# The Solar System

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# Why this lecture

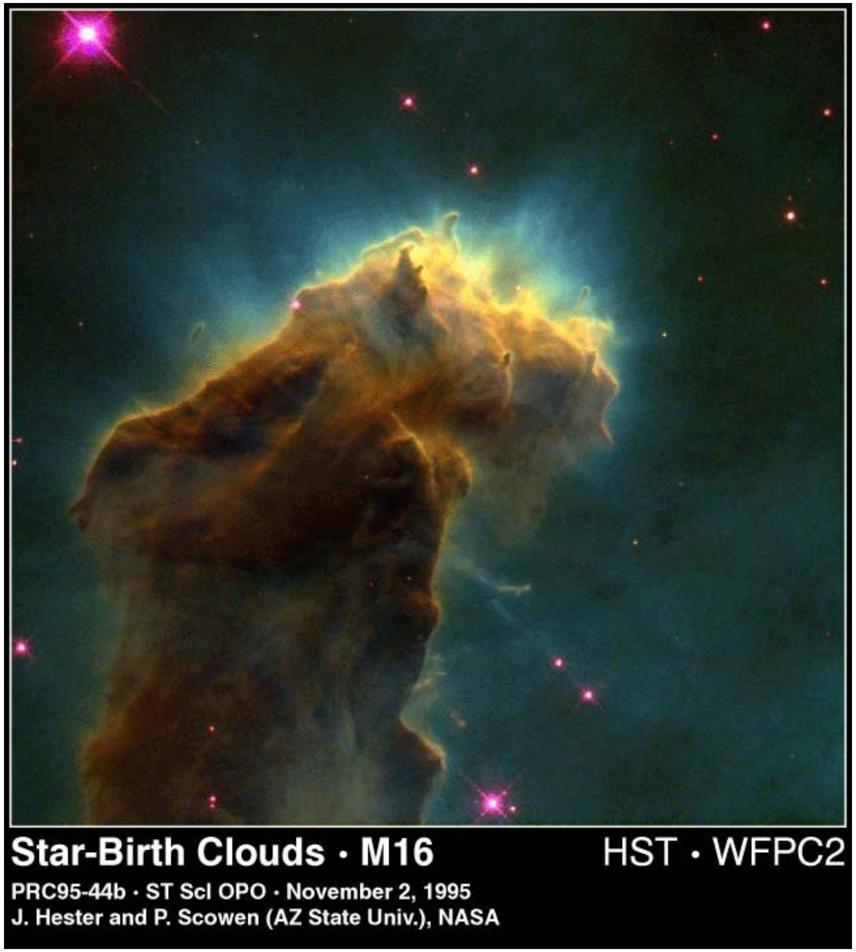
- The frequency with which stars are attended by planets is a key factor in the extraterrestrial life debate
- This frequency, in turn, depends on the mechanism by which planets are generally formed

# Goals for today

- Show the link between the origin of the universe and Solar System formation
- Review the sequence of main events in the formation of the planetary system
- Illustrate that catastrophic events are a common, and perhaps universal, aspect of planet formation

# Before the Solar System

- Our Solar System is thought to have formed from the gravitational collapse of a fragment of a giant molecular cloud
- A molecular cloud is a type of interstellar cloud, the density and size of which permit the formation of molecules, most commonly molecular hydrogen ($H_2$)
- The cloud itself had a size of about several light-years across, while the fragments were perhaps a few light years across
- The further collapse of the fragments led to the formation of dense cores 2'000-20'000 AU in size, one of which was the pre-solar nebula
- The pre-solar nebula was slightly more massive than the Sun, with hydrogen, some helium and trace amounts of lithium produced by Big Bang nucleosynthesis, forming about 98% of its mass
- The remaining 2% of the mass consisted of heavier elements that were created by nucleosynthesis in earlier generations of stars

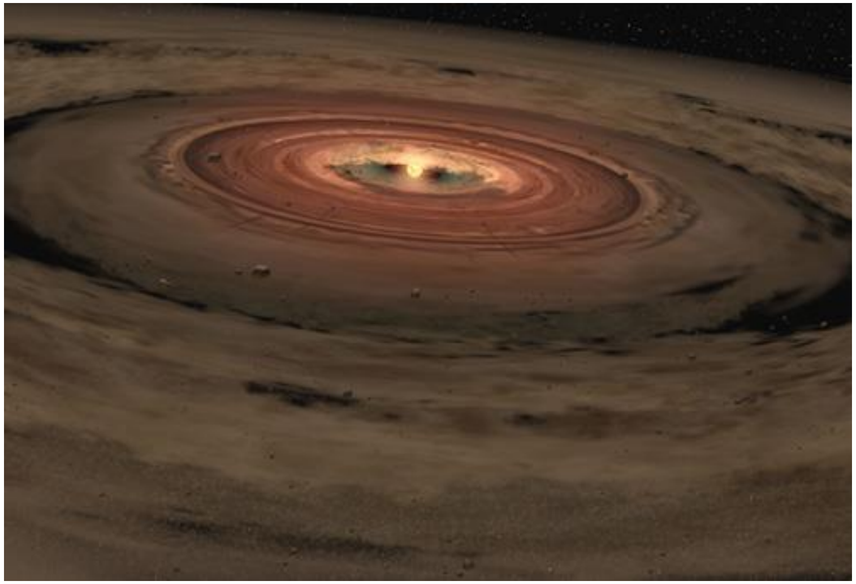


# The collapse of the pre-solar nebula

- The oldest inclusions found in meteorites, thought to trace the first solid material to form in the pre-solar nebula, are 4568.2 million years old
- Studies of ancient meteorites reveal traces of stable daughter nuclei of short-lived isotopes, such as iron-60, that only form in supernovae
- A shock wave from a supernova may have triggered the formation of the Sun by creating regions of over-density within the cloud, causing these regions to collapse
- Because only massive, short-lived stars produce supernovae, the Sun must have formed in a large star-forming region that produced massive stars, possibly similar to the Orion Nebula

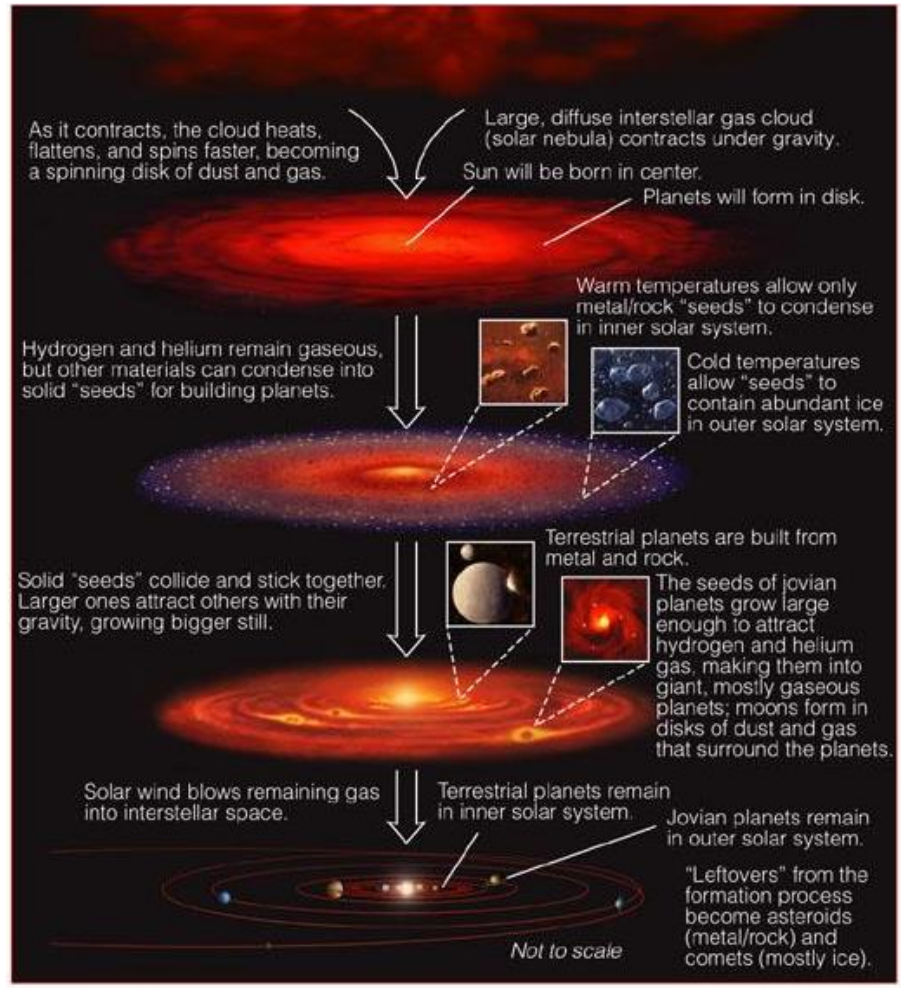
# The protoplanetary disc

- Because of the conservation of angular momentum, the nebula spun faster as it collapsed
- As the material within the nebula condensed, the atoms within it began to collide with increasing frequency, converting their kinetic energy into heat
- The center, where most of the mass collected, became increasingly hotter than the surrounding disc
- Over about 100'000 years, the competing forces of gravity, gas pressure, magnetic fields, and rotation caused the contracting nebula to flatten into a spinning protoplanetary disc with a diameter of ~200 AU
- At the center of the nebula, a hot, dense T Tauri protostar (a star in which hydrogen fusion has not yet begun) formed



# Formation of the planets

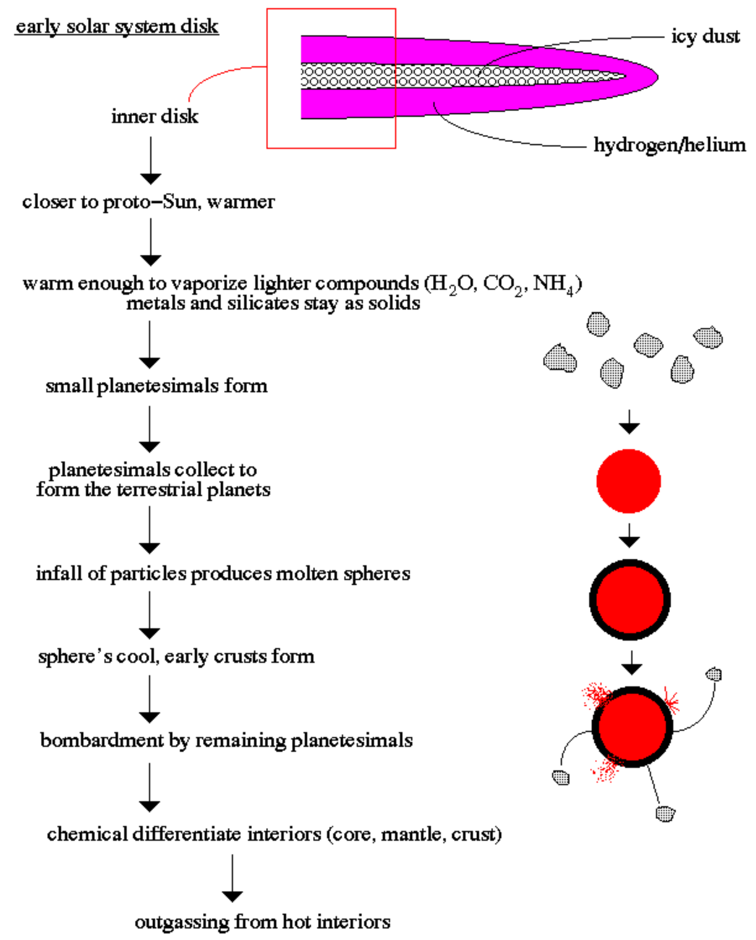
- The currently accepted method by which the planets formed is accretion, in which the planets began as dust grains in orbit around the central protostar
- Through direct contact, these grains formed into clumps up to 200 metres in diameter, which in turn collided to form larger bodies (planetesimals) of ~10 kilometres (km) in size
- These gradually increased through further collisions, growing at the rate of centimetres per year over the course of the next few million years




n, publishing as Addison Wesley.

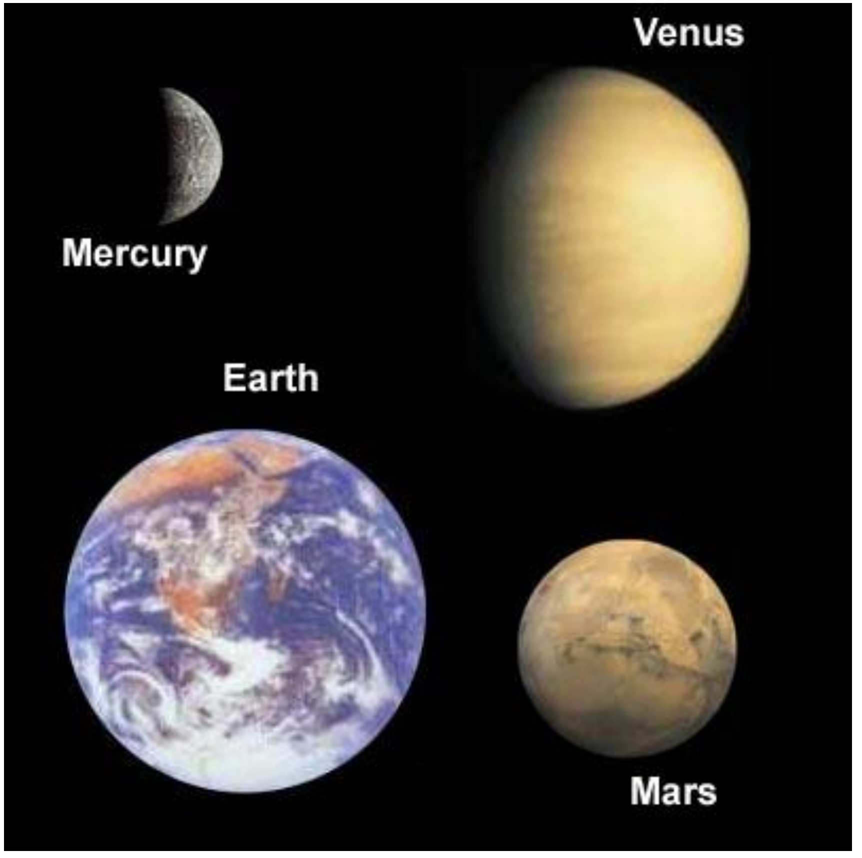
# The terrestrial planets

- The inner Solar System, the region of the Solar System inside 4 AU, was too warm for volatile molecules like water and methane to condense
- The planetesimals that formed there could contain only metals and rocky silicates
- These rocky bodies would become the terrestrial planets (Mercury, Venus, Earth, and Mars)
- These compounds are quite rare in the Universe, comprising only 0.6% of the mass of the nebula, so the terrestrial planets could not grow very large



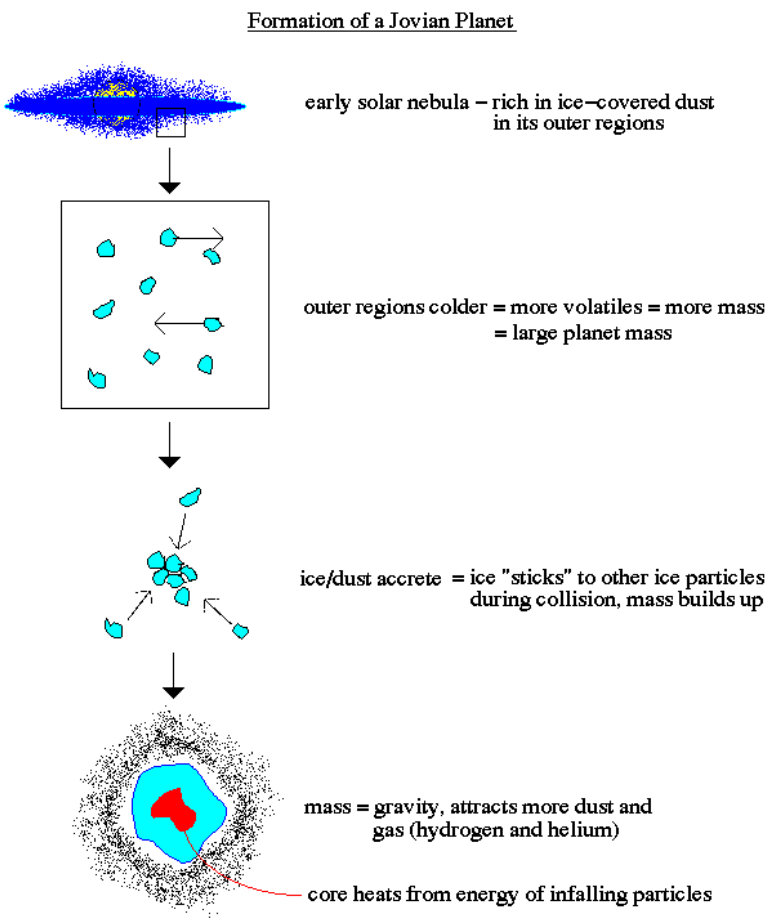
# The terrestrial planets (2)

