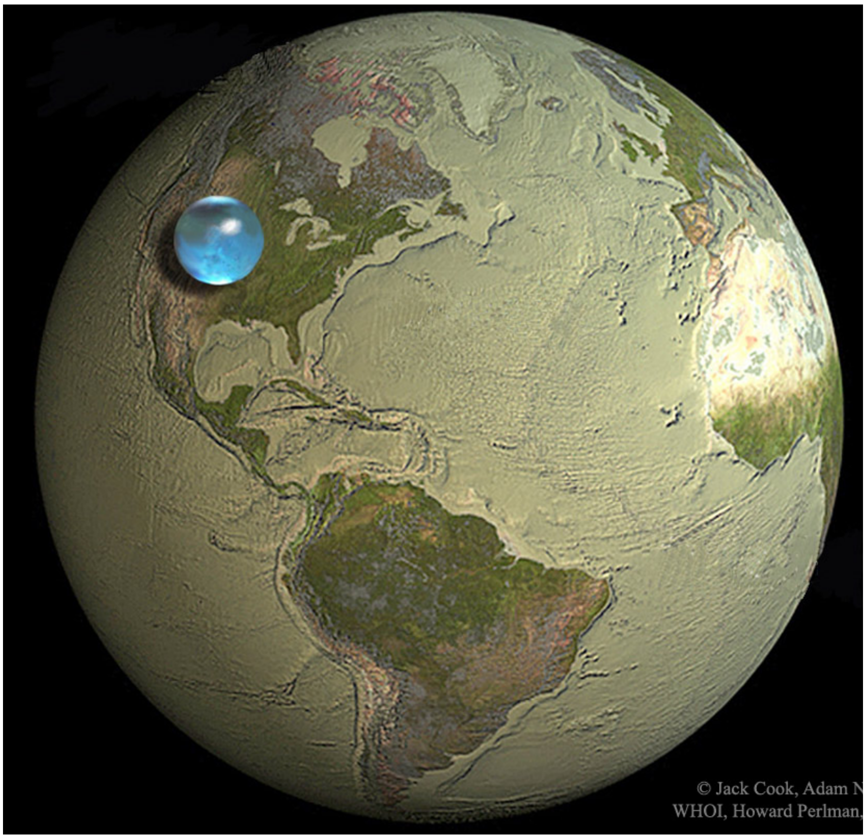


If they showed clouds at all, it was the small, wispy variety.

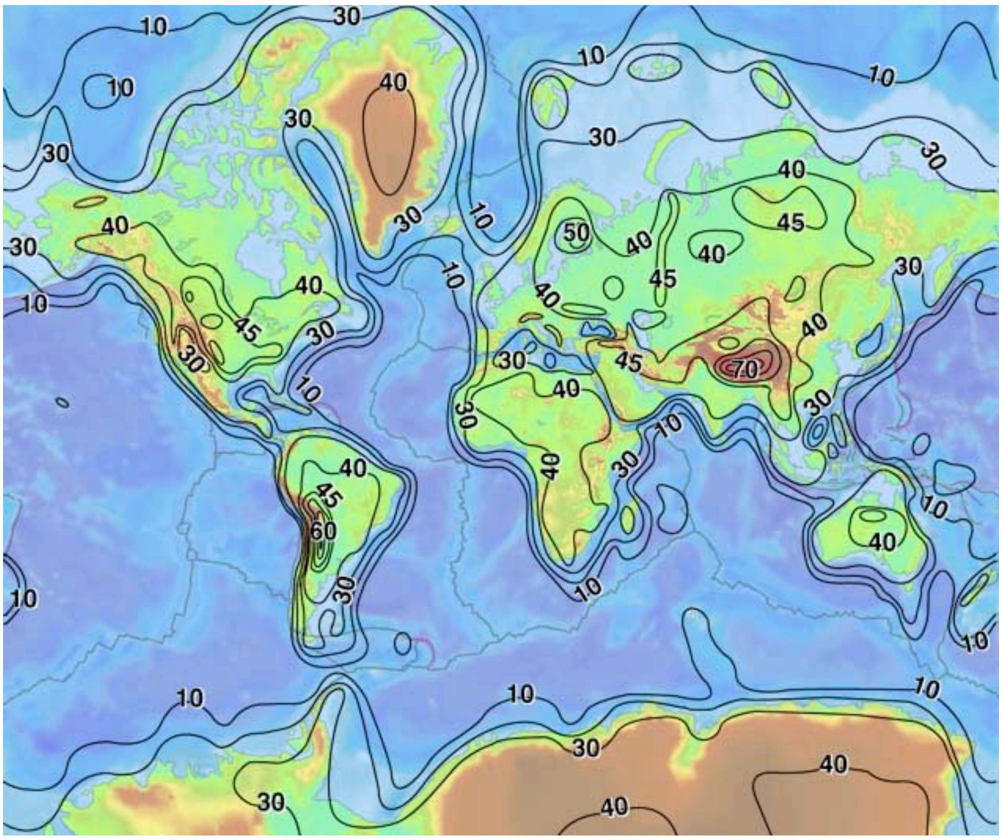
No-one seems to have imagined the continent-spanning cloud that is common-place, or anticipated that the Earth from space is far more *blue-white* than *blue-green.*


The surface of the Earth is concealed by the atmosphere, with its large cloud systems, by the large amounts of liquid water which cover 70% of the planet, and by vegetation; the latter two are unique in the Solar System.

Though oceans cover 70% of the planet, the total amount of water is small. Collected together, all the Earth's water would form a sphere about 1400 km in radius, less than half the size of the Moon.

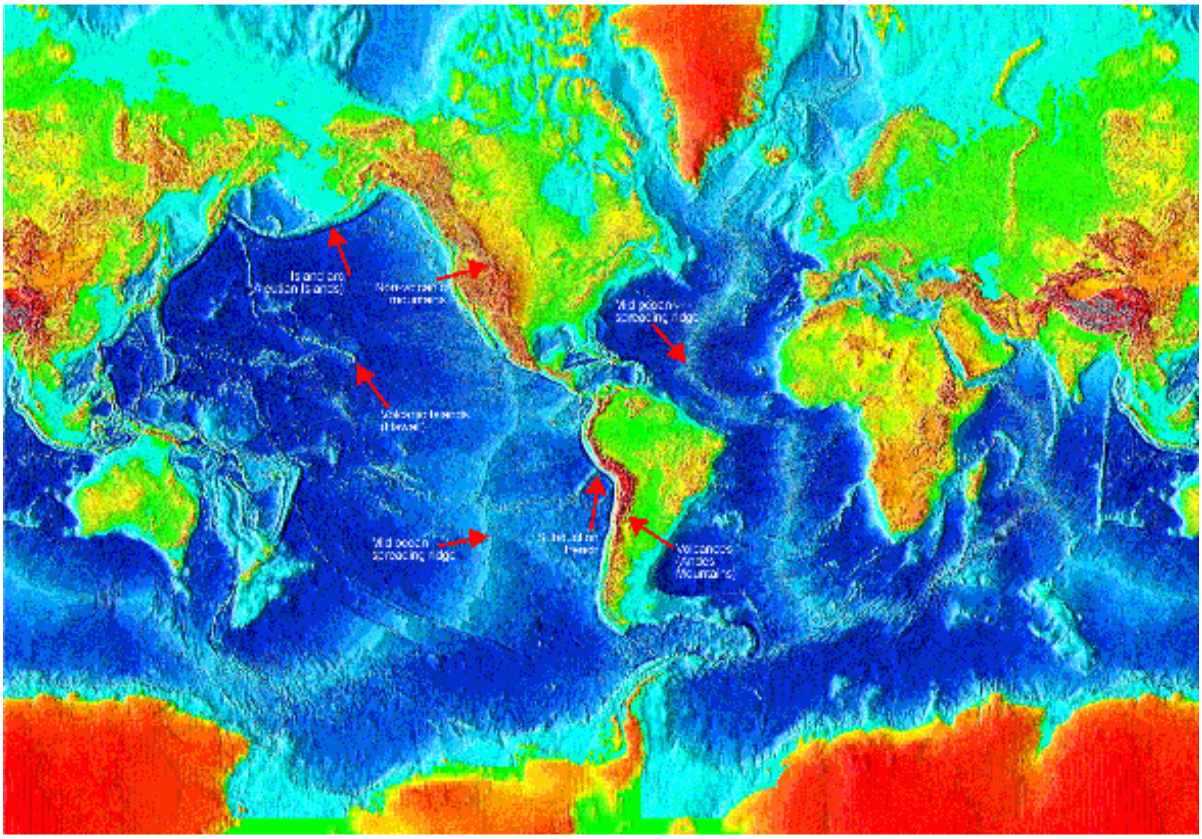


The University of Sydney



Underneath these layers of air and water, the Earth's surface is made of rock. The rock that makes up the continent is thick, that beneath the oceans is much thinner.

Thickness of the Earth's crust, with 10 km contour levels. The continents are essentially outlined by the 30 km contour.



Topographical map of the Earth, showing continental and sea-floor features

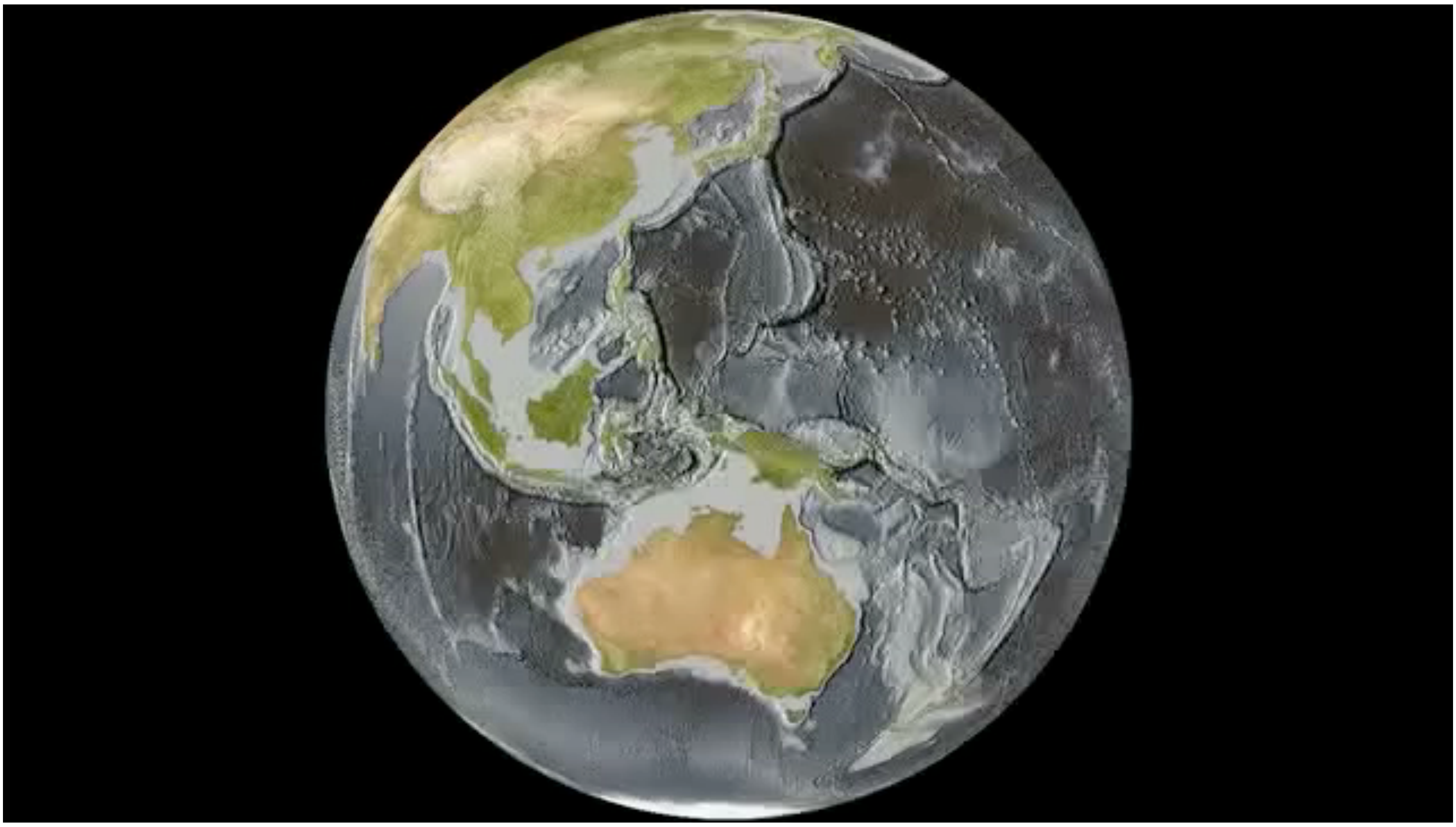
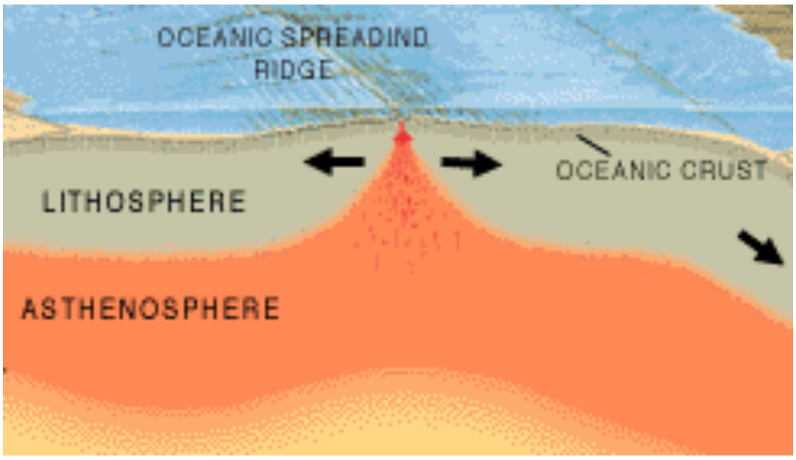


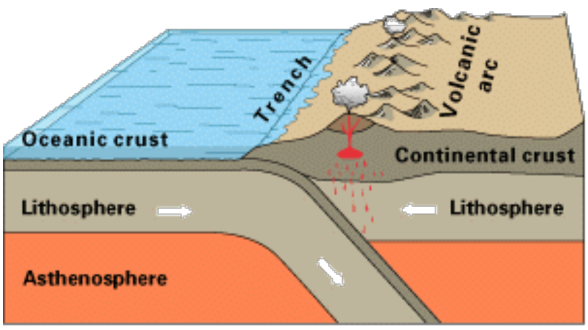
Plate tectonics

The earth's surface is divided into ten large rigid plates, which move as units. Where two plates move apart, lava rises from below to fill the gap, and the plates grow as they separate: *sea-floor spreading*.

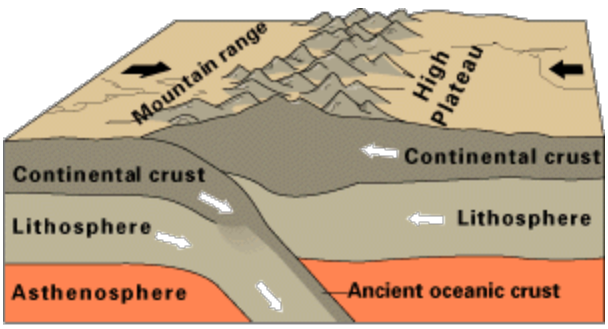


Where two plates move together, the edge of one plate is forced beneath the other. The continental material, being lighter, is forced upwards and crumples, forming mountain ranges, while the sea-floor material is dragged downwards, forming deep sea trenches.

Typical speeds are a few cm per year (similar to the rate your fingernails grow).

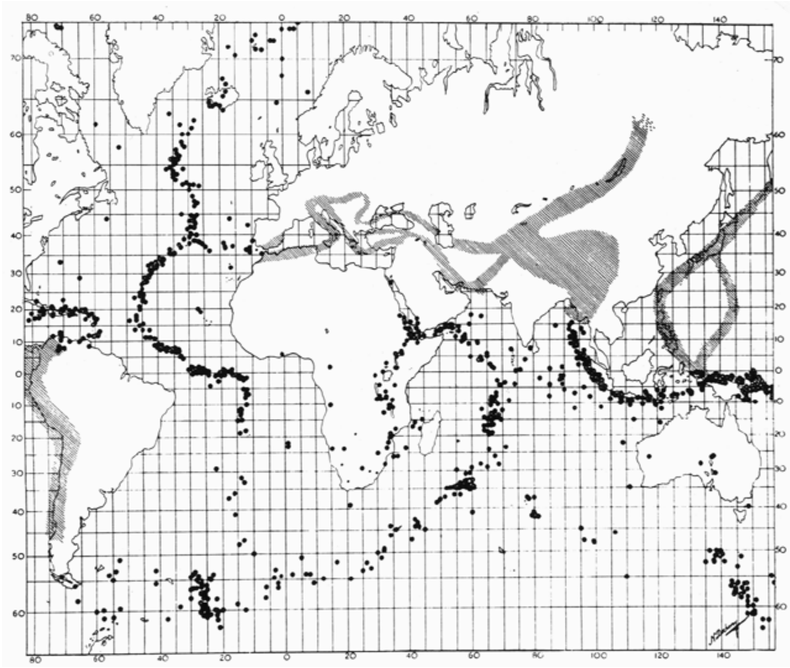


Oceanic-continental convergence

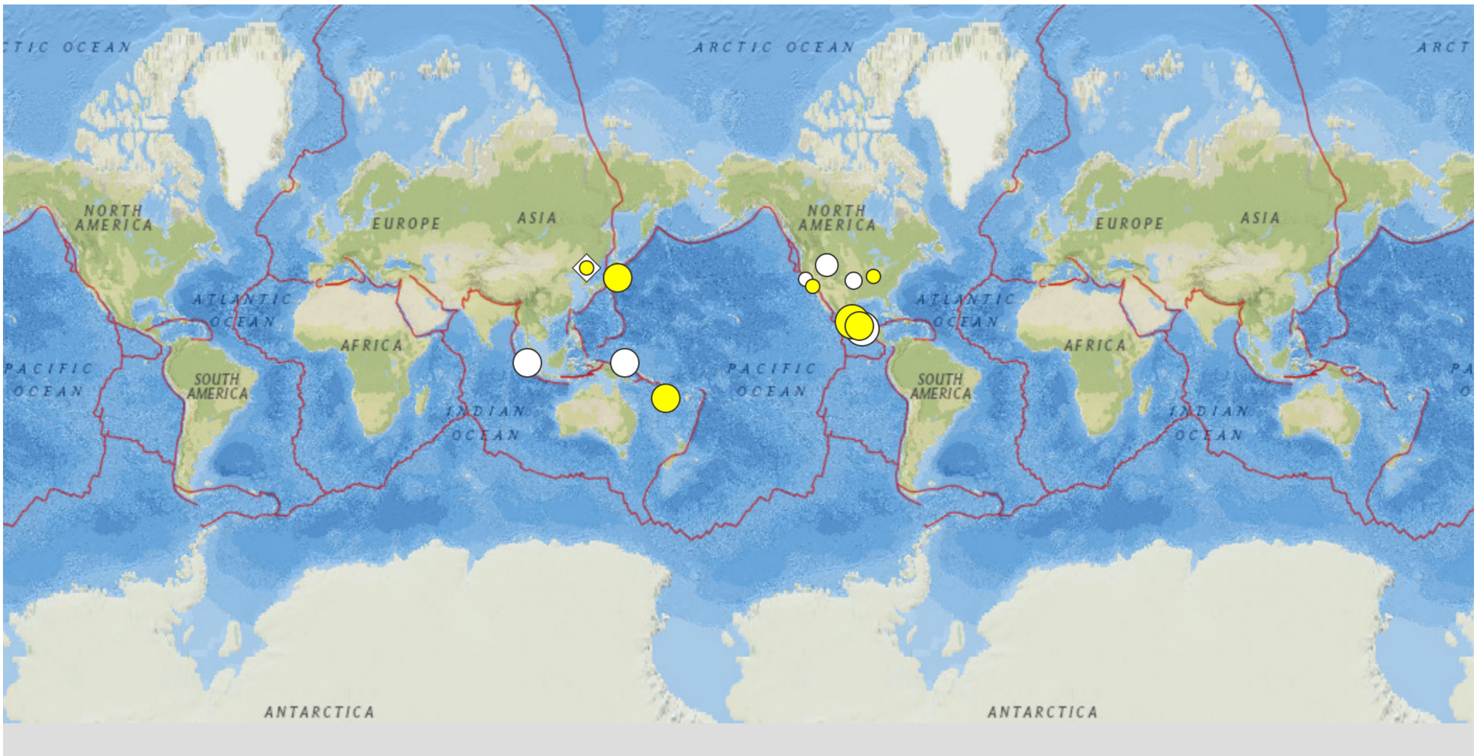


Continental-continental convergence

Great earthquakes occur along the contact between the plates.