- When the terrestrial planets were forming, they remained immersed in a disk of gas and dust
- The gas was partially supported by pressure and so did not orbit the Sun as rapidly as the planets
- The resulting drag caused a transfer of angular momentum, and as a result the planets gradually migrated to new orbits
- The net trend was for the inner planets to migrate inward as the disk dissipated, leaving the planets in their current orbits



# The giant planets

- The giant planets (Jupiter, Saturn, Uranus, and Neptune) formed further out, beyond the frost line, the point between the orbits of Mars and Jupiter where the material is cool enough for volatile icy compounds to remain solid
- The ices that formed the Jovian planets were more abundant than the metals and silicates that formed the terrestrial planets, allowing the giant planets to grow massive enough to capture hydrogen and helium
- Today, the four giant planets comprise just under 99% of all the mass orbiting the Sun

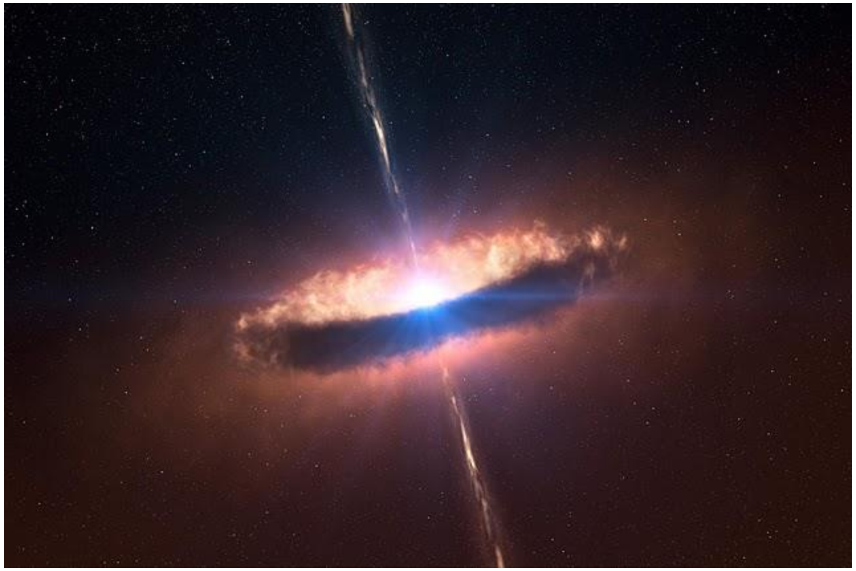


# The giant planets (2)

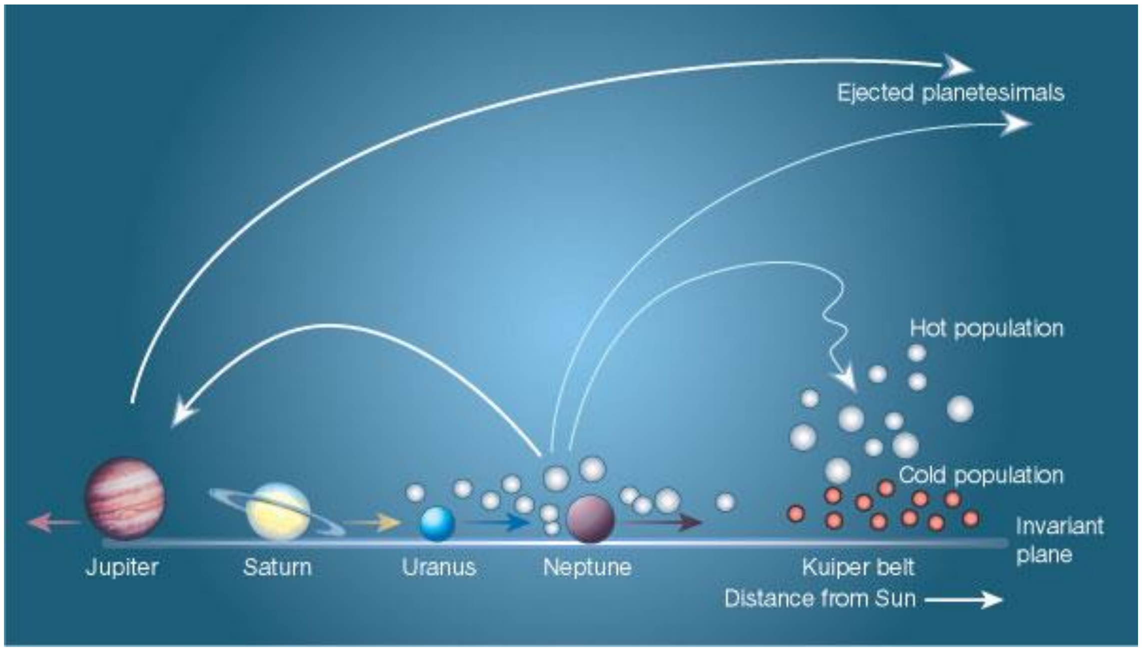
- T Tauri stars like the young Sun have far stronger stellar winds than more stable, older stars
- Uranus and Neptune are thought to have formed after Jupiter and Saturn did, when the strong solar wind had blown away much of the disc material
- As a result, the planets accumulated little hydrogen and helium - not more than one Earth mass each
- Uranus and Neptune are sometimes referred to as failed cores

# The giant planets (3)

- The main problem with formation theories for Uranus and Neptune is the timescale of their formation
- At the current locations it would have taken a hundred million years for their cores to accrete
- This means that they probably formed closer to the Sun, near or even between Jupiter and Saturn, and later migrated outward
- After between three and ten million years, the young Sun's solar wind would have cleared away all the gas and dust in the protoplanetary disc, blowing it into interstellar space, thus ending the growth of the planets



# Origin of minor bodies in the Solar System



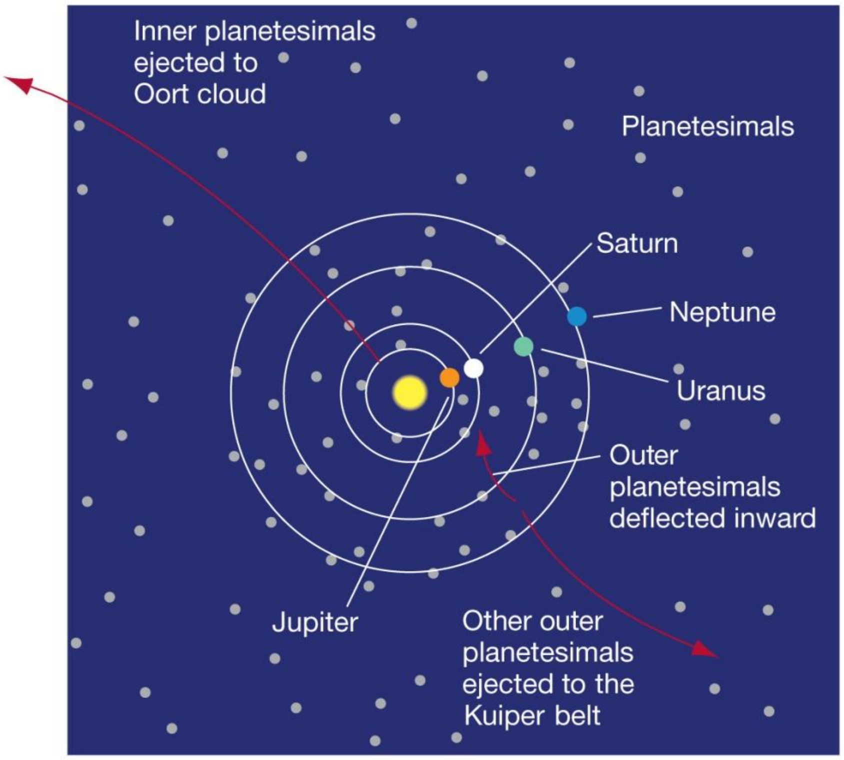

- Planetesimals that became modest in size but did not merge to form larger bodies became asteroids and comets
- The asteroid belt, between 2 and 4 AU from the Sun, may be result of fragmentation of planetisimals that were prevented from growing larger by the close proximity of Jupiter's gravitational pull
- The Kuiper Belt extends from the orbit of Neptune (at 30 AU) to approximately 50 AU from the Sun, and is similar to the asteroid belt
- Kuiper belt objects are composed largely of frozen volatiles such as methane, ammonia and water
- Other planetesimals were tossed about into random orbits from gravitational interaction with the larger planets and formed the Oort Cloud
- The Oort Cloud consists of some $10^{12}$ long-period comets that extends out to tens of thousands of AU, half way to our closest stellar neighbors

# Subsequent evolution of terrestrial planets

- At the end of the planetary formation epoch the inner Solar System was populated by 50-100 Moon- to Mars-sized planetary embryos.
- Further growth was possible only because these bodies collided and merged, which took less than 100 million years
- The inner Solar System's period of giant impacts probably played a role in the Earth acquiring its current water content from the early asteroid belt
- Water is too volatile to have been present at Earth's formation and must have been subsequently delivered from outer, colder parts of the Solar System
- The water was probably delivered by planetary embryos and small planetesimals thrown out of the asteroid belt by Jupiter

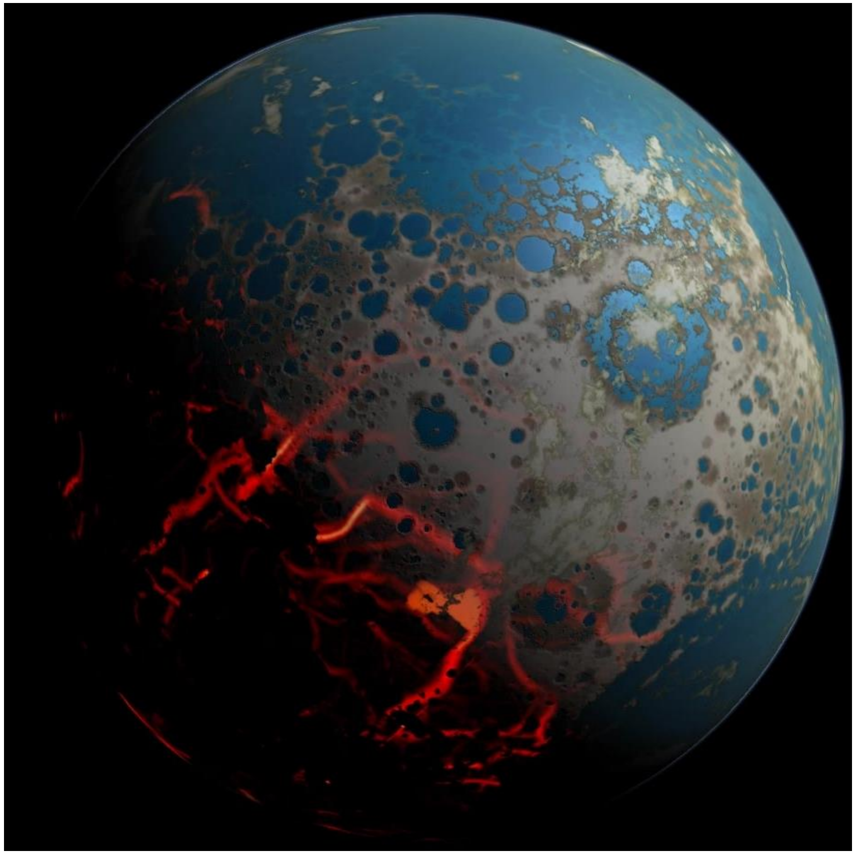
# Planetary migration in the outer Solar System

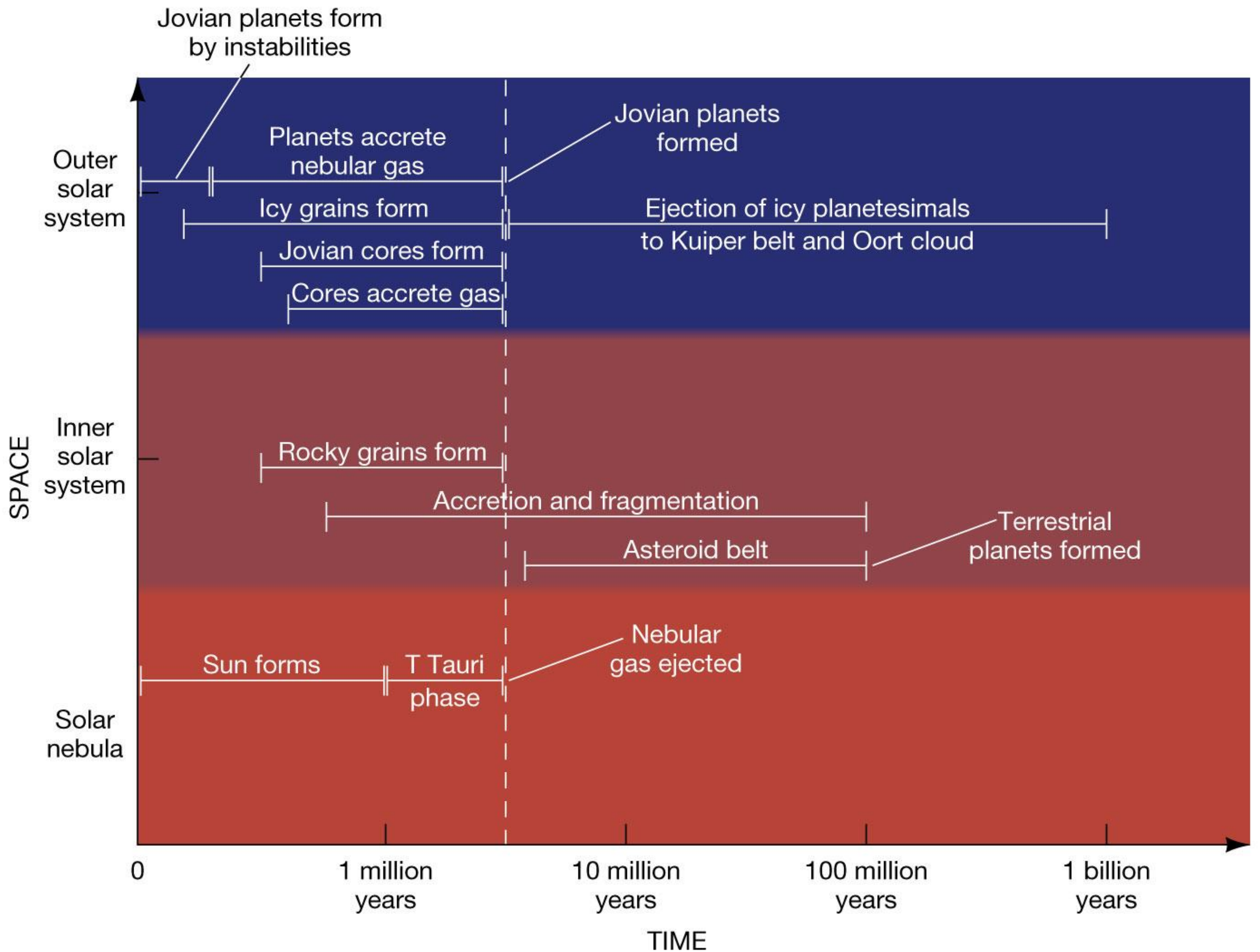
- After the formation of the Solar System, the orbits of all the giant planets continued to change slowly, influenced by their interaction with the large number of remaining planetesimals
- After 500-600 million years (about 4 billion years ago) Jupiter and Saturn fell into a 2:1 resonance: Saturn orbited the Sun once for every two Jupiter orbits
- This resonance created a gravitational push against the outer planets, causing Neptune to surge past Uranus and plough into the ancient Kuiper belt