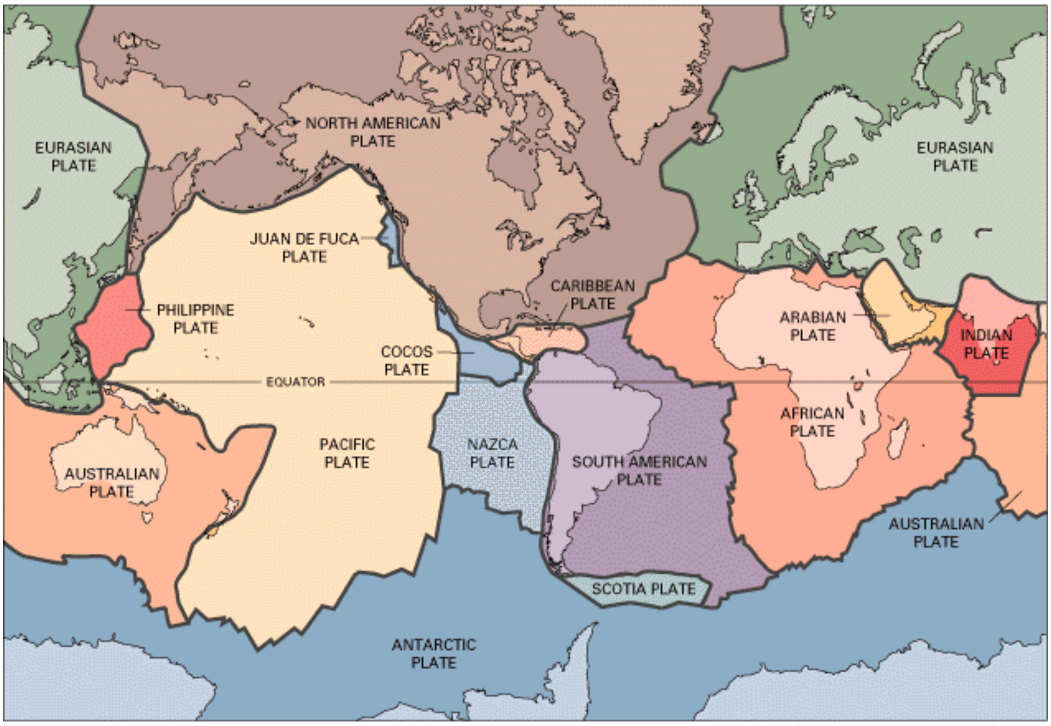


A 1954 map showing the concentration of earthquakes indicated by dots and cross-hatched areas.

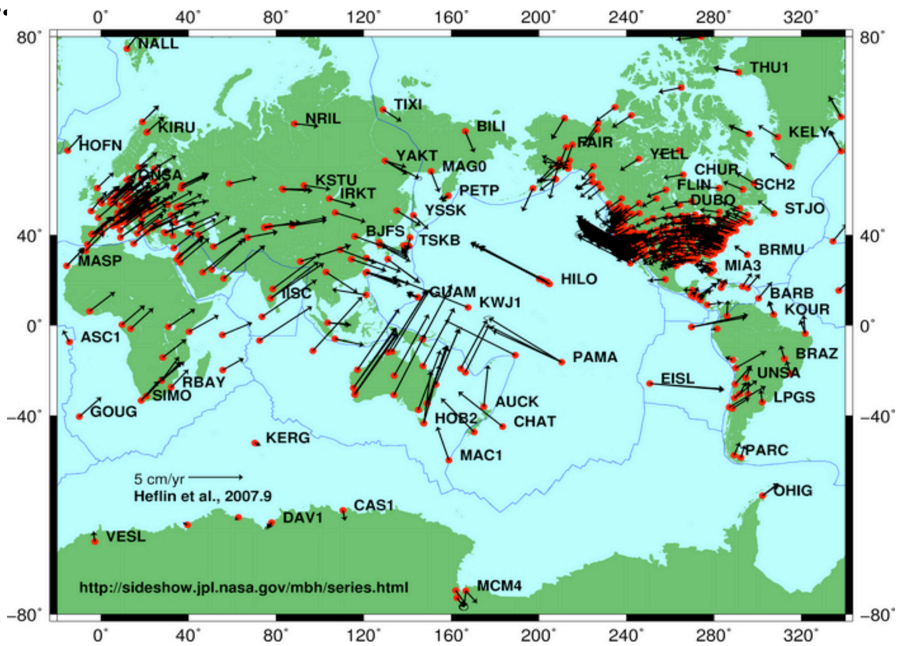


Significant earthquakes, September 2017

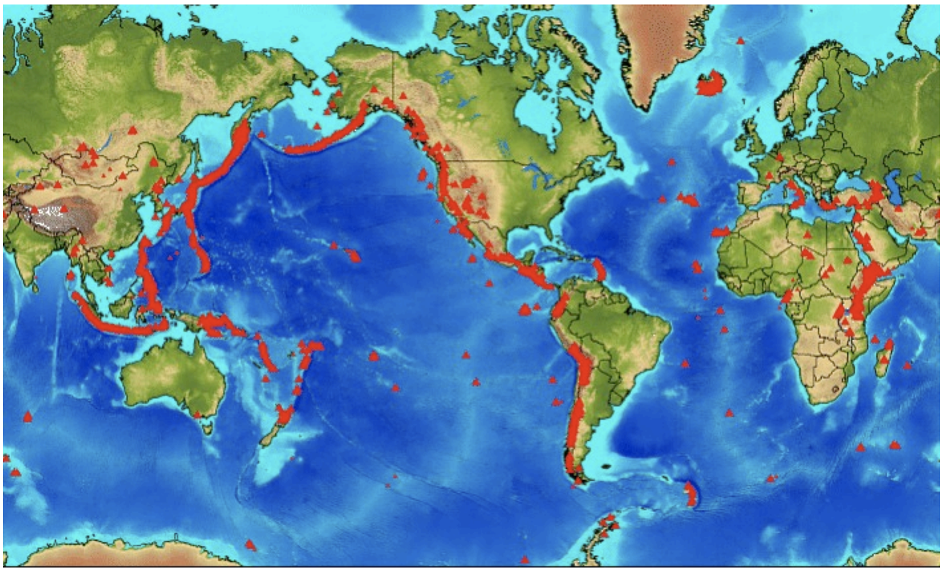
This evidence leads to the following picture of the plates



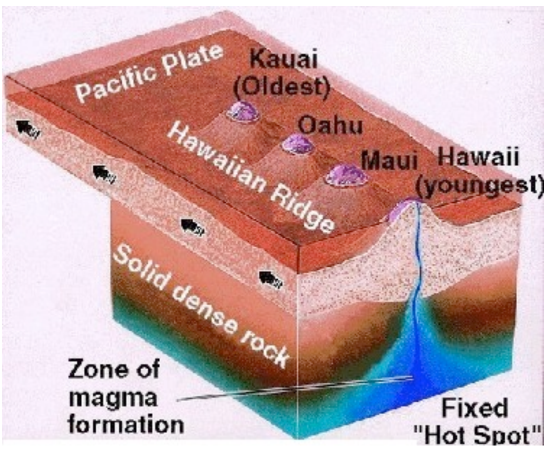
The GPS satellites can actually measure the speed and direction of the plates.

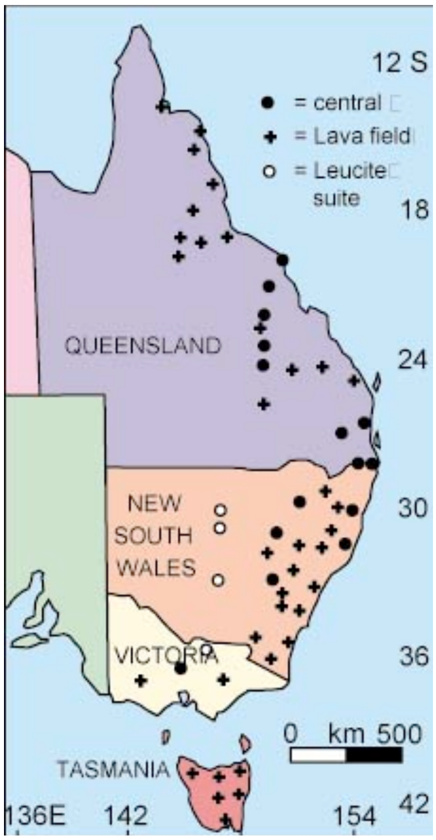


There are 550 volcanoes which have erupted at least once over the last 2000 years. At any one time, there are typically 20 volcanoes erupting, including 17 that have been active more-or-less continuously for the last 20 years.

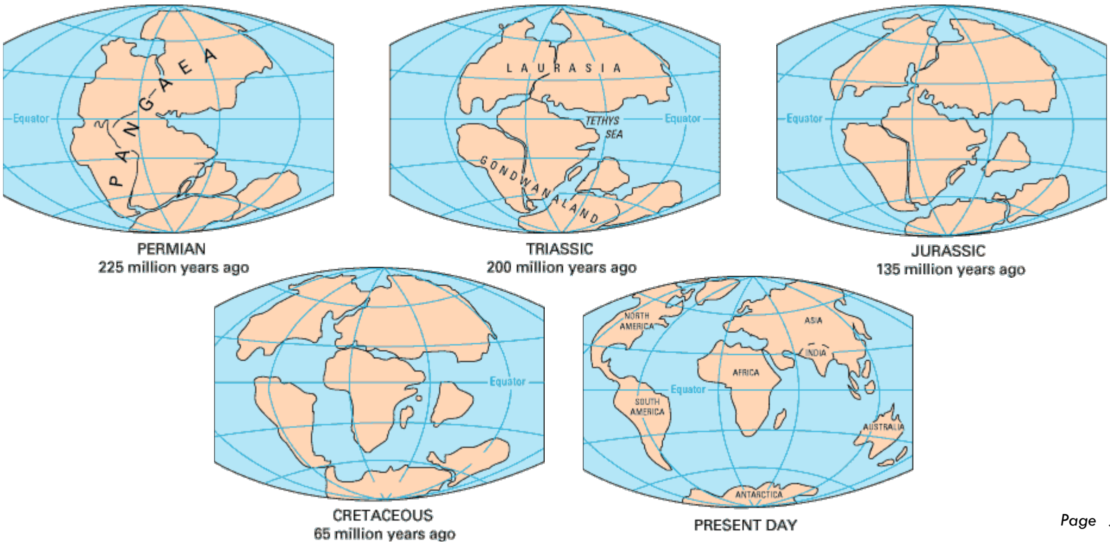


Tectonic plates moving over a fixed "hot spot" can leave a tell-tale chain of volcanoes which get older as you move along the chain. The Hawaiian volcanoes are the most famous example, but the (extinct) volcanoes of eastern Australia also form a chain.



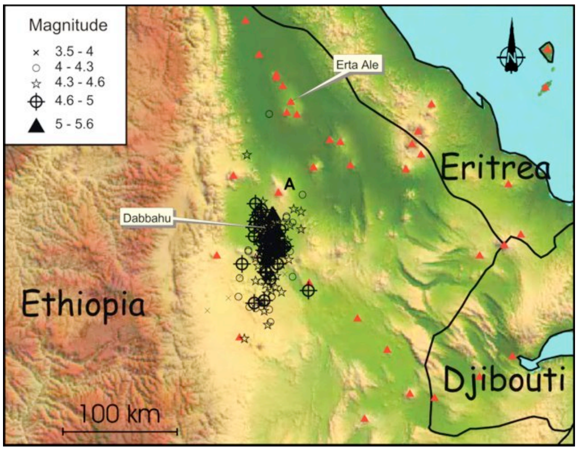


Fossil evidence indicates that the continents were once joined into a giant supercontinent called Pangaea, about 250 million years ago. Pangaea then split into two large fragments, with all the southern continents joined as Gondwana. The plates moved and split further, resulting in the present geography.



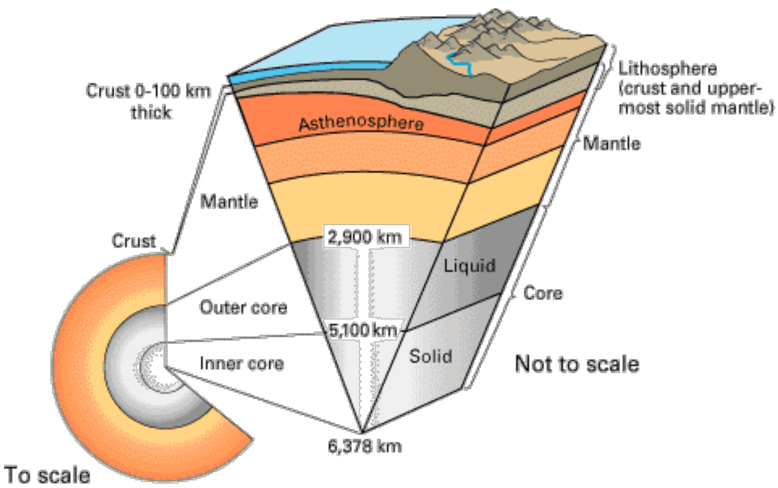
These processes are still going on. In 2005, a 60 km long fissure opened in the ground in Ethiopia, which scientists interpret as the birth of a new ocean basin.

Ash and pumice is thrown out at a vent site at the northern tip of the 60km-long segment in the Afar Desert in north-eastern Ethiopia.



During September 2005 a swarm of 131 earthquakes was recorded, followed by a volcanic eruption and the opening of the 60m deep rift.

The Earth's interior is divided into several zones. There is a dense iron *core*, a thin *crust* composed of lighter elements, and a *mantle* between.

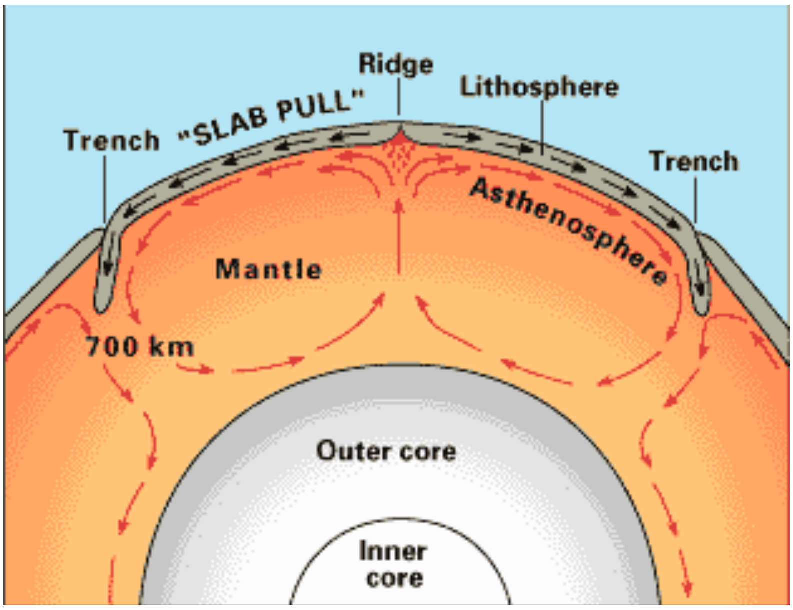


The boundary between the crust and mantle is called the *Mohorovičić discontinuity*.

Several attempts have been made to reach it: most famously, the *Moho project*.

On 6 April 2005, the *Integrated Ocean Drilling Program* (IODP) announced that it had drilled into the lower section of the Earth's crust for the first time.

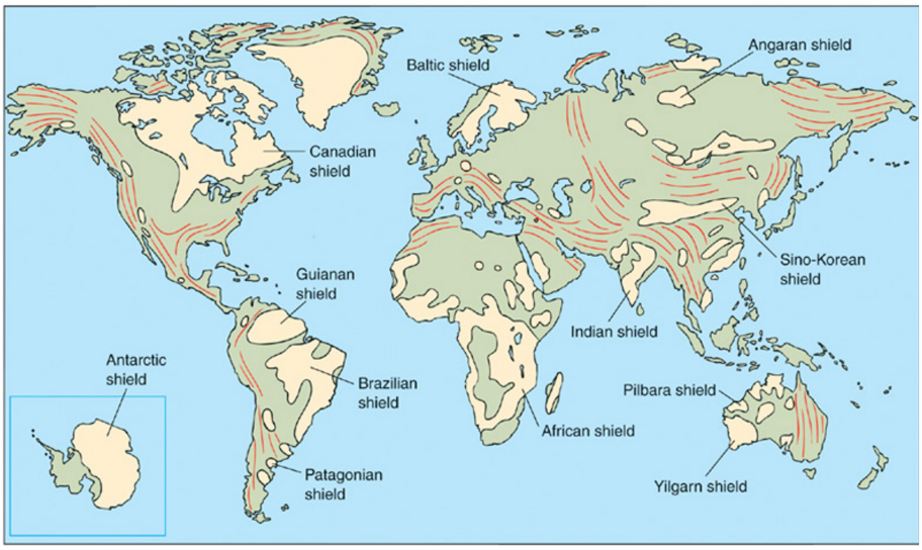
Convection in the mantle is probably the driver for the motion of the plates: the solid plates are carried along with the softened mantle rock. Below about 700 km the descending slabs melt and lose their form.



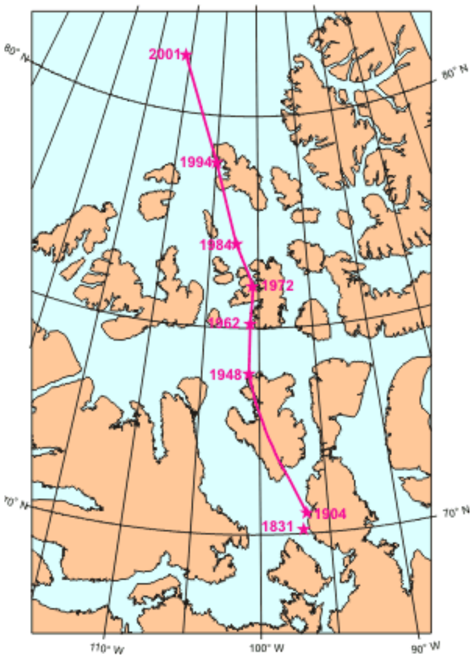
One consequence of this is that the surface of the Earth is very *young*: old sea-floor is constantly being destroyed in subduction zones, and old continental rock is deformed beyond recognition in mountain ranges.

About 3 cubic km per year of fresh rock is created at divergent boundaries.

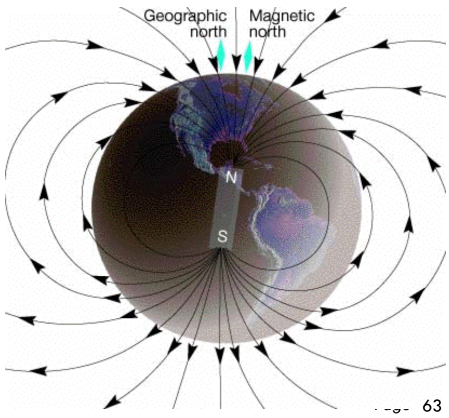
Only in the very interior of the oldest continental chunks will truly old rocks be found. Rocks from central Canada, for instance, have been dated to 2.5 billion years old. The oldest rocks found were in southwest Greenland, where a 3.8 billion year old rock has been found. As we will see, we have to look elsewhere than Earth to find rocks older than this.



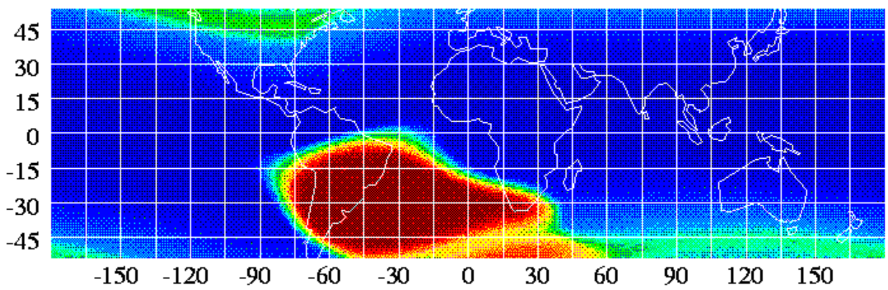
The Earth has a magnetic field, shaped like a bar magnet inclined 11° to the rotation axis and offset 550 km from the centre of the Earth.

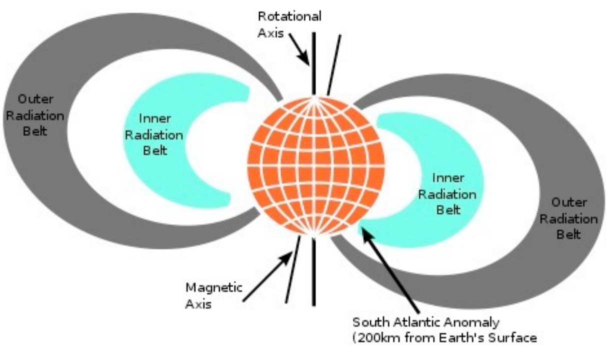


The magnetic field is constantly changing in strength and direction. At the moment, the north magnetic pole is in the Canadian arctic: it has moved 1100 km in the last century.