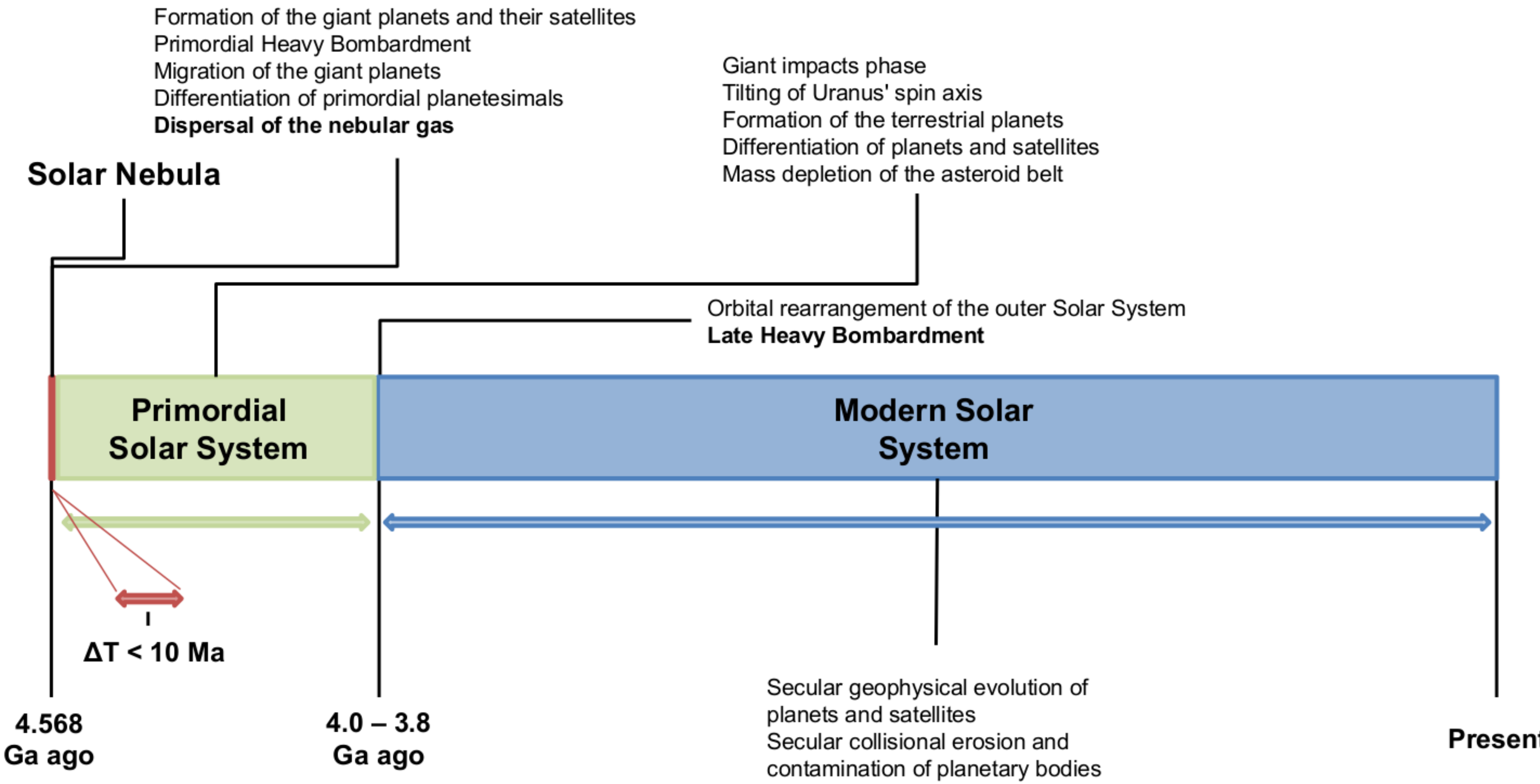
# Late Heavy Bombardment

- Gravitational disruption from the outer planets' migration would have sent large numbers of asteroids into the inner Solar System, severely depleting the original asteroid belt until it reached today's extremely low mass
- This event may have triggered the Late Heavy Bombardment that occurred approximately 4 billion years ago, 500-600 million years after the formation of the Solar System
- This period of heavy bombardment lasted several hundred million years and is evident in the cratering still visible on geologically dead bodies of the inner Solar System such as the Moon and Mercury
- The oldest known evidence for life on Earth dates to 3.8 billion years ago, almost immediately after the end of the Late Heavy Bombardment

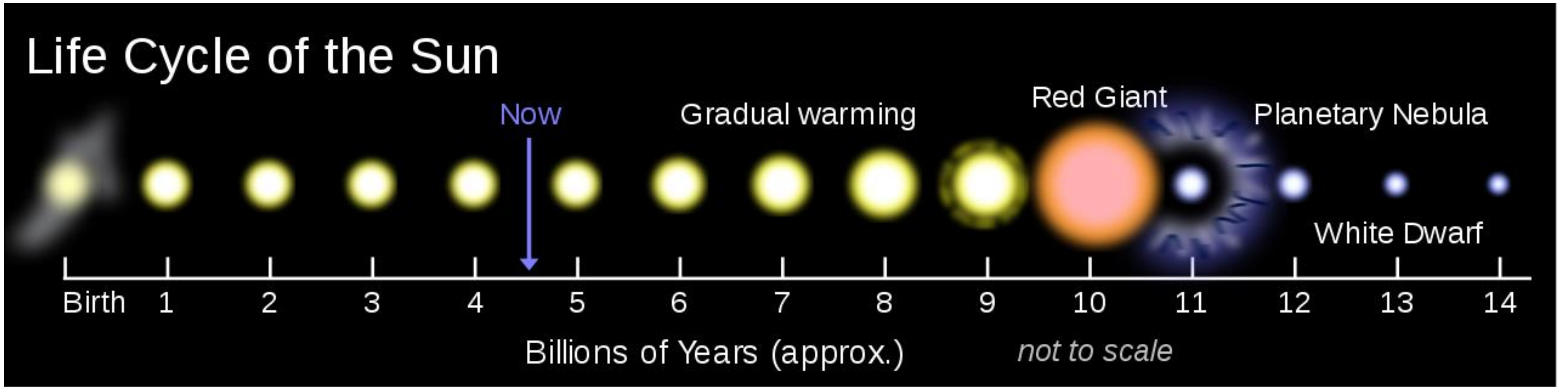




Jovian planets form by instabilities
Planets accrete nebular gas
Jovian planets formed
Icy grains form
Ejection of icy planetesimals to Kuiper belt and Oort cloud
Jovian cores form
Cores accrete gas
Outer solar system
Inner solar system
Solar nebula
SPACE
Rocky grains form
Accretion and fragmentation
Asteroid belt
Terrestrial planets formed
Sun forms
T Tauri phase
Nebular gas ejected
0
1 million years
10 million years
100 million years
1 billion years
TIME


Formation of the giant planets and their satellites
Primordial Heavy Bombardment
Migration of the giant planets
Differentiation of primordial planetesimals
Dispersal of the nebular gas
Solar Nebula
Giant impacts phase
Tilting of Uranus' spin axis
Formation of the terrestrial planets
Differentiation of planets and satellites
Mass depletion of the asteroid belt
Orbital rearrangement of the outer Solar System
Late Heavy Bombardment
Primordial Solar System
Modern Solar System
ΔT < 10 Ma
4.568 Ga ago
4.0 – 3.8 Ga ago
Secular geophysical evolution of planets and satellites
Secular collisional erosion and contamination of planetary bodies
Present

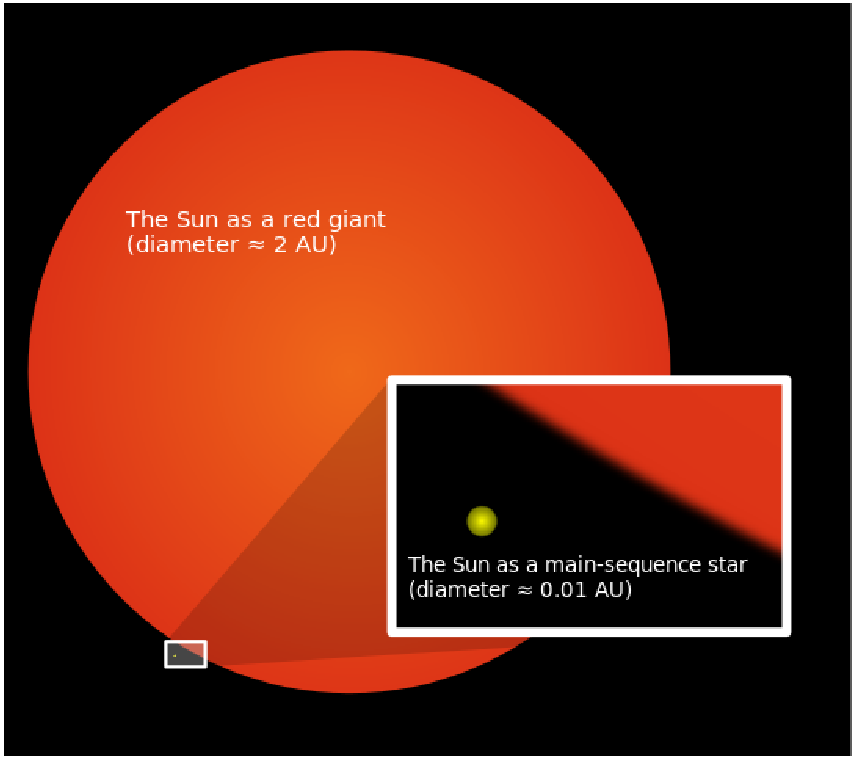
# The future of the Solar System




- Astronomers estimate that the current state of the Solar System will not change drastically until the Sun has fused almost all the hydrogen fuel in its core into helium, beginning its evolution from the main sequence of the Hertzsprung–Russell diagram and into its red-giant phase. The Solar System will continue to evolve until then.
- The Solar System is chaotic over million- and billion-year timescales, with the orbits of the planets open to long-term variations. One notable example of this chaos is the Neptune–Pluto system, which lies in a 3:2 orbital resonance. Although the resonance itself will remain stable, it becomes impossible to predict the position of Pluto with any degree of accuracy more than 10–20 million years (the Lyapunov time) into the future.
- Ultimately, the Solar System is stable in that none of the planets are likely to collide with each other or be ejected from the system in the next few billion years. Beyond this, within five billion years or so Mars's eccentricity may grow to around 0.2, such that it lies on an Earth-crossing orbit, leading to a potential collision.
- In the same timescale, Mercury's eccentricity may grow even further, and a close encounter with Venus could theoretically eject it from the Solar System altogether or send it on a collision course with Venus or Earth. This could happen within a billion years, according to numerical simulations in which Mercury's orbit is perturbed.

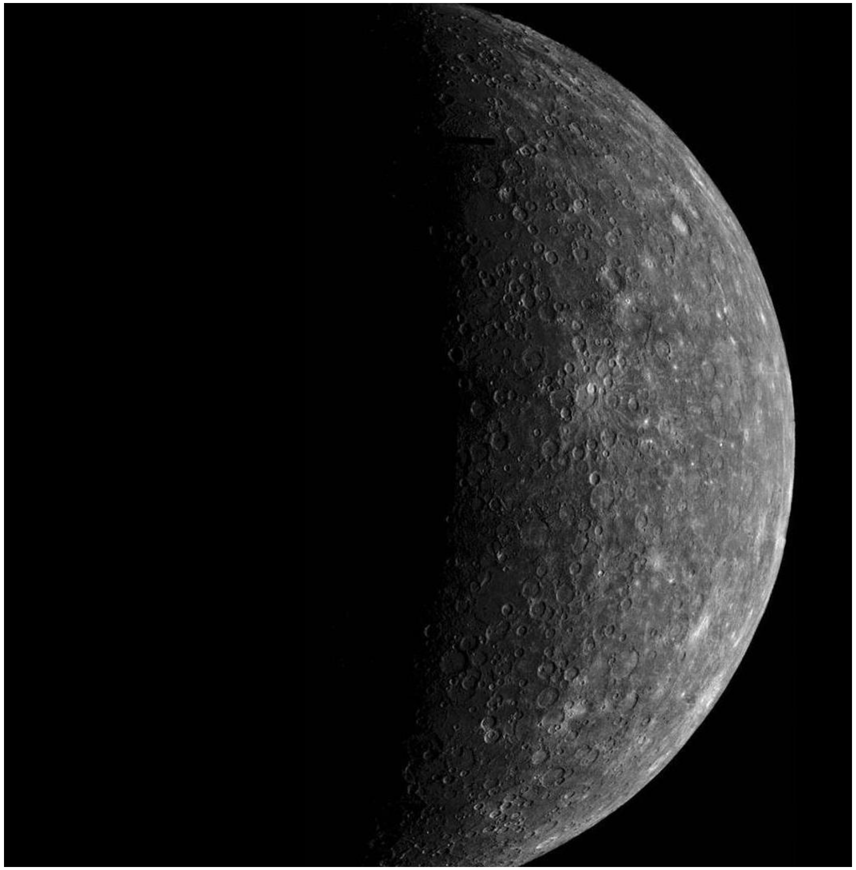
# The future of the Solar System (2)

- As the Sun burns through its supply of hydrogen fuel, it gets hotter and burns the remaining fuel even faster. As a result, the Sun is growing brighter at a rate of ten percent every 1.1 billion years.
- Around 5.4 billion years from now, the core of the Sun will become hot enough to trigger hydrogen fusion in its surrounding shell. This will cause the outer layers of the star to expand greatly, and the star will enter a phase of its life in which it is called a red giant.
- Within 7.5 billion years, the Sun will have expanded to a radius of 1.2 AU—256 times its current size. At the tip of the red giant branch, as a result of the vastly increased surface area, the Sun's surface will be much cooler (about 2600 K) than now and its luminosity much higher—up to 2,700 current solar luminosities. For part of its red giant life, the Sun will have a strong stellar wind that will carry away around 33% of its mass.
- As the Sun expands, it will swallow the planets Mercury and Venus. Earth's fate is less clear; although the Sun will envelop Earth's current orbit, the star's loss of mass (and thus weaker gravity) will cause the planets' orbits to move farther out.
- Afterwards, all that will remain of the Sun is a white dwarf, an extraordinarily dense object, 54% its original mass but only the size of the Earth. Initially, this white dwarf may be 100 times as luminous as the Sun is now. It will consist entirely of degenerate carbon and oxygen, but will never reach temperatures hot enough to fuse these elements. Thus the white dwarf Sun will gradually cool, growing dimmer and dimmer.
- As the Sun dies, its gravitational pull on the orbiting bodies such as planets, comets and asteroids will weaken due to its mass loss. All remaining planets' orbits will expand; if Venus, Earth, and Mars still exist, their orbits will lie roughly at 1.4 AU (210,000,000 km), 1.9 AU (280,000,000 km), and 2.8 AU (420,000,000 km). They and the other remaining planets will become dark, frigid hulks, completely devoid of any form of life.
- Eventually, after roughly 1 quadrillion years, the Sun will finally cease to shine altogether, becoming a black dwarf.



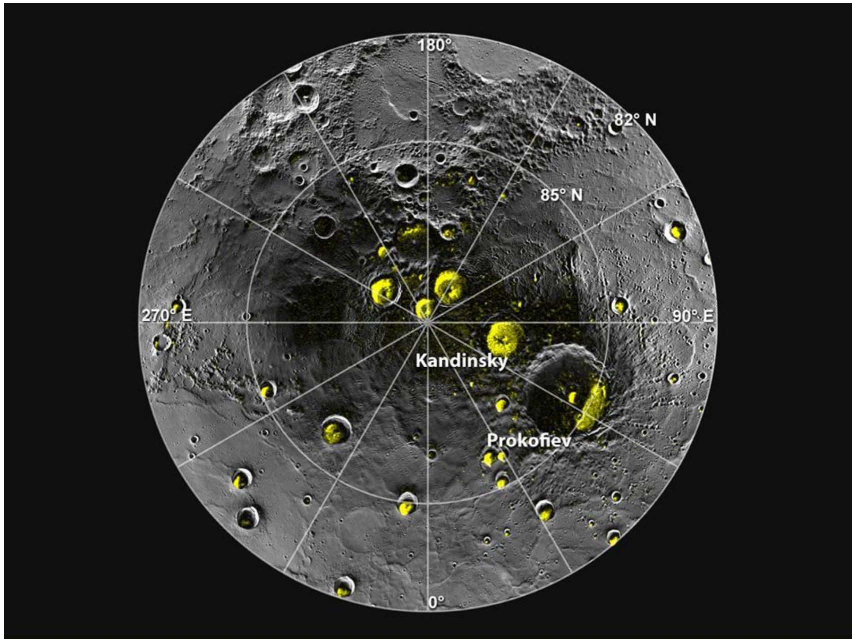
# Mercury

- Mercury's surface experiences the greatest temperature variation of the planets in the Solar System, ranging from 100 K at night to 700 K during the day at some equatorial regions
- Mercury's core has a higher iron content than that of any other major planet in the Solar System
- The most widely accepted theory is that Mercury originally had a metal-silicate ratio typical of the Solar System's rocky matter, and a mass approximately 2.25 times its current mass
- Early in the Solar System's history, Mercury may have been struck by a planetesimal of approximately 1/6 that mass and several thousand kilometers across
- The impact would have stripped away much of the original crust and mantle, leaving the core behind as a relatively major component



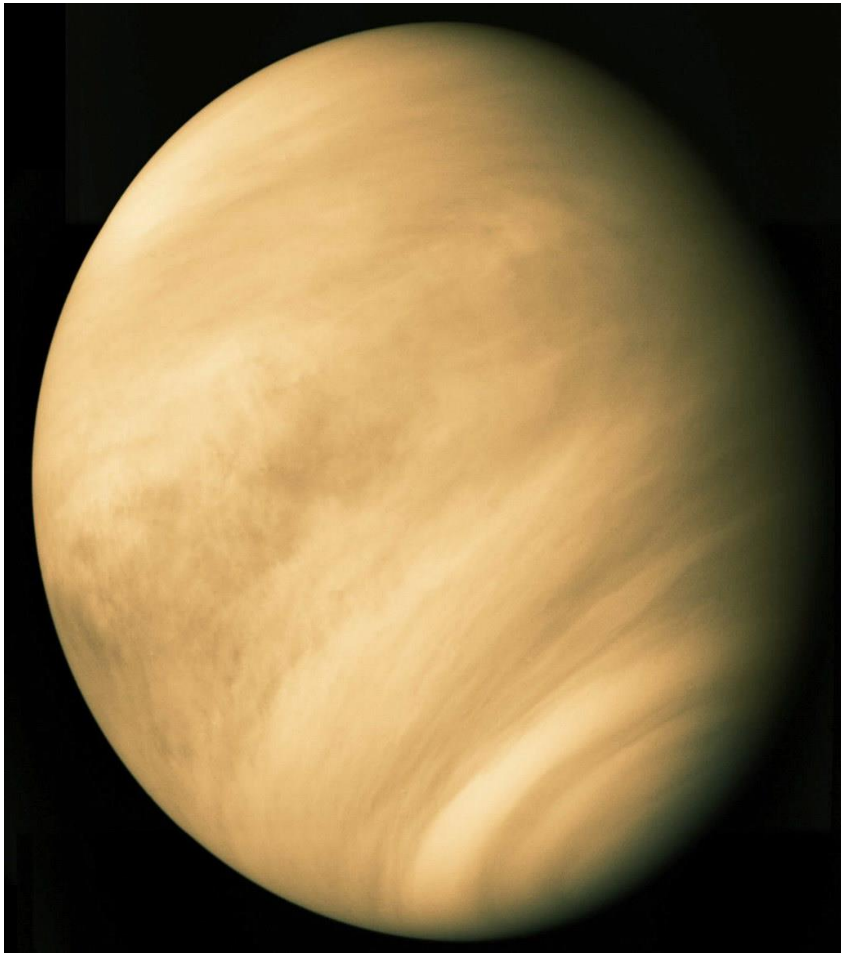
# Mercury (2)

- Although the daylight temperature at the surface of Mercury is generally extremely high, it is believed that ice (frozen water) exists on Mercury
- The floors of deep craters at the poles are never exposed to direct sunlight, and temperatures there remain below 102 K
- Water ice strongly reflects radar, and observations by the 70 m Goldstone telescope and the VLA in the early 1990s revealed that there are patches of high radar reflection near the poles
- Although ice is not the only possible cause of these reflective regions, it is believed to be the most likely
- The two most likely sources of the ice on Mercury are outgassing of water from the planet's interior or deposition by impacts of comets



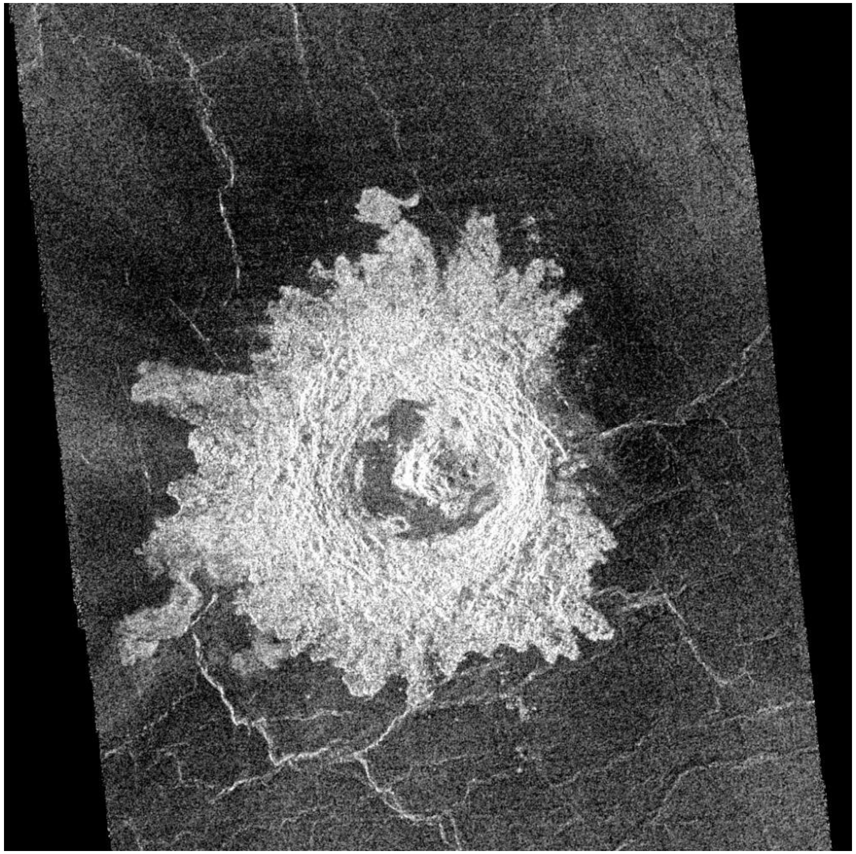
# Venus

- Venus is a terrestrial planet and is sometimes called Earth's "sister planet" because of their similar size, mass, proximity to the Sun and bulk composition
- It has the densest atmosphere of the four terrestrial planets, consisting of more than 96% carbon dioxide
- The atmospheric pressure at the planet's surface is 92 times that of Earth's
- With a mean surface temperature of 735 K, Venus is by far the hottest planet in the Solar System due to the greenhouse effect
- Venus is shrouded by an opaque layer of highly reflective clouds of sulfuric acid, preventing its surface from being seen from space in visible light
- Venus' surface is a dry desert interspersed with slab-like rocks and periodically refreshed by volcanism.

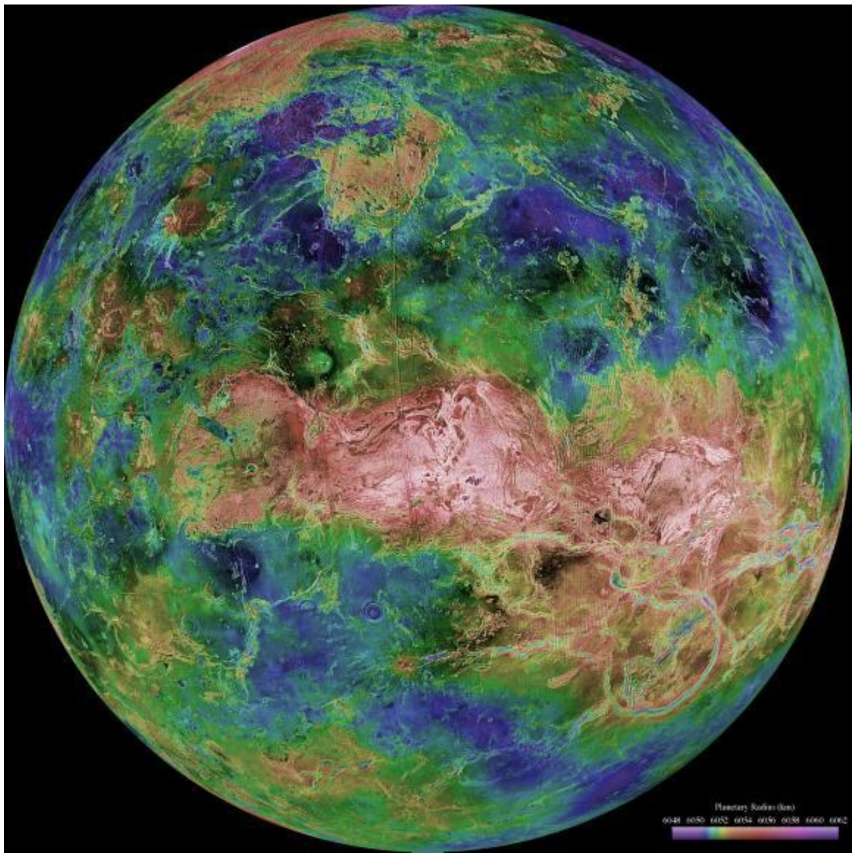


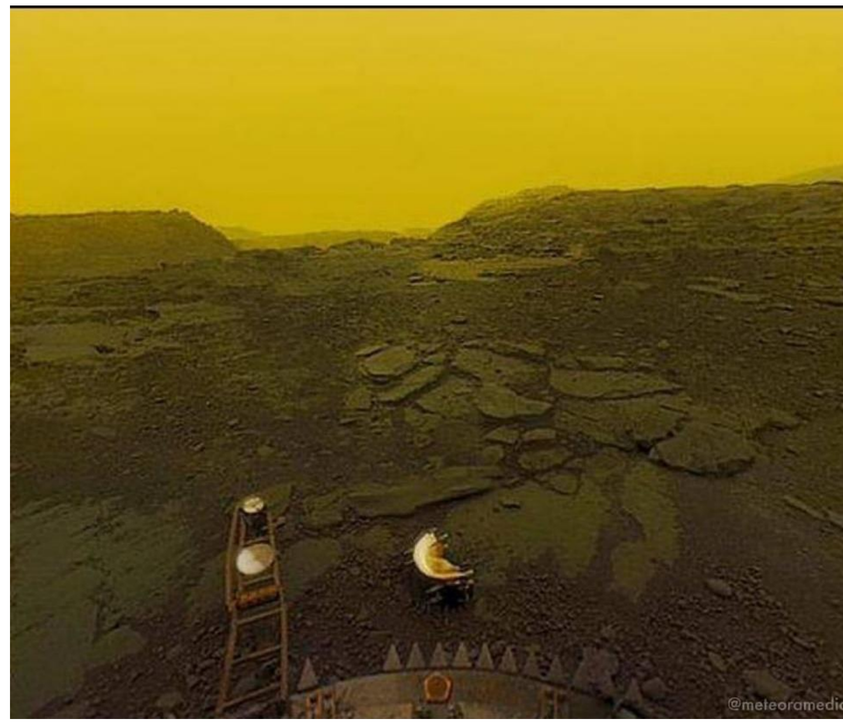
# Geology of Venus

- Venus has several times as many volcanoes as Earth, and it possesses 167 large volcanoes that are over 100 km across
- This is not because Venus is more volcanically active than Earth, but because its crust is older
- Earth's oceanic crust is continually recycled by subduction at the boundaries of tectonic plates, and has an average age of about 100 million years
- The number of craters, together with their well-preserved condition, indicates that Venus underwent a global resurfacing event about 300-600 million years ago, followed by a decay in volcanism
- Without plate tectonics to dissipate heat from its mantle, Venus undergoes a cyclical process in which mantle temperatures rise until they reach a critical level that weakens the crust
- Then, over a period of about 100 million years, subduction occurs on an enormous scale, completely recycling the crust

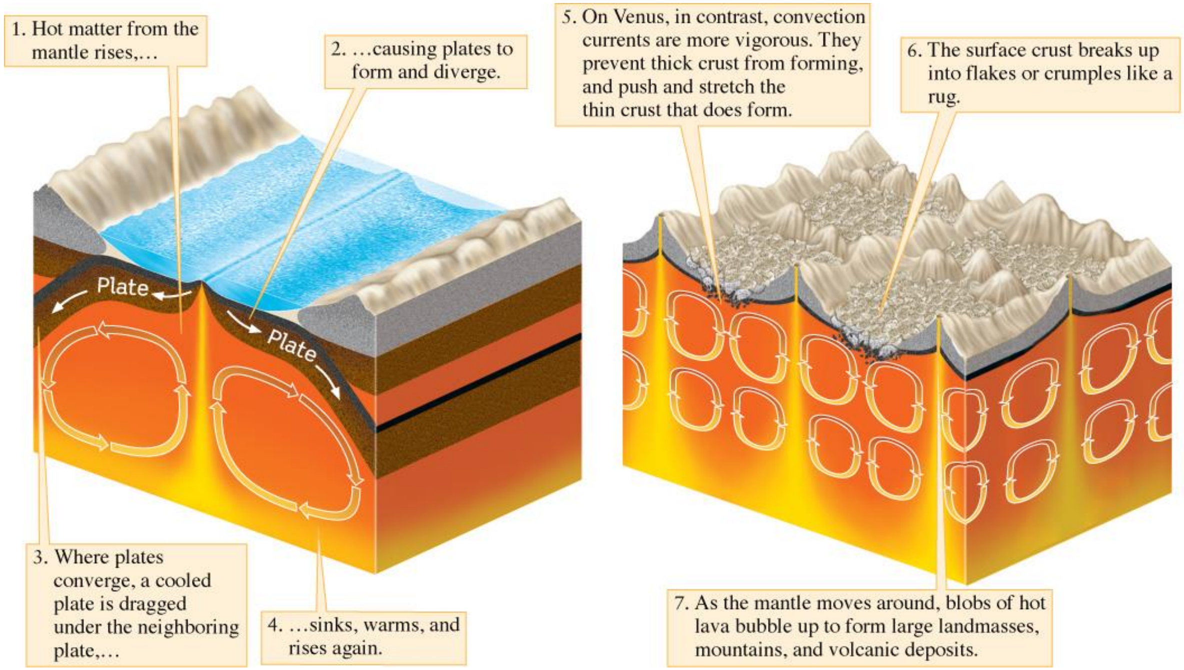


# The surface of Venus



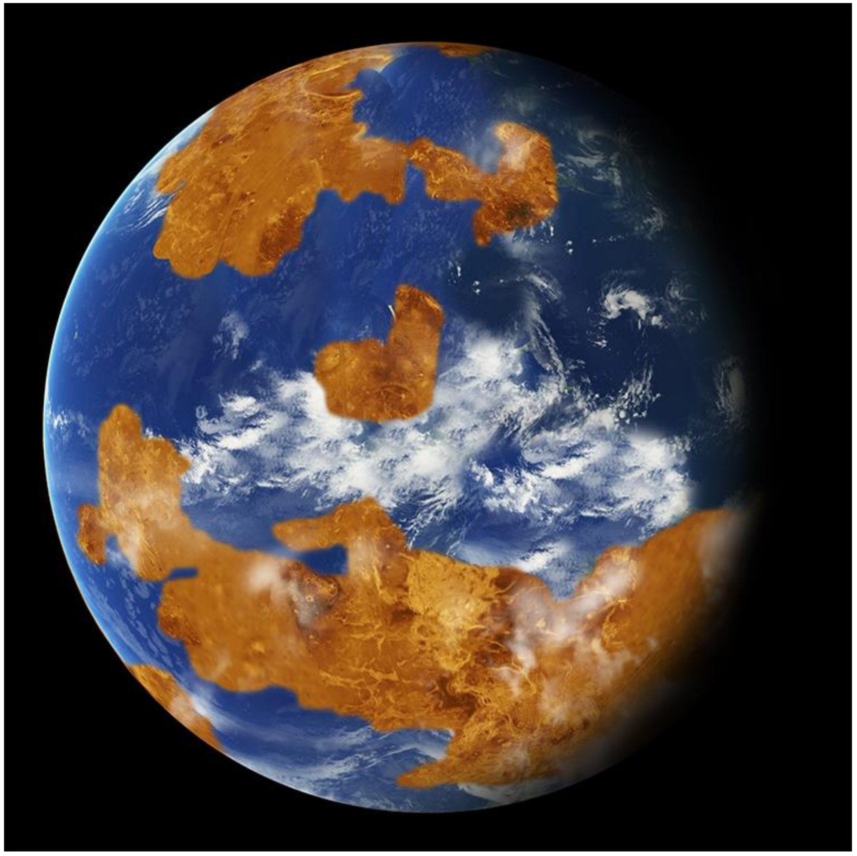
# Stagnant lid tectonics




- Lid tectonics, commonly thought of as stagnant lid tectonics, is the type of tectonics that is believed to exist on several planets and moons in the Solar System, and possibly on Earth during the early part of its history.
- The lid is the equivalent of the lithosphere in plate tectonics, formed of solid silicate minerals (or solid ice in the case of icy planets and moons). The lid will not participate in the underlying convection of the mantle and will not effectively mix a mantle.
- Venus has plumes similar to Earth, that would rise to the surface, and cold "drips" of lithosphere would sink back down.
- There are many characteristics of a planetary body that influence the presence and degree of lid tectonics: the temperature of a body's core–mantle boundary, and the presence of water strongly affect the rheological, composition, and thermal diagnostics of lid tectonics.
- Stagnant lid regime is the most common type of plate tectonics style that exists in the solar system.
- Beside Venus, Mercury, the Moon, and Io are all believed to have been dominated by lid tectonics for their entire history.
- Mars is also believed to have stagnant lid tectonics, albeit, much slower in comparison to Venus

# Ancient Venus

- According to computer modeling of the planet's ancient climate, Venus may have had a shallow liquid-water ocean and habitable surface temperatures for up to 2 billion years of its early history.
- Measurements by NASA's Pioneer mission to Venus in the 1980s first suggested Venus originally may have had an ocean. However, Venus is closer to the sun than Earth and receives far more sunlight.
- As a result, the planet's early ocean evaporated, water-vapor molecules were broken apart by ultraviolet radiation, and hydrogen escaped to space.
- With no water left on the surface, carbon dioxide built up in the atmosphere, leading to a so-called runaway greenhouse effect that created present conditions.
- Modelling results suggest that Venus' slow spin warmed the surface and produced rain creating a thick layer of clouds, shielding the surface from much of the solar heating.
- The result is mean climate temperatures that are actually a few degrees cooler than Earth's today.
- The slow increase of solar luminosity eventually led to the current state of the planet.