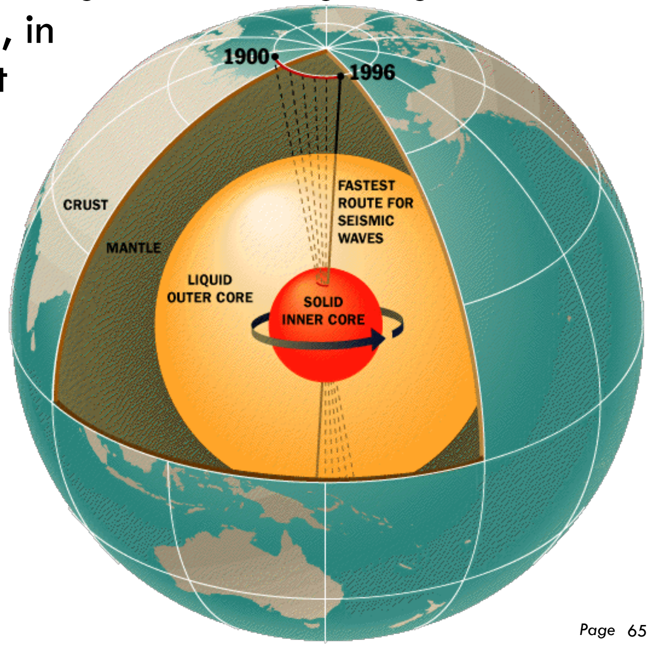


The 550 km offset from the centre gives rise to the *South Atlantic Anomaly*, a region of intense radiation which is damaging to satellites.





The field is generated in the electrically conductive fluid of the outer core. The flow of this molten material through the existing magnetic field generates electrical current which, in turn, creates new magnetic energy that sustains the field.

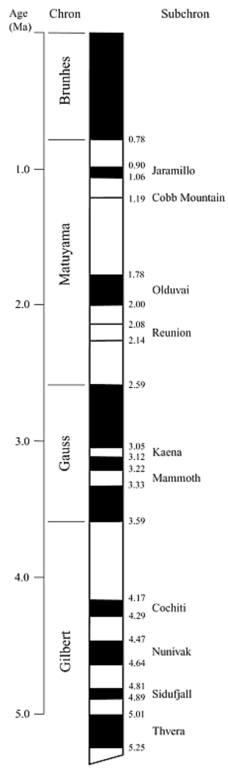


Earth’s magnetic field reverses periodically (as evidenced by magnetic fields frozen into e.g. lava flows).

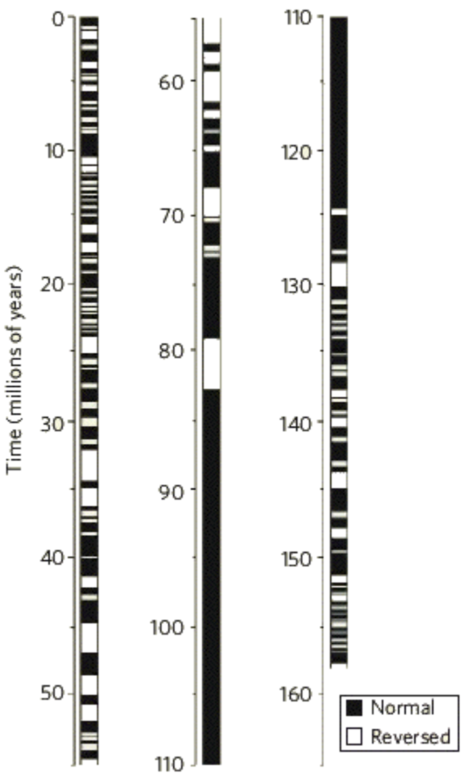
The typical time between reversals is about 200,000 years, and may take several thousand years to complete the flip.

The last major pole flip occupied the time from 795 to 776 kyr ago.

Based on mean time between reversals, we are rather overdue for the next one. The average surface field strength has declined about 10% in the last 170 years



Over even longer timescales, there have been very long periods (*superchrons*) where there were no magnetic reversals at all. The Cretaceous Normal Superchron lasted from 124 to 80 million years ago.

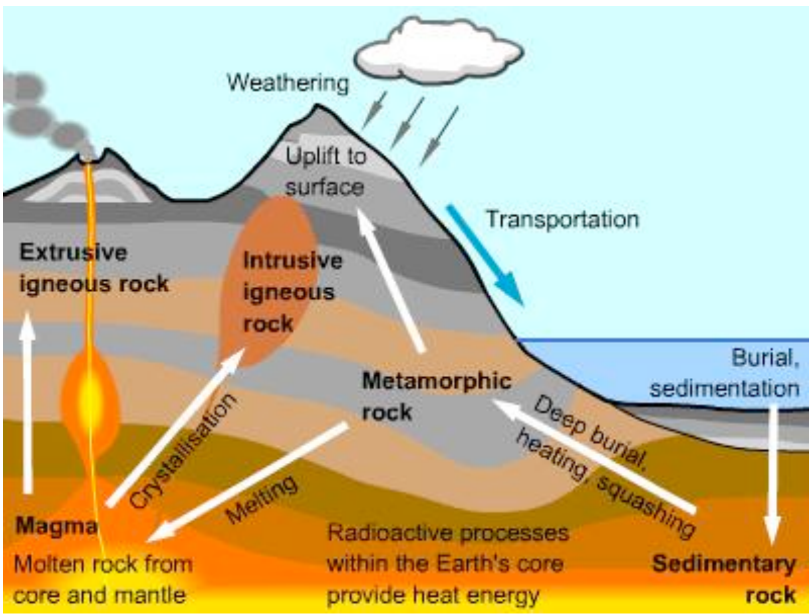


We find three main types of rocks on Earth:

- *sedimentary*, formed from sediments precipitating out of water. Examples are shales, sandstone.
- *igneous*, formed from cooling molten rock. Examples are basalt, granite.
- *metamorphic*, formed when existing rock is transformed by increased temperature and/or pressure. Examples are slate, marble.

Rocks are made of minerals, which are chemical compounds of definite composition. Most rocks are made of silicates: compounds of silicon and oxygen, with other elements like calcium, sodium, iron, magnesium etc.

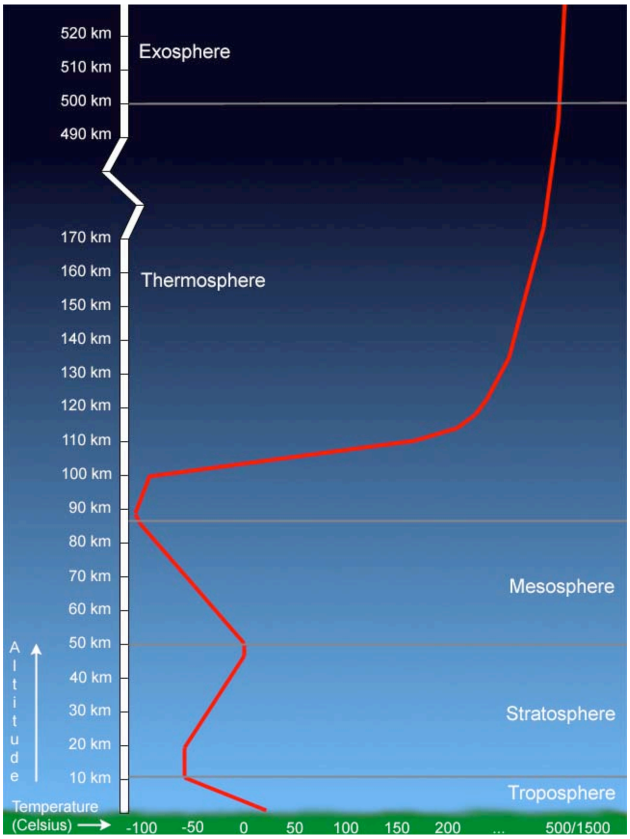
Rocks on Earth are formed, eroded, recycled in a variety of ways: the rock cycle. The Earth's surface is constantly changing in this way.



There are 160 terrestrial impact craters known.

Barringer Meteor Crater in Arizona:
1.2 km in diameter, 49,000 years old

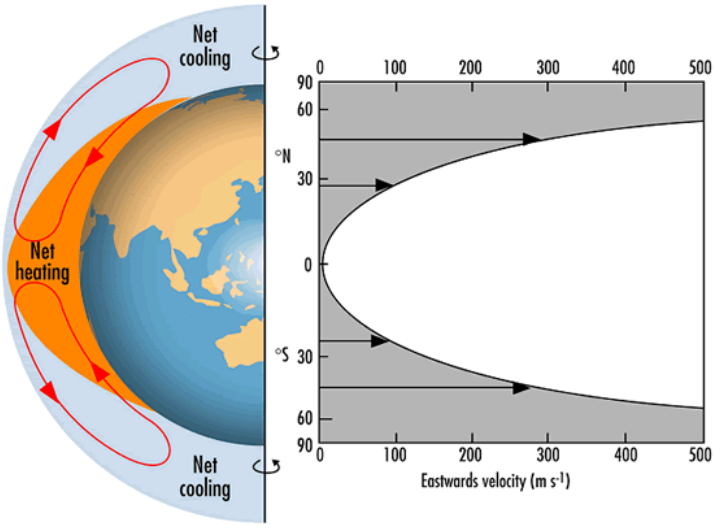
Wolfe Creek Crater in the Kimberleys, Western Australia.
880 m diameter, 300,000 years old.



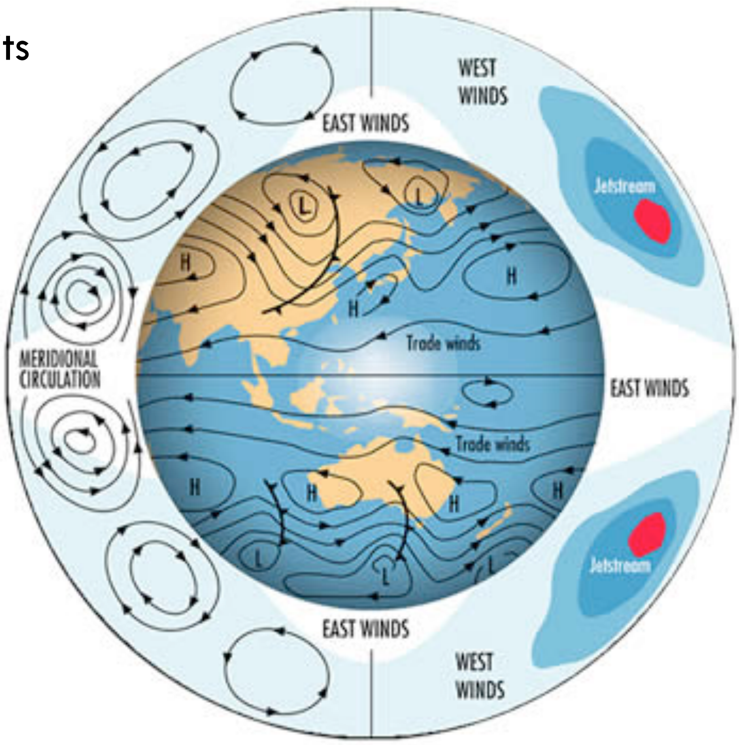
The Earth's atmosphere is divided into 5 layers:

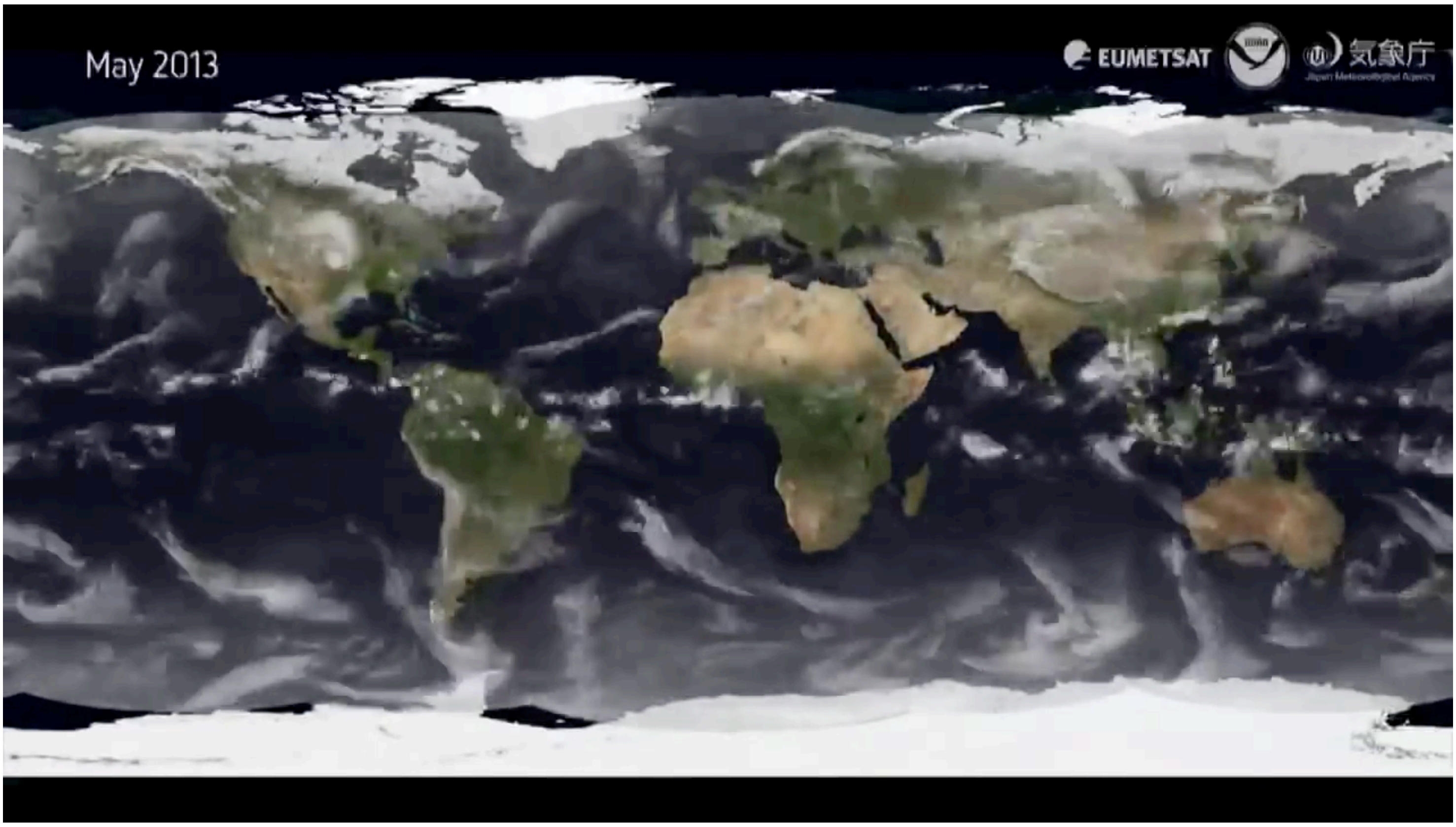
- *troposphere* – contains half the atmosphere. Weather happens here.
- *stratosphere* – where aircraft fly. Contains the ozone layer.
- *mesosphere* – where meteors burn up
- *thermosphere* – where aurorae form
- *exosphere* – where the atmosphere merges into space

The atmosphere is not static, but has large-scale circulation patterns. Solar heating causes air to rise at the equator and sink at the pole; but the rotation of the Earth means that as the air moves poleward, it is moving faster than the surface.

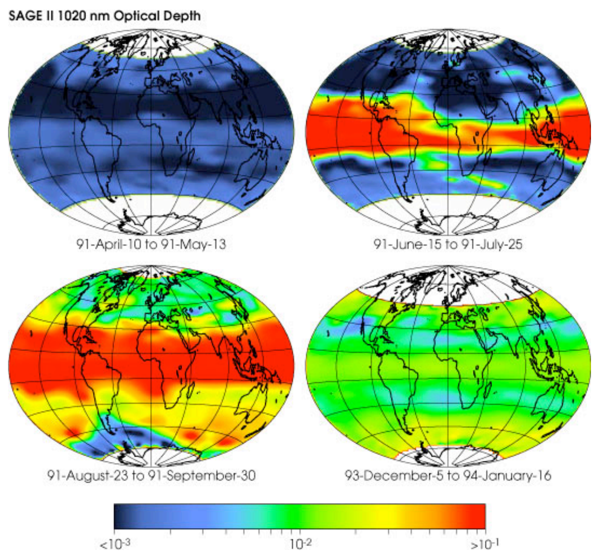


This "Coriolis deflection" short-circuits the circulation cell, and three circulation cells exist in each hemisphere, each about 30° wide.





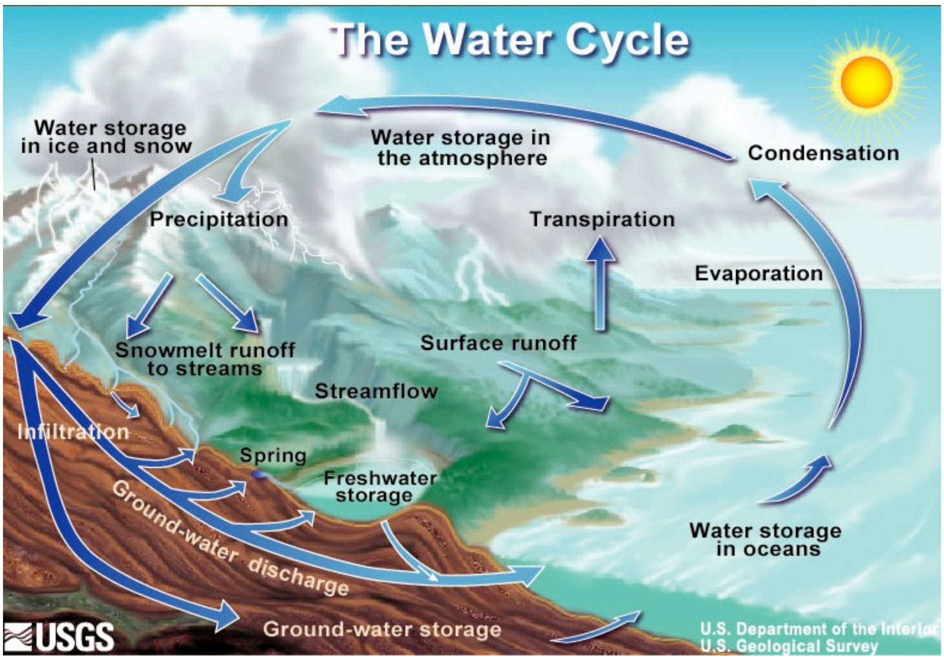
These air movements mean that pollutants can travel easily in the east-west direction but are trapped in bands in the north-south direction.



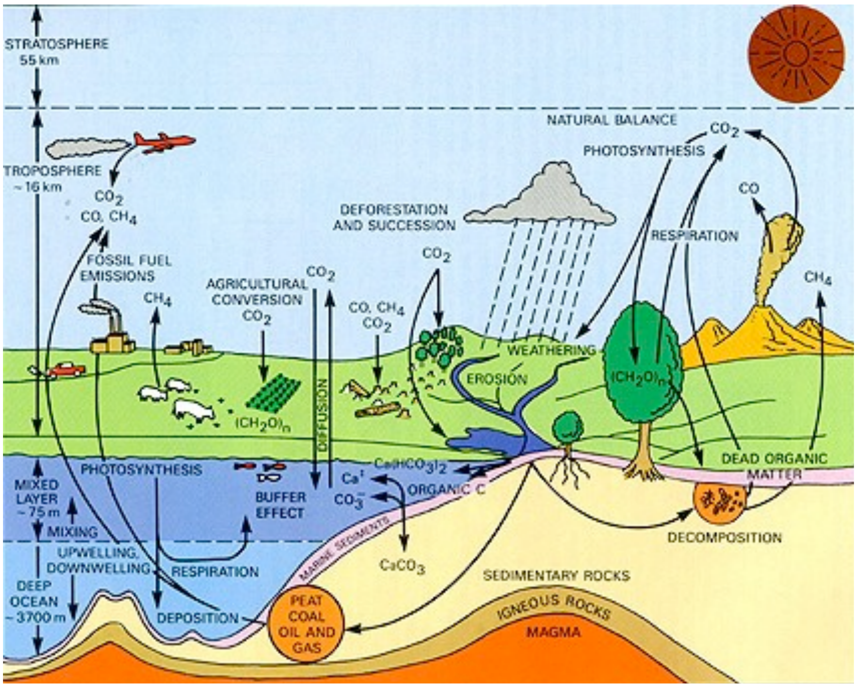
Dust from the 1991 Mt Pinatubo eruption spreads around the globe

The atmosphere is also the site of our weather.

The atmosphere and the oceans interact together in complex chemical cycles, most notably the *water cycle*.



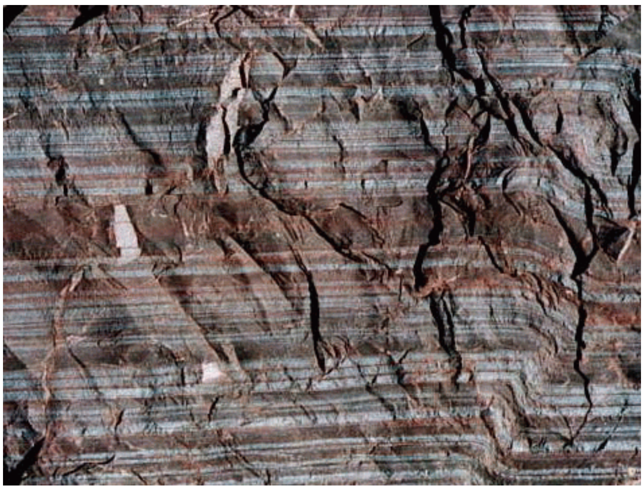
The *carbon cycle* is also vitally important, not only for us, but for maintaining the Earth's atmosphere and climate.



The University of Sydney

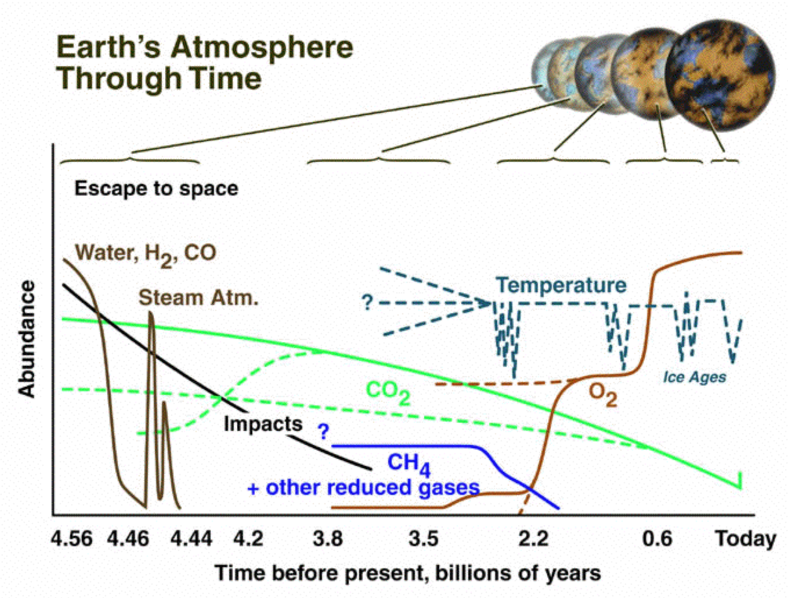
Earth's atmosphere and climate has not been constant over the last 4 billion years.

The biggest change was when the composition of the Earth's atmosphere changed from N_2–CO_2 to N_2–O_2, a process begun and maintained by photosynthesis, i.e. life.



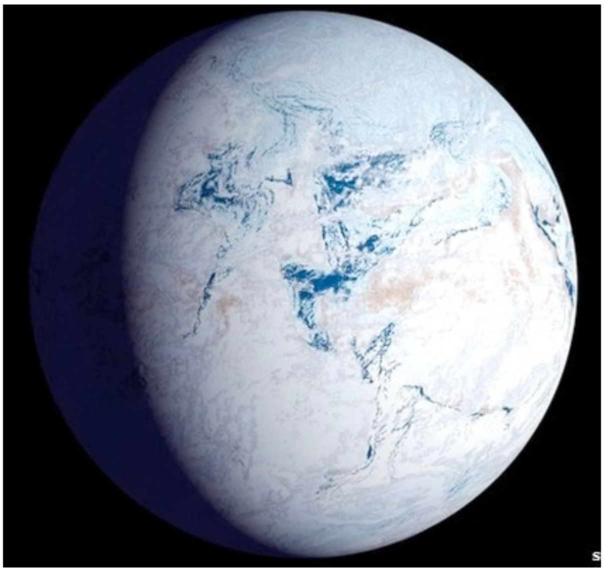
Banded iron formations in Western Australia, laid down when accumulating atmospheric oxygen began precipitating iron from sea-water

Near-modern oxygen levels were probably reached about 2.2 billion years ago, though there is evidence for continued increase in levels through the "Cambrian explosion" about 500 million years ago.

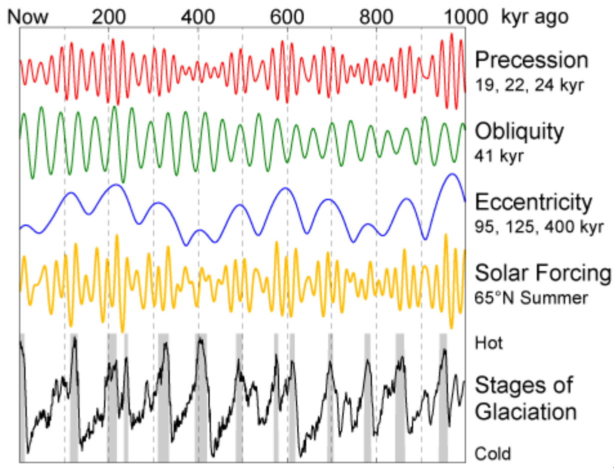


There is growing evidence that the world's climate has undergone at least one major shift. 2.3 Gyr ago the Earth plunged into a global freeze, with glaciers even at the equator: "*Snowball Earth*".

This episode almost wiped out life. It was followed by the Cambrian explosion, when the ancestors of familiar animals suddenly appeared in the fossil record.

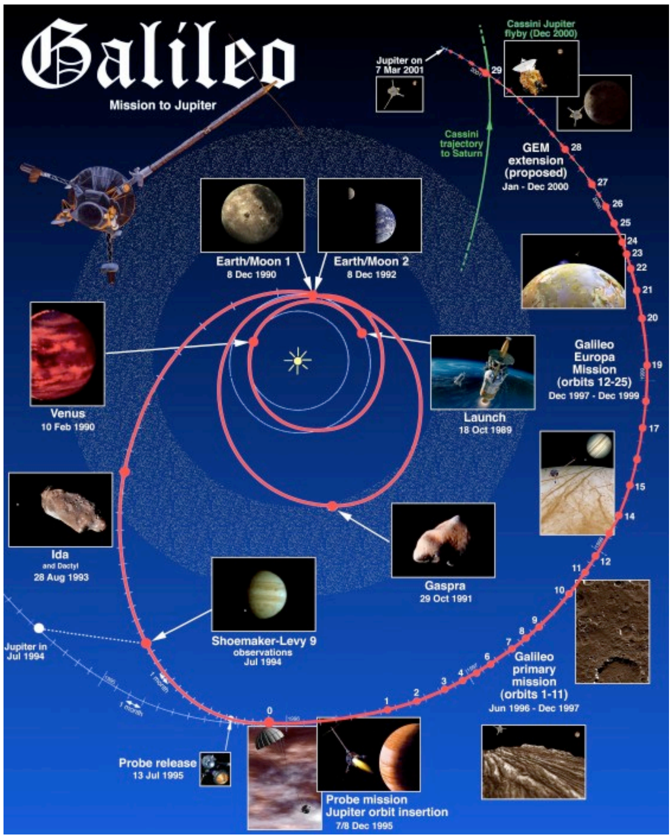


The Earth's climate also fluctuates on shorter timescales. In particular, the temperature has fluctuated significantly over timescales of 10^5–10^6 millions of years. Some of these fluctuations are correlated with changes in the Earth's orbit (the *Milankovitch cycles*).



Would there be any sign of (intelligent) life from outside the Earth?

The *Galileo* spacecraft, on its way past Earth to Jupiter, trained all its instruments on Earth to see what it would detect.



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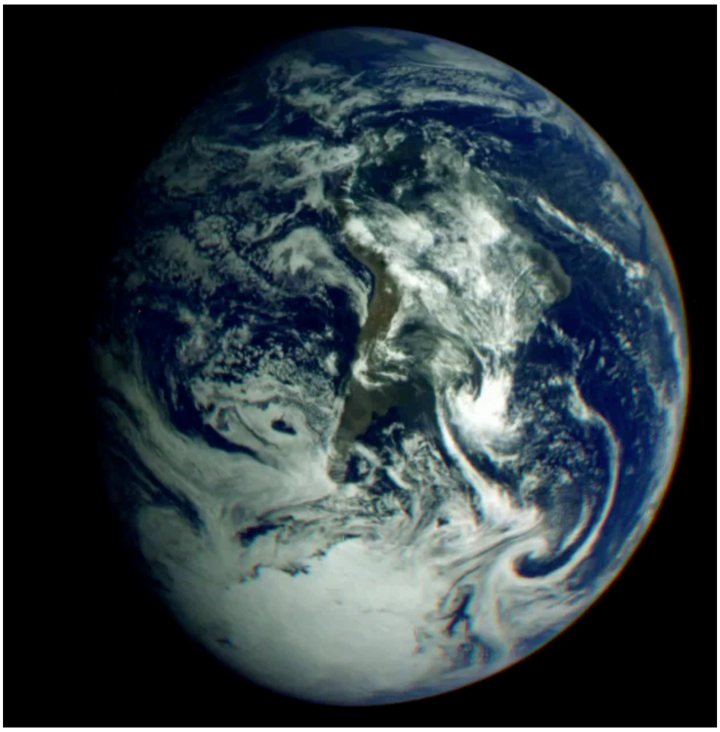

Movie created from images taken every half-hour for 25 hours during the first Galileo flyby

It detected several signs that Earth may contain life:

I. strong absorption of red light, particularly over continents

II. an atmosphere rich in molecular oxygen

III. spectral lines of methane, which is unstable in an oxygen-rich atmosphere

IV. modulated narrowband radio transmissions, unlike natural sources like lightning

"From the Galileo flyby, an observer unfamiliar with the Earth would be able to draw the following conclusions: The planet is covered with large amounts of water present as vapour, as snow and ice, and as oceans. If any biota exists, it is plausibly water-based. There is so much O_2 in the atmosphere as to cast doubt on the proposition that UV photodissociation of water vapour and the escape of hydrogen provide an adequate source. An alternative explanation is biologically mediated photo-dissociation of water by visible light as the first step in photosynthesis. An unusual red-absorbing pigment that may serve this purpose corresponding to no plausible mineral is found widely on land."

– Carl Sagan, "Search for Life on Earth"

These "*Sagan criteria for life*" are seen as important first guesses for tests which might be used in remote sensing of extra-terrestrial life.

Further reading

For the whole course:

There are many good introductions to the planets around. Here are a few I have found to be particularly useful.

- Up-to-date planet information can be found at the NASA Planetary Sciences page http://nssdc.gsfc.nasa.gov/planetary/. This includes data on the planets, images, and information on the space missions, as well as links to other useful resources.
- NASA has a site with all the publicly released images from its Solar System program at the Planetary Photojournal, http://photojournal.jpl.nasa.gov/index.html.
- If you like your data in book form, “**The Cambridge Planetary Handbook**” by Michael E. Bakich (Cambridge UP, 2000) is an excellent up-to-date reference to planetary data.
- “**The Cambridge Photographic Guide to the Planets**” by F.W. Taylor (Cambridge UP, 2001) is a lovely book , which contains very good descriptions of what is known about each planet, together with spectacular pictures.
- There is an absolutely gorgeous book called “**Beyond: Visions of the Interplanetary Probes**” by Michael Benson (Harry N. Abrams, 2003). The author has compiled and digitally processed the best images sent back by the space probes into one of the most beautiful collections you’ll ever see.

- “**The New Solar System**” by Beatty, Petersen and Chaikin (Cambridge UP, 4th edition, 1998) is a really good guide to recent work on the solar system, with chapters written by various world experts. It’s at a nice level: more than just pretty pictures, but doesn’t assume too much prior knowledge.
- The BBC documentary “**The Planets**”, available on DVD. An excellent introduction to the solar system and its formation, including some wonderful interviews with many of the project scientists for Voyager and other missions.