# Phosphine

- The presence of phosphine in the clouds of Venus has recently been announced, based on measurement by microwave telescopes from Earth.
- No ordinary chemical pathway could explain its presence, a biotic origin has been suggested.
- The viability of the high atmosphere of Venus for life has been hypothesized already in 2007.
- Recent reanalysis of observational data has led to a reduced estimate of the quantity of phosphine in Venus'atmosphere.

# The Earth

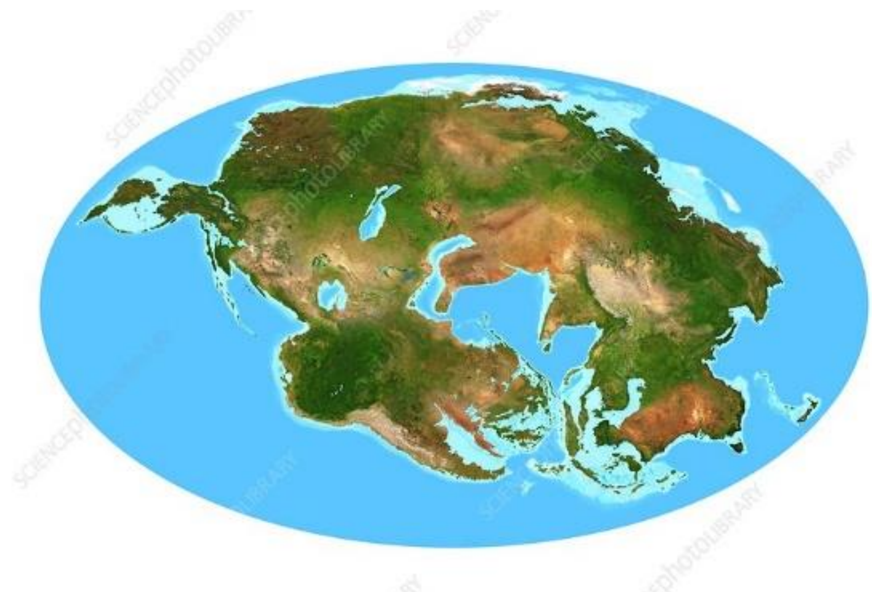
- Earth is the densest planet in the Solar System, the largest of the Solar System's four terrestrial planets, and the only astronomical object known to accommodate life
- The earliest life on Earth arose at least 3.5 billion years ago, and biodiversity has expanded continually except when interrupted by mass extinctions
- Although scholars estimate that over 99 percent of all species that ever lived on the planet are extinct, Earth is currently home to 10-14 million species of life
- Earth's biosphere has significantly altered its atmosphere
- Oxygenic photosynthesis evolved 2.7 billion years ago, forming the primarily nitrogen-oxygen atmosphere of today
- This change enabled the proliferation of aerobic organisms as well as the formation of the ozone layer, which blocks ultraviolet solar radiation, permitting life on land

# The Moon

- The Moon is Earth's only natural satellite, and is the largest moon in the Solar System relative to the size of its planet
- The Moon may have dramatically affected the development of life by moderating the planet's climate
- Paleontological evidence and computer simulations show that Earth's axial tilt is stabilized by tidal interactions with the Moon
- Without this stabilization against the torques applied by the Sun and planets to Earth's equatorial bulge, the rotational axis might be chaotically unstable, as appears to be the case for Mars
- The most widely accepted theory of the Moon's origin, the giant impact theory, states that it formed from the collision of a Mars-size protoplanet with the early Earth
- This hypothesis explains the Moon's relative lack of iron and volatile elements, and the fact that its composition is nearly identical to that of Earth's crust

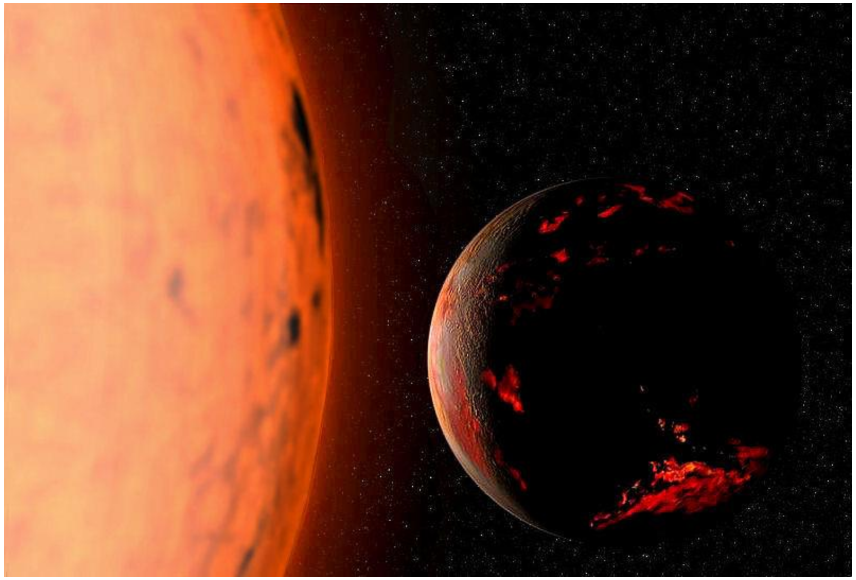
# The future of the Earth

- The biological and geological future of Earth can be extrapolated based upon the estimated effects of several long-term influences. These include the chemistry at Earth's surface, the rate of cooling of the planet's interior, the gravitational interactions with other objects in the Solar System, and a steady increase in the Sun's luminosity.
- Over time intervals of hundreds of millions of years, random celestial events pose a global risk to the biosphere, which can result in mass extinctions. These include impacts by comets or asteroids, and the possibility of a massive stellar explosion, called a supernova, within a 100-light-year radius of the Sun.
- Other large-scale geological events are more predictable. Milankovitch theory predicts that the planet will continue to undergo glacial periods at least until the Quaternary glaciation comes to an end. These periods are caused by variations in eccentricity, axial tilt, and precession of the Earth's orbit.

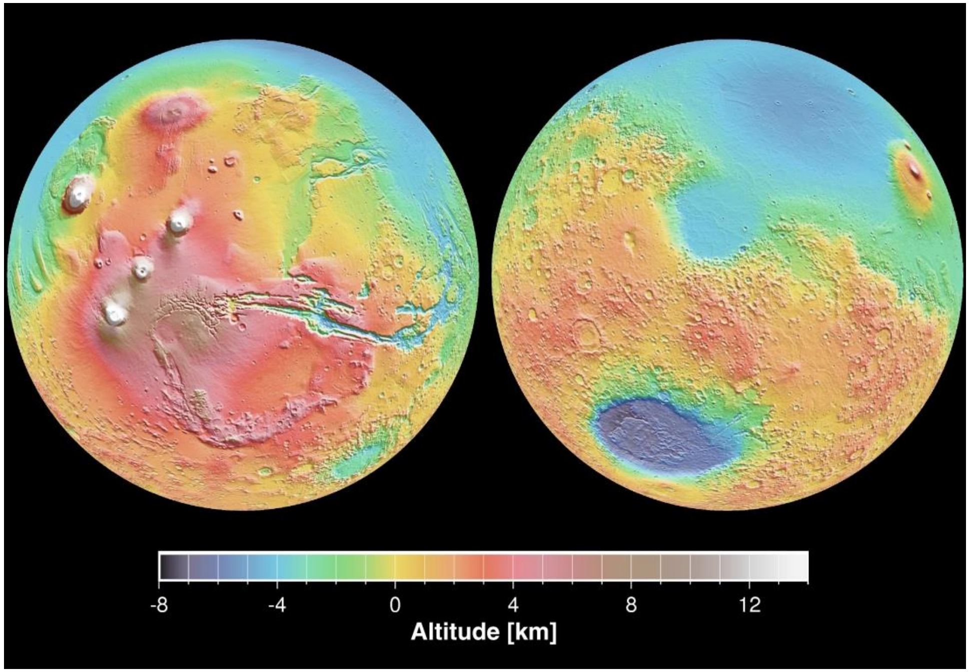


# The future of the Earth (2)

- The luminosity of the Sun will steadily increase, resulting in a rise in the solar radiation reaching the Earth. This will result in a higher rate of weathering of silicate minerals, which will cause a decrease in the level of carbon dioxide in the atmosphere.
- In about 600 million years from now, the level of carbon dioxide will fall below the level needed to sustain C3 carbon fixation photosynthesis used by trees. Some plants use the C4 carbon fixation method, allowing them to persist at carbon dioxide concentrations as low as 10 parts per million. However, the long-term trend is for plant life to die off altogether. The extinction of plants will be the demise of almost all animal life, since plants are the base of the food chain on Earth.
- In about one billion years, the solar luminosity will be 10% higher than at present. This will cause the atmosphere to become a "moist greenhouse", resulting in a runaway evaporation of the oceans. As a likely consequence, plate tectonics will come to an end, and with them the entire carbon cycle.
- Following this event, in about 2–3 billion years, the planet's magnetic dynamo may cease, causing the magnetosphere to decay and leading to an accelerated loss of volatiles from the outer atmosphere. Four billion years from now, the increase in the Earth's surface temperature will cause a runaway greenhouse effect, heating the surface enough to melt it. By that point, all life on the Earth will be extinct.
- The most probable fate of the planet is absorption by the Sun in about 7.5 billion years, after the star has entered the red giant phase and expanded beyond the planet's current orbit.



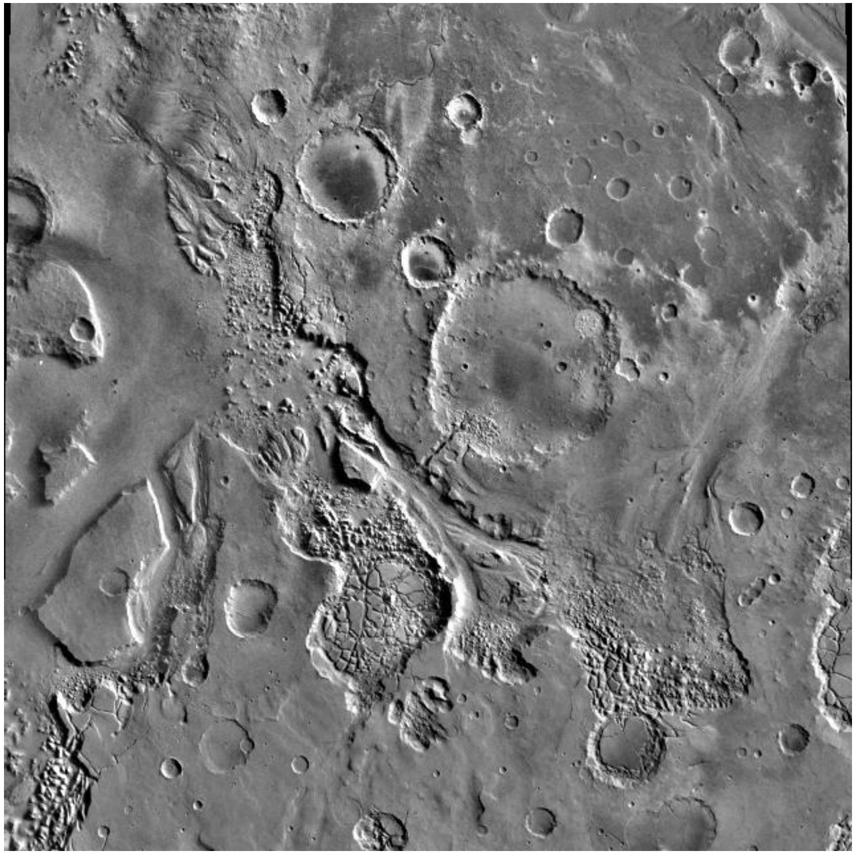
# Mars



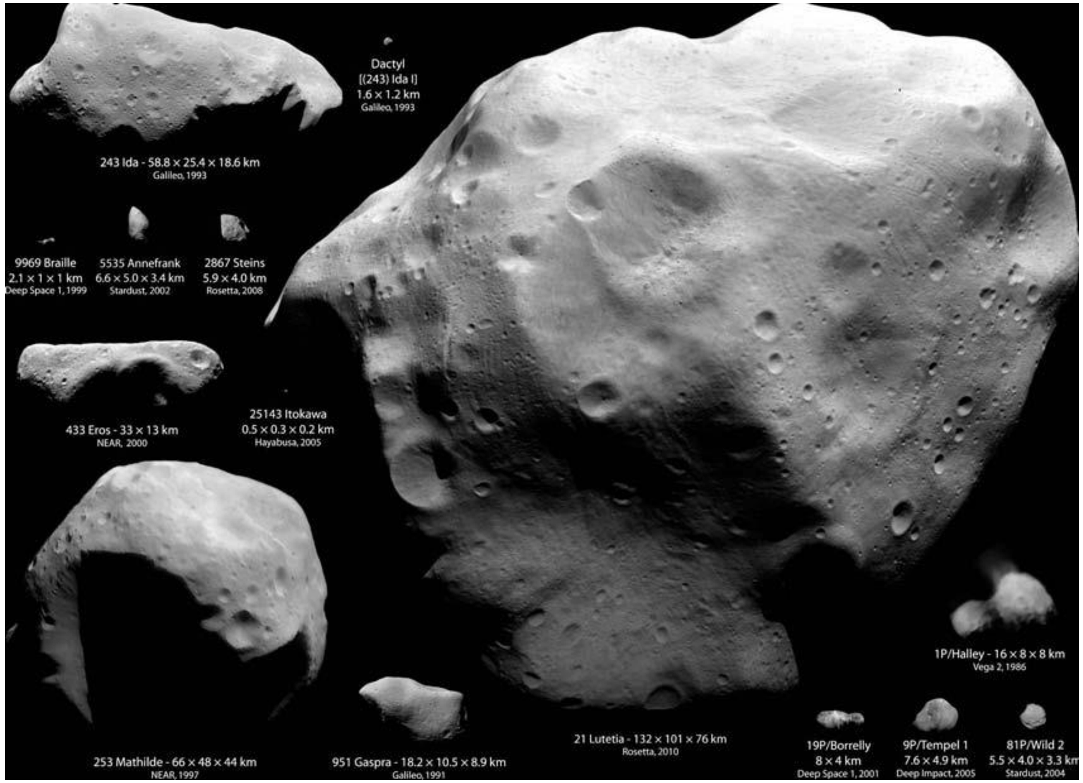

- Mars is a terrestrial planet with a thin atmosphere, having surface features reminiscent both of the impact craters of the Moon and the volcanoes, valleys, deserts, and polar ice caps of Earth
- There is no global magnetic field, but parts of the planet's crust have been magnetized, and alternating polarity reversals of its dipole field have occurred in the past
- About 60% of the surface of Mars shows a record of impacts from the Late Heavy Bombardment
- It is hypothesized that Mars was struck by a Pluto-sized body about four billion years ago, creating the smooth Borealis basin that covers 40% of the planet
- The two polar ice caps appear to be made largely of water ice for a volume that, if melted, would be sufficient to cover the entire planetary surface to a depth of about 20 meters
- A permafrost mantle stretches from the pole to latitudes of about 60°, containing an unknown quantity of water ice

# Mars (2)

- Landforms visible on Mars strongly suggest that liquid water has at least at times existed on the planet's surface
- Huge linear swathes of scoured ground, known as outflow channels, cut across the surface in around 25 places
- These are thought to record erosion which occurred during the catastrophic release of water from subsurface aquifers early in Mars's history
- Finer-scale, dendritic networks of valleys are spread across the oldest areas of the Martian surface
- Features of these valleys and their distribution strongly imply that they were carved by runoff resulting from rain or snow fall in early Mars history
- Subsurface water flow and groundwater sapping may play important subsidiary roles in some networks



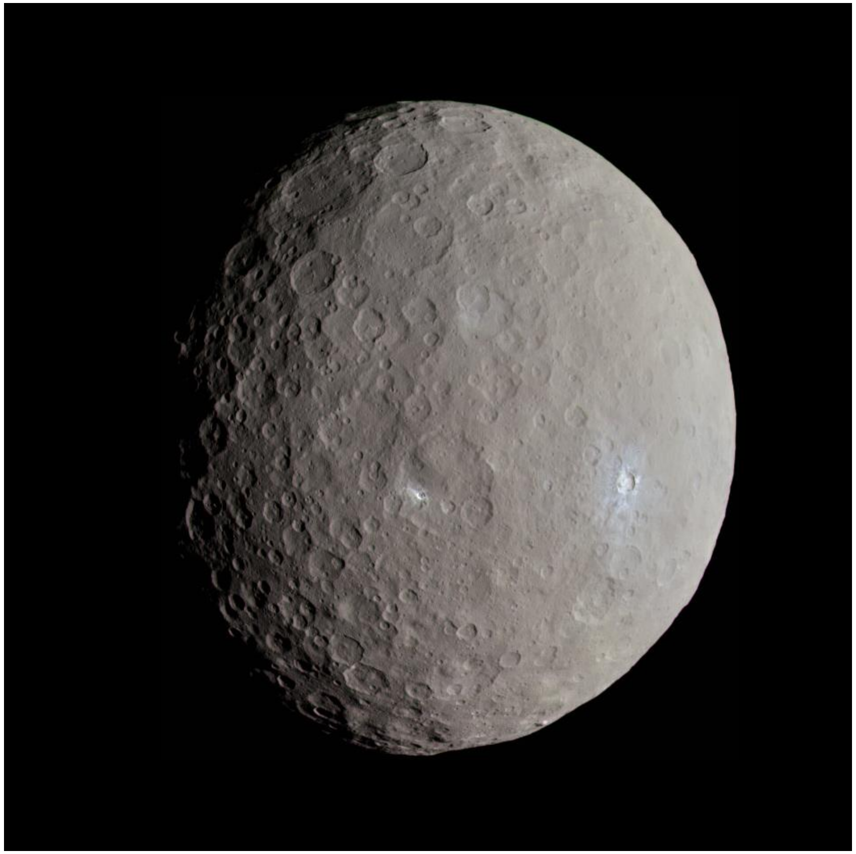
# The asteroid belt




- The asteroid belt initially contained more than enough matter to form 2-3 Earth-like planets
- Planetesimals in this region later coalesced and formed 20-30 Moon- to Mars-sized planetary embryos
- The proximity of Jupiter meant that after this planet formed, 3 million years after the Sun, the region's history changed dramatically
- Orbital resonances with Jupiter and Saturn are particularly strong in the asteroid belt, and gravitational interactions with more massive embryos scattered many planetesimals into those resonances
- Jupiter's gravity increased the velocity of objects within these resonances, causing them to shatter upon collision with other bodies, rather than accrete

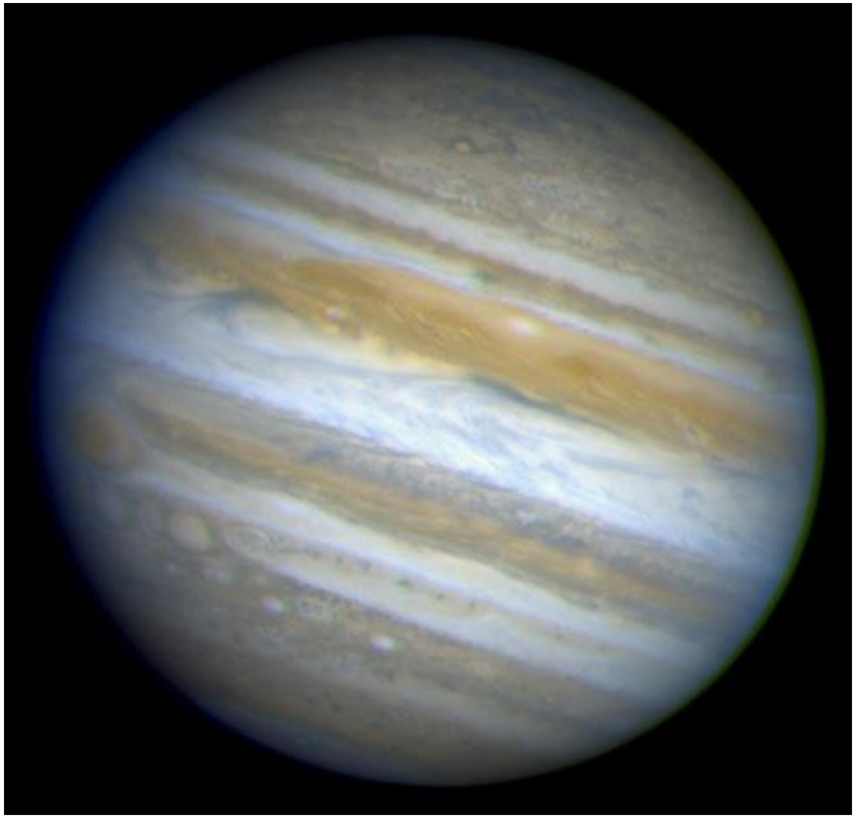
# Ceres

- Ceres is the largest object in the asteroid belt, and contains approximately one-third of its total mass
- It is the only object in the asteroid belt known to be rounded by its own gravity
- Ceres appears to be differentiated into a rocky core and an icy mantle, and may have a remnant internal ocean of liquid water under the layer of ice
- The surface is a mixture of water ice and various hydrated minerals such as carbonates and clay
- In January 2014, emissions of water vapor were detected from several regions of Ceres



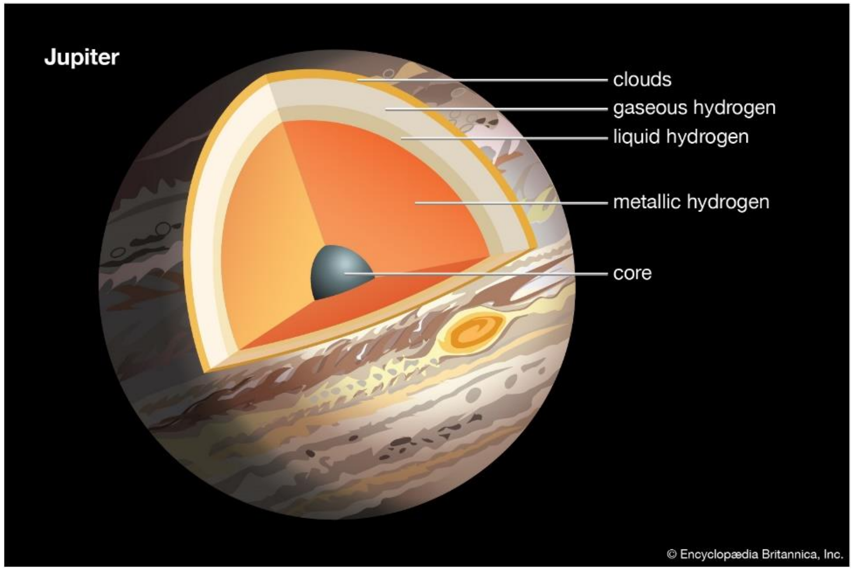
# Jupiter

- Jupiter is the largest planet in the Solar System, with a mass two and a half times that of all the other planets in the Solar System combined
- It is primarily composed of hydrogen with a quarter of its mass being helium
- It may also have a rocky core of heavier elements, but like the other giant planets, Jupiter lacks a well-defined solid surface
- Because of its rapid rotation, the planet's shape is that of an oblate spheroid
- The outer atmosphere is visibly segregated into several bands at different latitudes, resulting in turbulence and storms along their interacting boundaries
- Surrounding Jupiter is a faint planetary ring system and a powerful magnetosphere
- Jupiter has at least 67 moons, including the four large Galilean moons discovered by Galileo Galilei in 1610



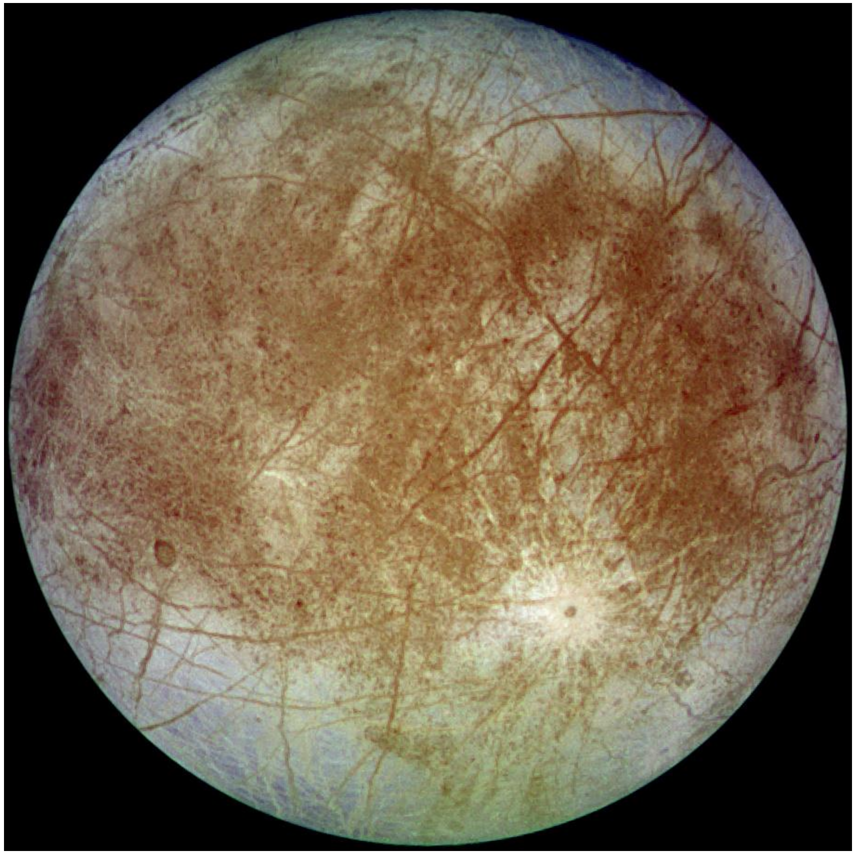
# Internal structure of Jupiter

- Jupiter is thought to consist of a dense core with a mixture of elements, a surrounding layer of liquid metallic hydrogen with some helium, and an outer layer predominantly of molecular hydrogen. Beyond this basic outline, there is still considerable uncertainty. The core is often described as rocky, but its detailed composition is unknown, as are the properties of materials at the temperatures and pressures of those depths.
- The presence of a core during at least part of Jupiter's history is suggested by models of planetary formation that require the formation of a rocky or icy core massive enough to collect its bulk of hydrogen and helium from the protosolar nebula. Assuming it did exist, it may have shrunk as convection currents of hot liquid metallic hydrogen mixed with the molten core and carried its contents to higher levels in the planetary interior.
- The core region may be surrounded by dense metallic hydrogen, which extends outward to about 78% of the radius of the planet. Rain-like droplets of helium and neon precipitate downward through this layer, depleting the abundance of these elements in the upper atmosphere. Rainfalls of extraterrestrial diamonds have been suggested to occur on Jupiter, as well as on Saturn and the ice giants Uranus and Neptune.
- Above the layer of metallic hydrogen lies a transparent interior atmosphere of hydrogen. At this depth, the pressure and temperature are above hydrogen's critical pressure of 1.2858 MPa and critical temperature of only 32.938 K. In this state, there are no distinct liquid and gas phases—hydrogen is said to be in a supercritical fluid state.
- Jupiter radiates about 1.6 times as much heat, in the form of infrared energy, as it receives from the Sun. This indicates that Jupiter has an internal source of energy - probably heat created by Jupiter's collapse when it was formed.



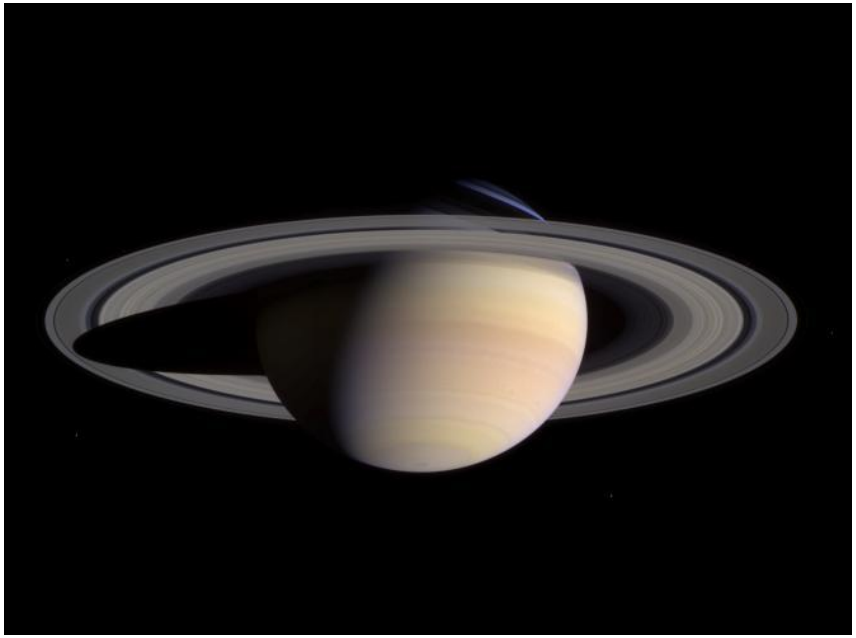
# Europa

- Europa is the smallest of its four Galilean satellites, but still the sixth-largest moon in the Solar System
- Slightly smaller than the Moon, Europa is primarily made of silicate rock and has a water-ice crust and probably an iron-nickel core
- It has a tenuous atmosphere composed primarily of oxygen
- Its surface is striated by cracks and streaks, whereas craters are relatively rare
- It has the smoothest surface of any known solid object in the Solar System
- The apparent youth and smoothness of the surface have led to the hypothesis that a water ocean exists beneath it, which could conceivably serve as an abode for extraterrestrial life
- This hypothesis proposes that heat from tidal flexing causes the ocean to remain liquid and drives geological activity similar to plate tectonics



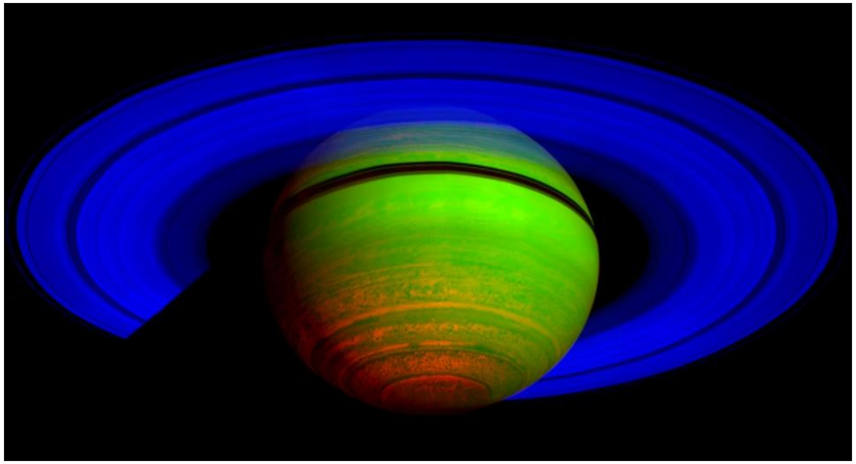
# Saturn

- Saturn is a gas giant with an average radius about nine times that of Earth
- Saturn's interior is probably composed of a core consisting of iron-nickel and rock, surrounded by a deep layer of metallic hydrogen, an intermediate layer of liquid hydrogen and liquid helium and an outer gaseous layer
- Saturn has a prominent ring system that consists of nine continuous main rings and three discontinuous arcs, composed mostly of ice particles with a smaller amount of rocky debris and dust
- Sixty-two known moons orbit the planet, of which fifty-three are officially named
- Titan, Saturn's largest and the Solar System's second largest moon, is larger than the planet Mercury and is the only moon in the Solar System to retain a substantial atmosphere