- "**Space Odyssey: Voyage to the Planets**" is a two-part BBC “mockumentary”, describing a fictional five-person mission to the planets. It's fun, and certainly gives a good feeling what visiting these worlds would be like.
- “**Views of the Solar System**” by Calvin J. Hamilton, http://www.solarviews.com/eng/homepage.htm, is an excellent collection of images and animations of the solar system.
- “Solar System Live” at http://www.fourmilab.ch/solar/solar.html enables you to show the positions of all the solar system bodies at any time you like. Great fun to play with. You can even plot the positions of comets or asteroids to see where they are too.
- For general astronomical images, you can’t do better than the “Astronomy Picture of the Day” website, http://antwrp.gsfc.nasa.gov/apod/. A new picture every day, with links to many other interesting sites where you can follow up the topic.
- A marvelous illustration of how much empty space there is in the Solar System: http://joshworth.com/dev/pixelspace/pixelspace_solarsystem.html, subtitled "If the moon was only 1 pixel: A tediously accurate scale model of the solar system”.

For the Earth:

- "**Earth: An Intimate History**" by Richard Fortey (HarperPerrenial, 2005) is an extremely readable book about modern geology. It rambles a bit, and is probably not the right book to start out with if you want to learn the basics, but is a fascinating account of how the story of the Earth and plate tectonics is written in rocks all around us. He has a nice description of the evidence for the continental chunks that existed before the current continents.
- "**Mysteries of Terra Firma: The Age and Evolution of the Earth**" by James Lawrence Powell (The Free Press, 2001) is a popular-level history of three major controversies in geology: the age of the Earth, plate tectonics, and the impact theory. A very nice read.
- "**Worlds on Fire: Volcanoes on the Earth, the Moon, Mars, Venus and Io**" by Charles Frankel (Cambridge UP, 2005) is a terrific book all about volcanism, which does a great job of comparing volcanoes on the five Solar System bodies where they're currently active. This book is extremely applicable to the upcoming lectures on these worlds.
- The "Snowball Earth" hypothesis is discussed in some detail in "**Snowball Earth: The story of a maverick scientist and his theory of the global catastrophe that spawned life as we know it**" by Gabrielle Walker (Three Rivers Press, 2003). The book is focused on the scientists involved, but does a good job of describing the science behind the (controversial) theory. There's also a web-site devoted to the theory, at http://www.snowballearth.org/slides.html.
- The US Geological Survey has a site called "This Dynamic Earth: the story of plate tectonics" at http://pubs.usgs.gov/publications/text/dynamic.html, which covers the basics of geology very nicely.
- There's a good article on geomagnetic reversals by David Gubbins in Nature vol. 452 p. 165; I found a copy online at www.ladhyx.polytechnique.fr/people/willis/papers/Nature425.pdf

Sources for images used:

- Illustration of the Late Heavy Bombardment, from National Geographic, art by Dana Berry http://ngm.nationalgeographic.com/2013/07/125-solar-system/image-gallery#/2
- Current space missions: from http://www.planetary.org/multimedia/space-images/charts/whats-up-in-the-solar-system-frohn.html
- Sun: SOHO image of the Sun, taken in ultraviolet light, http://sohowww.nascom.nasa.gov
- Voyager Solar System Family Portrait: from NSSDC Photo Gallery, http://nssdc.gsfc.nasa.gov/photo_gallery/
- MESSENGER Solar System Family Portrait: https://www.nasa.gov/mission_pages/messenger/media/SolarSytemPortrait.html
- Solar system montage: The Sun and nine planets approximately to scale. http://www.solarviews.com/eng/solarsys.htm
- Planetary data: from NSSDC Planetary Fact Sheets, http://nssdc.gsfc.nasa.gov/planetary/planetfact.html
- Sizes of orbits: from http://www.solarviews.com/eng/solarsys.htm
- Titius-Bode law: from Wikipedia http://en.wikipedia.org/?title=Titius-Bode_law
- Jupiter and Saturn families of moons: from NSSDC Photo Gallery, http://nssdc.gsfc.nasa.gov/photo_gallery/
- Moons: from Paul Schenk, "Satellites of the Outer Planets – An Image Tour" http://www.lpi.usra.edu/research/outerp/moons.html
- Moons by size: http://www.solarviews.com/eng/solarsys.htm
- Co-planar and circular orbits: generated using "Solar System Live" http://www.fourmilab.ch/solar/solar.html. These particular positions are for 1 March 2005, viewed from heliocentric latitude 0°, longitude 180° and latitude 90°, longitude 0°.
- Earth title image: from APOD 2007 March 25 https://apod.nasa.gov/apod/ap070325.html
- Sun at perihelion and aphelion: image by Enrique Luque Cervigón, from APOD 2007 July 9 http://antwrp.gsfc.nasa.gov/apod/ap070709.html
- Earth: view from Apollo 17, Astronaut Photography of the Earth, http://eol.jsc.nasa.gov/scripts/sseop/photo.pl?mission=AS17&roll=148&frame=22727; Galileo image of Earth, http://www2.jpl.nasa.gov/galileo/images/australia.html; image of jet stream from Views of the Solar System, http://www.solarviews.com/cap/earth/jet.htm
- Clouds and crescent moon viewed from space: ISS/NASA picture, from Astronomy Picture of the Day 2007 March 20 http://antwrp.gsfc.nasa.gov/apod/ap070320.html
- All the water on planet Earth: from APOD 2016 September 11 https://apod.nasa.gov/apod/ap160911.html
- Thickness of crust: from USGS http://quake.wr.usgs.gov/research/structure/CrustalStructure/
- Topography of the sea floor: from Windows to the Universe, at http://www.windows.ucar.edu/ ; movie from Science on a Sphere http://sos.noaa.gov/datasets/Land/etopo2.html
- Earthquake maps: from USGS https://earthquake.usgs.gov/earthquakes/map
- Plate tectonics diagrams: from "This Dynamic Earth: The Story of Plate Tectonics" , online edition http://pubs.usgs.gov/publications/text/dynamic.html
- GPS plate motions: from NASA GPS Time Series http://sideshow.jpl.nasa.gov/mbh/series.html
- Volcano map: from the Smithsonian Institute:'s "Global Volcanism Program: Volcanoes of the World" http://www.volcano.si.edu/world/find_regions.cfm
- Volcanic chains: from "Volcano World" http://volcano.oregonstate.edu/vwdocs/vwlessons/hot_spots/introduction.html and http://volcano.oregonstate.edu/vwdocs/volc_images/australia/volc_australia.html
- Plate tectonics animation: from UC Berkeley Geology: Plate Tectonics http://www.ucmp.berkeley.edu/geology/tectonics.html
- Birth of a new ocean: from "Geologists witness 'ocean birth', BBC News 8 December 2005, http://news.bbc.co.uk/2/hi/science/nature/4512244.stm and http://www.futurity.org/earth-environment/seafloor-dynamics-at-work-splitting-continent/
- Images of the rift: from Global Volcanism Program: Monthly Reports http://www.volcano.si.edu/world/volcano.cfm?vnum=0201-113&volpage=var

- IODP drilling platform: from NSF Press Release 06-071 http://www.nsf.gov/news/news_summ.jsp?cntn_id=106899
- Earth's magnetic field: from CSULA Geology 150: Plate Tectonics http://www.calstatela.edu/faculty/acolvil/plates.html
- Oldest rocks on Earth: from "The Earth through Time" by Harold Levin, chapter 8 http://higheredbcs.wiley.com/legacy/college/levin/0471697435/chap_tut/chaps/chapter08-07.html
- Movement of the magnetic pole: from Geological Survey of Canada: Geomagnetism http://gsc.nrcan.gc.ca/geomag/nmp/long_mvt_nmp_e.php
- Magnetic dynamo: from Science@NASA: Earth's Inconstant Magnetic Field http://science.nasa.gov/headlines/y2003/29dec_magneticfield.htm
- Geomagnetic reversals: from Wikipedia http://en.wikipedia.org/wiki/Geomagnetic_reversal
- Craters: from Windows to the Universe, at http://www.windows.ucar.edu/
- Atmosphere temperature profile: from Windows to the Universe, at http://www.windows.ucar.edu/. Atmospheric circulation: from "The Greenhouse Effect and Climate Change", Australian Bureau of Meteorology, http://www.bom.gov.au/info/climate/change/gallery/
- 2013's weather systems in 60 seconds: from https://www.theguardian.com/uk-news/video/2014/jan/29/2013-weather-systems-60-seconds-video
- Mt Pinatubo eruption: Wikipedia http://commons.wikimedia.org/wiki/File:Pinatubo91eruption_clark_air_base.jpg. Dust spreading: from NASA's Visible Earth http://visibleearth.nasa.gov/view_rec.php?id=1803
- Cyclone off Brazil: from Astronomy Picture of the Day, 2004 April 6 http://antwrp.gsfc.nasa.gov/apod/ap040406.html; Cumulonimbus clouds over Siding Spring mountain: photo by HMJ; Storm over Lane Cove, photo by HMJ.
- Tropical Cyclone Billy: from Earth Observatory News, http://earthobservatory.nasa.gov/IOTD/view.php?id=36272
- Field of cumulonimbus: from Shuttle views the Earth: Clouds from space http://www.lpi.usra.edu/publications/slidesets/clouds/clouds_index.shtml
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- The water cycle: from USGS Water Science Basics, http://ga.water.usgs.gov/edu/watercycle.html
- The carbon cycle: from NASA's Remote Sensing Tutorial, Section 16: Earth System Cycles, http://rst.gsfc.nasa.gov/Sect16/Sect16_4.html
- Banded iron formations: from ATM S211: Climate and Climate Change, http://www.atmos.washington.edu/2002Q4/211/notes_evolution.html
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- Snowball Earth: from BBC, "Life may have survived 'Snowball Earth' in ocean pockets', http://www.bbc.co.uk/news/science-environment-11992299
- Milankovitch cycles: from Wikipedia http://en.wikipedia.org/wiki/Milankovitch_cycles
- Earth at night: http://earthobservatory.nasa.gov/Newsroom/BlueMarble/
- Galileo image of Earth: from the NSSDC Photo Gallery: Earth http://nssdc.gsfc.nasa.gov/photo_gallery/photogallery-earth.html#galileo; Earth Spin movie from http://svs.gsfc.nasa.gov/stories/nasm/movies.html
- Carl Sagan, "A search for life on Earth from the Galileo spacecraft", Nature 1993, 365:715-21
- Next week: Apollo 11 service module "Columbia" viewed from the Eagle, from https://pics-about-space.com/apollo-11-moon-landing?p=2#img6715942733813473089