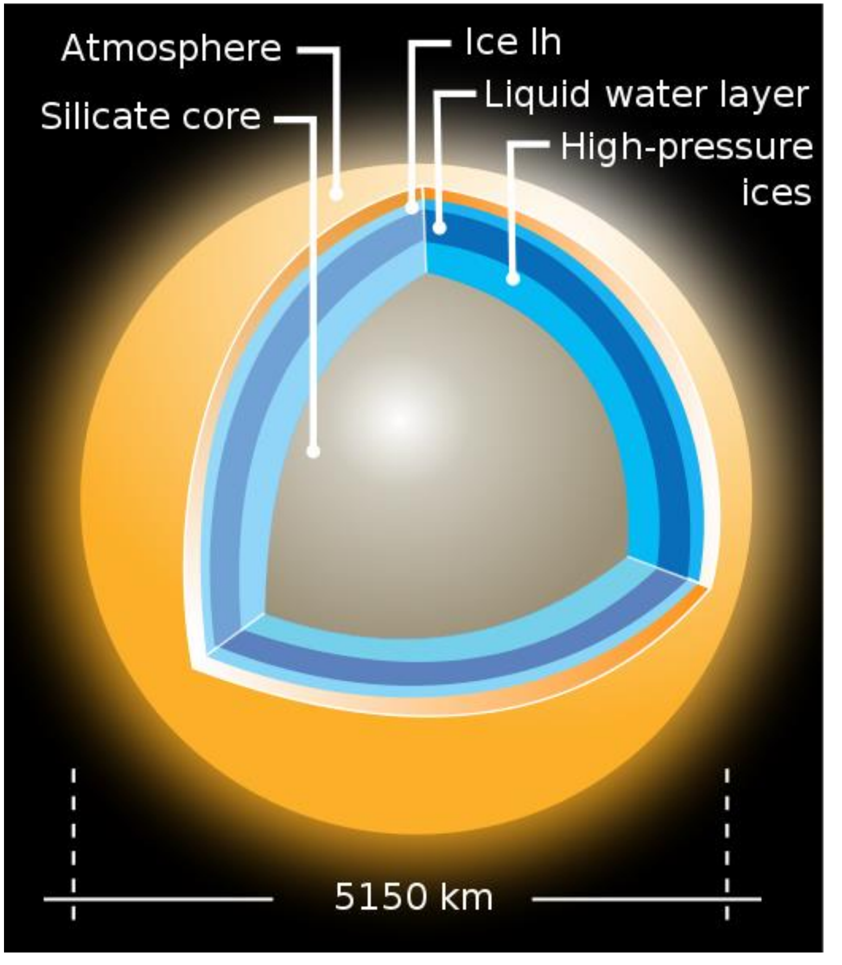
# Saturn’s energy budget

- Careful measurements of Saturn's energy budget (balance of energy absorbed versus energy radiated) show that the planet radiates 1.5–2.5 times more energy into space than it receives from the Sun.
- This radiated energy indicates that the planet must have an internal heat source.
- It is thought that Saturn draws its extra energy from two sources: (1) heat left over from the planet's formation approximately 4.5 billion years ago, still radiating out into space, and (2) the "raining out" of atmospheric helium.
- Just as water condenses in terrestrial clouds to produce rain, droplets of liquid helium form in Saturn's atmosphere. As these droplets fall through Saturn's atmosphere they acquire kinetic energy. This energy is absorbed into deeper layers where the droplets meet resistance and slow their fall, and the temperature in those regions increases.
- This thermal energy is eventually circulated by convection back up through the higher layers of the atmosphere and radiated into space. The helium raining out of Saturn's upper layers is left over from the planet's formation; in about two billion more years all of Saturn's helium will have sunk deep into the planet, at which time heating by helium condensation will cease.



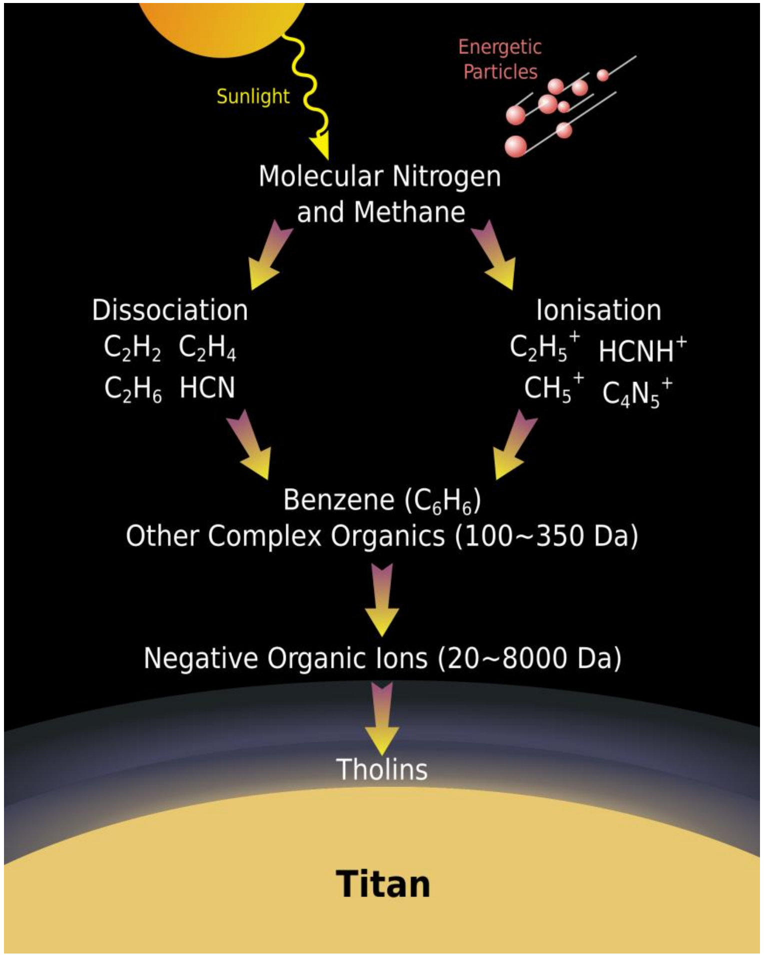
# Titan

- Titan is the only natural satellite known to have a dense atmosphere, and the only object other than Earth where clear evidence of stable bodies of surface liquid has been found
- Titan is primarily composed of water ice and rocky material, but it also has liquid hydrocarbon lakes in its polar regions
- The geologically young surface is generally smooth, with few impact craters, although mountains and several possible cryovolcanoes have been found
- The atmosphere of Titan is largely nitrogen; minor components lead to the formation of methane and ethane clouds and nitrogen-rich organic smog
- The climate - including wind and rain - creates surface features similar to those of Earth, such as dunes, rivers, lakes, seas and deltas, and is dominated by seasonal weather patterns as on Earth
- Titan's methane cycle is viewed as an analogy to Earth's water cycle, although at a much lower temperature



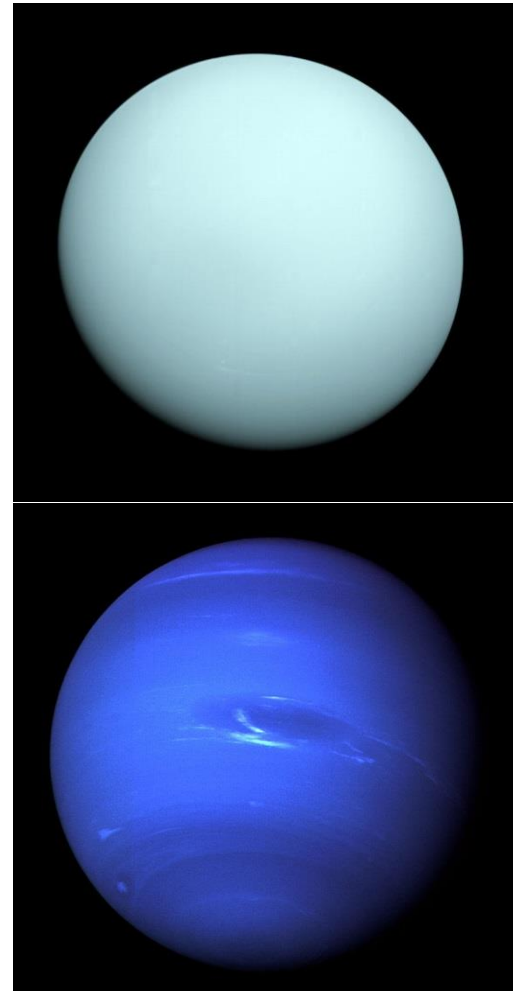
# Titan (2)

- Titan is thought to be a prebiotic environment rich in complex organic chemistry with a possible subsurface liquid ocean serving as a biotic environment
- The atmosphere of early Earth was similar in composition to the current atmosphere on Titan, with the important exception of a lack of water vapor on Titan
- The Miller-Urey experiment and several following experiments have shown that with an atmosphere similar to that of Titan and the addition of UV radiation, complex molecules and polymer substances like tholins can be generated
- The reaction starts with dissociation of nitrogen and methane, forming hydrogen cyanide and acetylene
- The five nucleotide bases - building blocks of DNA and RNA - and amino acids were found among the many compounds produced when energy was applied to a combination of gases like those in Titan's atmosphere, without liquid water being present



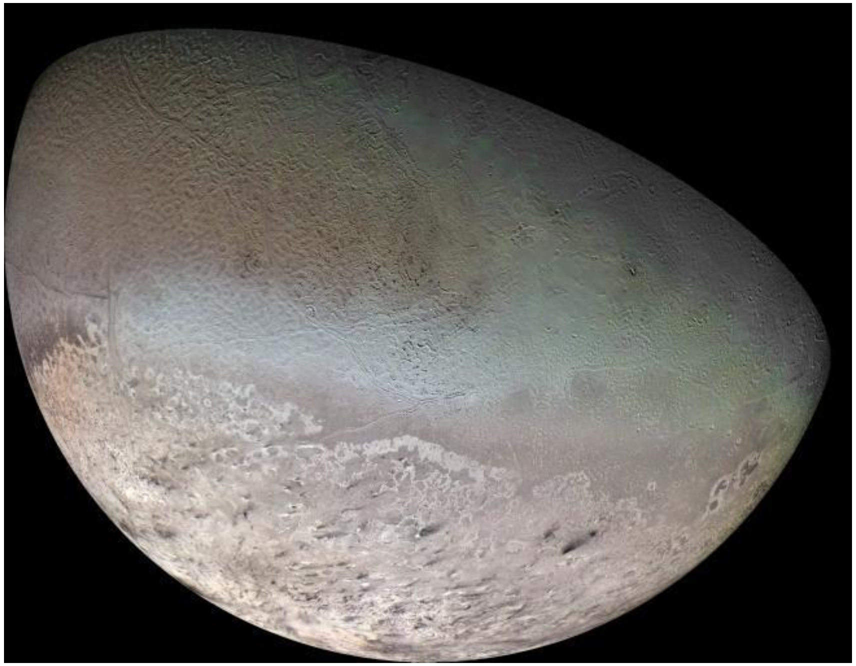
# Uranus and Neptune

- Uranus and Neptune have similar bulk composition, which is different from that of the larger gas giants Jupiter and Saturn
- They are called "ice giants", because their atmosphere, although composed primarily of hydrogen and helium, contains more "ices", such as water, ammonia, and methane, along with traces of other hydrocarbons
- Uranus's atmosphere is the coldest in the Solar System, with a minimum temperature of 49 K, and has a complex, layered cloud structure, with water thought to make up the lowest clouds, and methane the uppermost layer of clouds
- The interior of Uranus and Neptune is mainly composed of ices and rock
- Perhaps the core has a solid surface, but the temperature would be thousands of degrees and the atmospheric pressure crushing



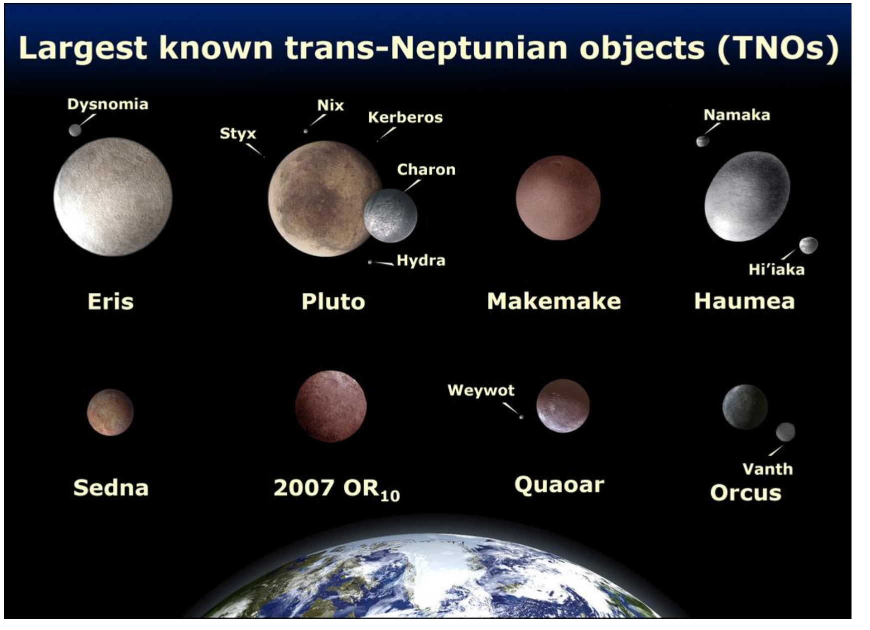
# Triton

- Triton is the largest of Neptune's 13 moons. It is unusual because it is the only large moon in our solar system that orbits in the opposite direction of its planet's rotation—a retrograde orbit.
- Scientists think Triton is a Kuiper Belt Object captured by Neptune's gravity millions of years ago. It shares many similarities with Pluto, the best known world of the Kuiper Belt.
- Like our own moon, Triton is locked in synchronous rotation with Neptune—one side faces the planet at all times. But because of its unusual orbital inclination both polar regions take turns facing the Sun.
- Triton consists of a crust of frozen nitrogen over an icy mantle believed to cover a core of rock and metal. Triton has a density about twice that of water. This is a higher density than that measured for almost any other satellite of an outer planet. Europa and Io have higher densities. This implies that Triton contains more rock in its interior than the icy satellites of Saturn and Uranus.
- Triton's thin atmosphere is composed mainly of nitrogen with small amounts of methane. This atmosphere most likely originates from Triton's volcanic activity, which is driven by seasonal heating by the Sun. Triton, Io and Venus are the only bodies in the solar system besides Earth that are known to be volcanically active at the present time.



# The Kuiper Belt

- The Kuiper belt, sometimes called the Edgeworth-Kuiper belt, is a region of the Solar System beyond the planets, extending from the orbit of Neptune (at 30 AU) to approximately 50 AU from the Sun
- It is similar to the asteroid belt, but it is far larger - 20 times as wide and 20 to 200 times as massive
- It is now considered to be the source of the short-period comets
- Like the asteroid belt, it consists mainly of small bodies, or remnants from the Solar System's formation
- Most Kuiper belt objects are composed largely of frozen volatiles, such as methane, ammonia and water
- The Kuiper belt is home to three officially recognized dwarf planets: Pluto, Haumea, and Makemake
- It is estimated that there are at least 35'000 Kuiper Belt objects greater than 100 km in diameter, which is several hundred times the number (and mass) of similar sized objects in the main asteroid belt

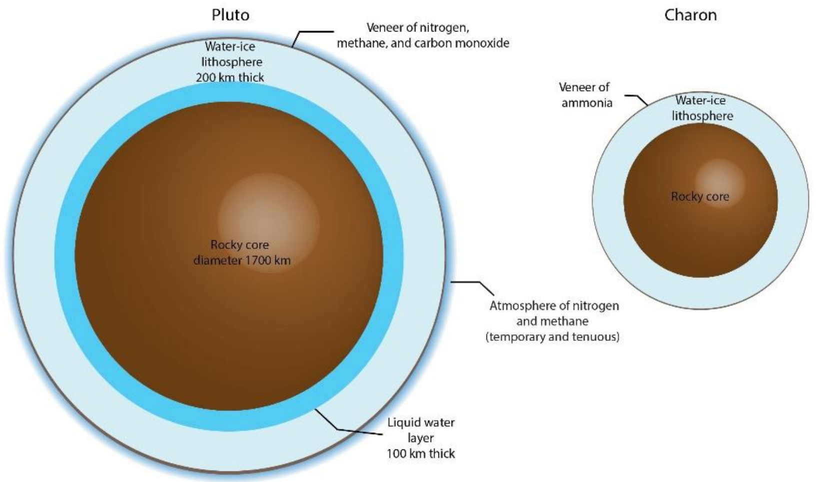


# Pluto

- Pluto (minor planet designation: 134340 Pluto) is a dwarf planet in the Kuiper belt. Despite Pluto's orbit appearing to cross that of Neptune when viewed from directly above, the two objects' orbits are aligned so that they can never collide or even approach closely.
- Pluto's rotation period, its day, is equal to 6.39 Earth days. Like Uranus, Pluto rotates on its "side" in its orbital plane, with an axial tilt of 120°, and so its seasonal variation is extreme. This unusual orientation may be due to the way that a body's spin will always adjust to minimise energy. This could mean a body reorienting itself to put extraneous mass near the equator and regions lacking mass tend towards the poles. This could be caused by masses of frozen nitrogen building up in shadowed areas of the dwarf planet.
- The plains on Pluto's surface are composed of more than 98 percent nitrogen ice, with traces of methane and carbon monoxide. Nitrogen and carbon monoxide are most abundant on the anti-Charon face of Pluto (around 180° longitude, where Tombaugh Regio's western lobe, Sputnik Planitia, is located), whereas methane is most abundant near 300° east.
- Sputnik Planitia, the western lobe of the "Heart", is a 1,000 km-wide basin of frozen nitrogen and carbon monoxide ices, divided into polygonal cells, which are interpreted as convection cells that carry floating blocks of water ice crust and sublimation pits towards their margins
- Pluto has a tenuous atmosphere consisting of nitrogen ($N_2$), methane ($CH_4$), and carbon monoxide (CO), which are in equilibrium with their ices on Pluto's surface.

# Structure and origin of Pluto

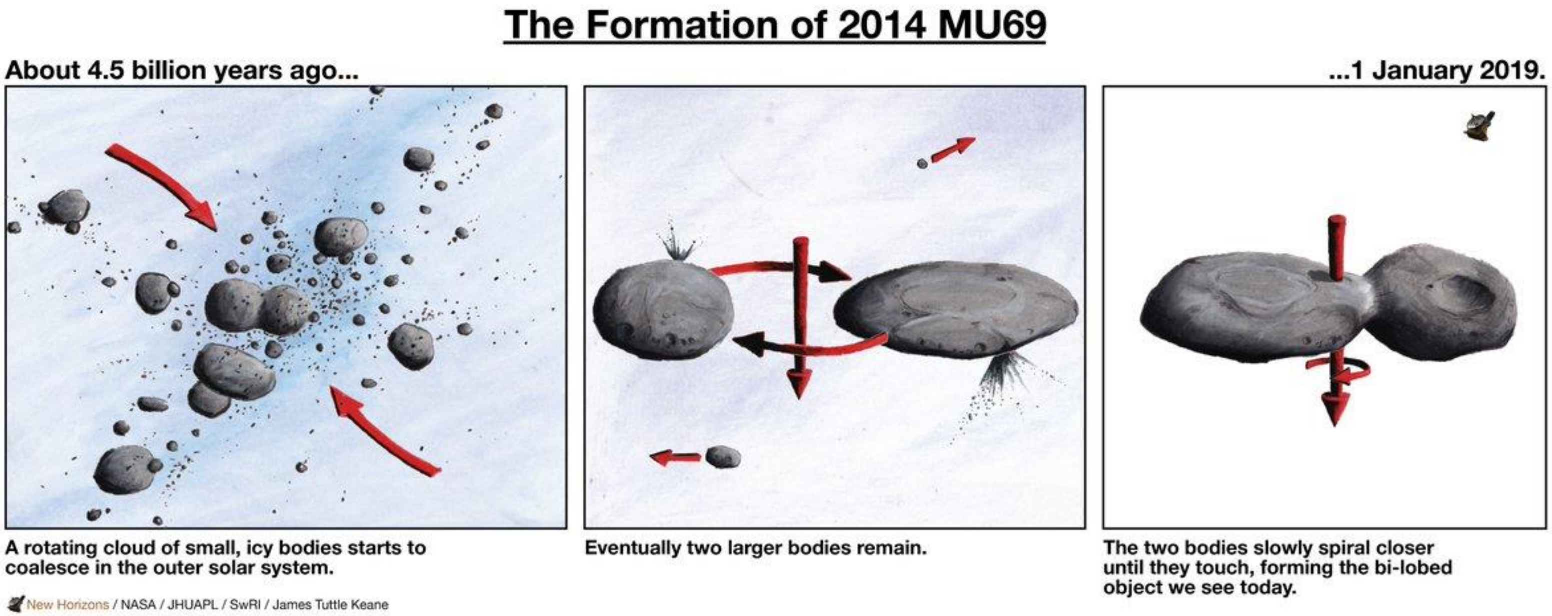
- Pluto's density is 1.860±0.013 g/cm3. Because the decay of radioactive elements would eventually heat the ices enough for the rock to separate from them, Pluto's internal structure is expected to be differentiated, with the rocky material having settled into a dense core surrounded by a mantle of water ice.
- It is possible that such heating continues today, creating a subsurface ocean of liquid water 100 to 180 km thick at the core–mantle boundary.
- Simulations of the impact thought to have formed Sputnik Planitia showed that it might have been the result of liquid water upwelling from below after the collision, implying the existence of a subsurface ocean at least 100 km deep.
- Like other members of the Kuiper belt, Pluto is thought to be a residual planetesimal; a component of the original protoplanetary disc around the Sun that failed to fully coalesce into a full-fledged planet.
- Most astronomers agree that Pluto owes its current position to a sudden migration undergone by Neptune early in the Solar System's formation.
- As Neptune migrated outward, it approached the objects in the proto-Kuiper belt, setting one in orbit around itself (Triton), locking others into resonances, and knocking others into chaotic orbits.
- The objects in the scattered disc, a dynamically unstable region overlapping the Kuiper belt, are thought to have been placed in their current positions by interactions with Neptune's migrating resonances.



# 2014 MU69, Ultima Thule, or Arrokoth

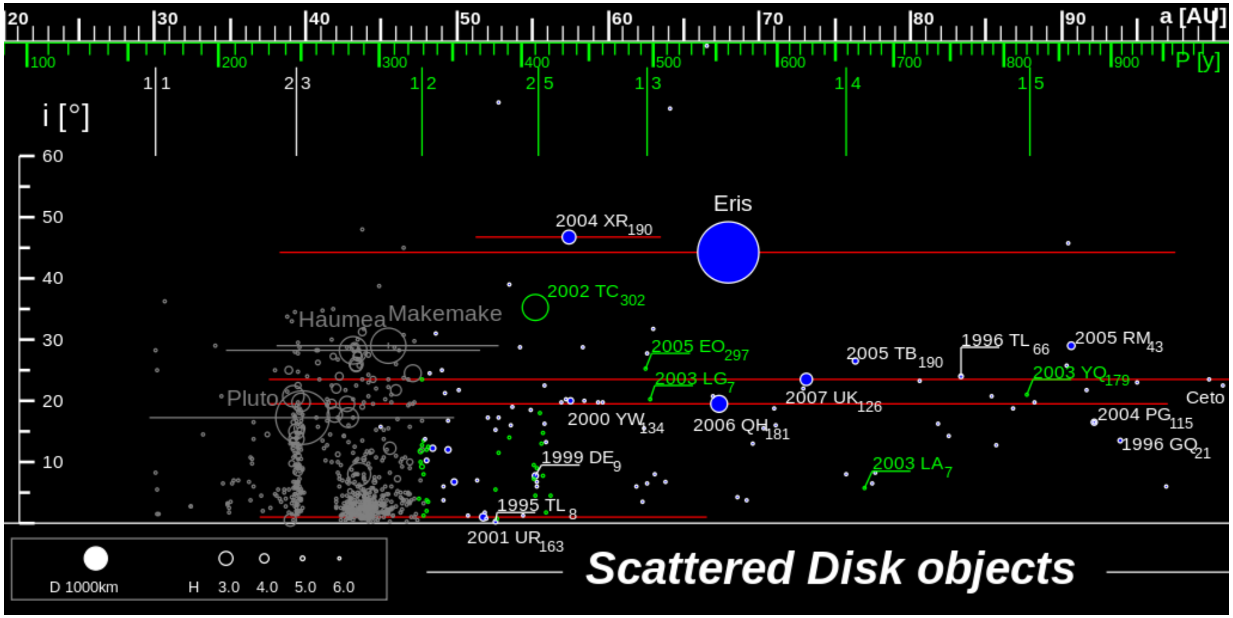
- Arrokoth is a contact binary 36 km long, composed of two planetesimals 22 km and 15 km across, nicknamed "Ultima" and "Thule", respectively, that are joined along their major axes.
- Ultima, which is flatter than Thule, appears to be an aggregate of 8 or so smaller units, each approximately 5 km across, that fused together before Ultima and Thule came into contact.
- Because there have been few to no disruptive impacts on Arrokoth since it formed, the details of its formation have been preserved.
- Spectral measurements from LEISA have revealed the presence of methanol, water ice, and organic compounds on the surface
- The red coloration of Arrokoth is caused by the presence of a mix of complex organic compounds called tholins, which are thought to have been produced from the photolysis of simple organic compounds and volatiles irradiated by cosmic rays and ultraviolet solar radiation.

# The origin and evolution of Arrokoth




- Arrokoth's surface lacks small impact craters less than 1 km in size, implying a lack of impacts throughout its history. The occurrence of impact events in the Kuiper belt is thought to be uncommon. Due to the slower orbital speeds of Kuiper belt objects, the speed of objects impacting Arrokoth is expected to be low.
- Topography variations at the limb of Arrokoth suggest that its interior is likely composed of mechanically strong material consisting of mostly amorphous water ice and rocky material.
- Trace amounts of methane and other volatile gases in the form of vapors may be also present in Arrokoth's interior, trapped in water ice.
- Under the assumption that Arrokoth has a low comet-like density of around 0.5 g/cm3, its internal structure is expected to be porous, as volatile gases trapped in Arrokoth's interior are thought to escape from the interior to the surface.

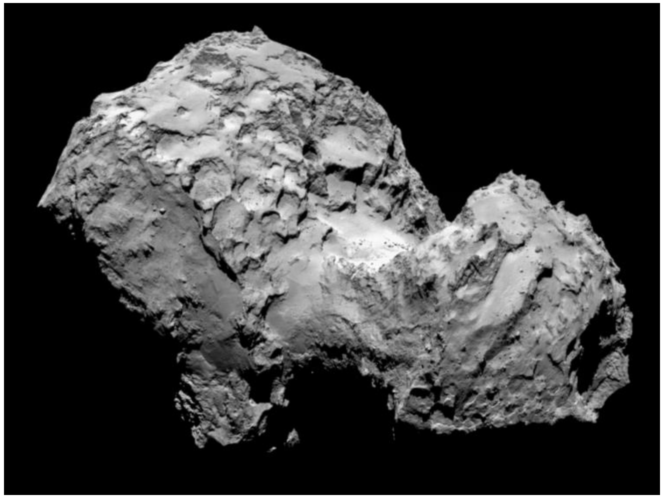
# The scattered disc




- The scattered disc is a distant region of the Solar System that is sparsely populated by icy minor planets
- The scattered-disc objects (SDOs) have orbital eccentricities ranging as high as 0.8, inclinations as high as 40°, and perihelia greater than 30 astronomical units
- These extreme orbits are believed to be the result of gravitational "scattering" by the gas giants, and the objects continue to be subject to perturbation by the planet Neptune
- Although the closest scattered-disc objects approach the Sun at about 30-35 AU, their orbits can extend well beyond 100 AU
- Scattered objects are thus among the most distant and coldest objects in the Solar System
- The innermost portion of the scattered disc overlaps with the Kuiper belt, but its outer limits reach much farther away from the Sun and farther above and below the ecliptic than the Kuiper belt proper

# Comets

- The Kuiper belt was initially thought to be the source of the Solar System's ecliptic comets.
- However, studies of the region since 1992 have shown that the orbits within the Kuiper belt are relatively stable, and that ecliptic comets originate from the scattered disc, where orbits are generally less stable.
- Comets can loosely be divided into two categories: short-period and long-period—the latter being thought to originate in the Oort cloud.
- The two major categories of short-period comets are Jupiter-family comets (JFCs) and Halley-type comets.
- Halley-type comets, which are named after their prototype, Halley's Comet, are thought to have originated in the Oort cloud but to have been drawn into the inner Solar System by the gravity of the giant planets, whereas the JFCs are thought to have originated in the scattered disc.
- The centaurs are thought to be a dynamically intermediate stage between the scattered disc and the Jupiter family.

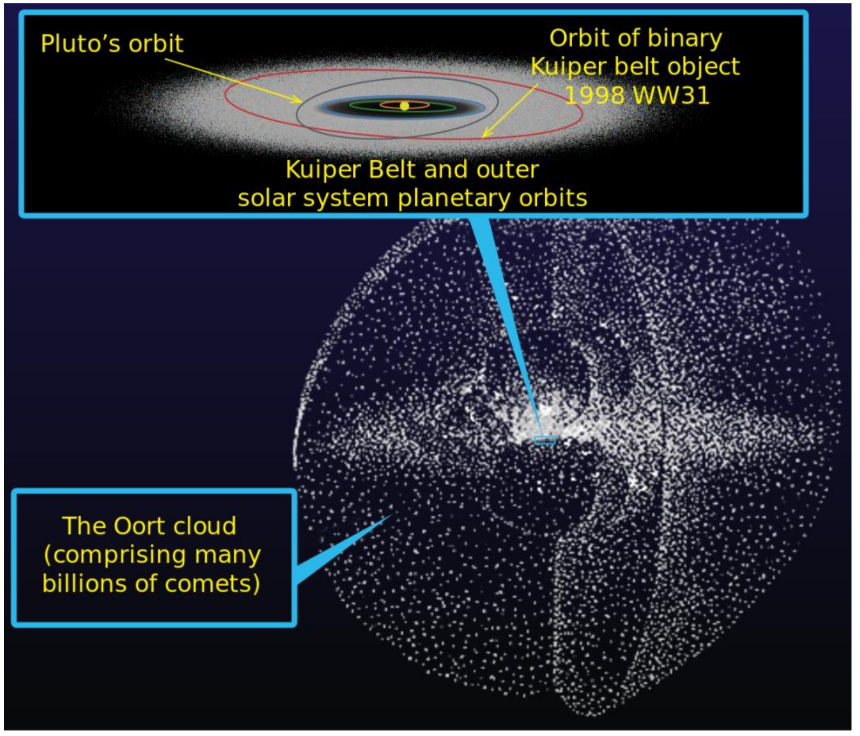


# Comets and life

- The conditions of comet impacts on Earth at the time when life first appeared, around four billion years ago, were simulated.
- Frozen mixtures of amino acid, water ice and silicate at – 196°C were shot by a propellant gun to simulate the shock of a comet impact.
- After studying the post-impact mixture with gas chromatography, it was found that some of the amino acids had joined into short peptides of up to three units long.
- Based on the experimental data, it was estimated that the amount of peptides produced would be around the same as had been thought to be produced by normal Earth processes, such as lighting storms or hydration and dehydration cycles.
- This indicates that comet impacts played an important role in delivering the seeds of life to the early Earth.
- It also opens the likelihood that we will have seen similar chemical evolution in other alien planets, starting with cometary-derived peptides.
- Once the process is kick-started, then much less energy is needed to make longer chain peptides in a terrestrial, aquatic environment.

# The Oort Cloud

- The Oort cloud or Öpik-Oort cloud, is a spherical cloud of predominantly icy planetesimals believed to surround the Sun at a distance of up to around 100'000 AU (2 light years, half of the distance to Proxima Centauri)
- The outer limit of the Oort cloud defines the cosmographical boundary of the Solar System and the region of the Sun's gravitational dominance
- The matter composing the Oort cloud formed closer to the Sun and was scattered far into space by the gravitational effects of the giant planets early in the Solar System's evolution
- It is the source of all long-period and Halley-type comets entering the inner Solar System, and many of the centaurs and Jupiter-family comets as well
- The outer Oort cloud is only loosely bound to the Solar System, and thus is easily affected by the gravitational pull both of passing stars and of the Milky Way itself
- These forces occasionally dislodge comets from their orbits within the cloud and send them towards the inner Solar System



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and also from the text and graphic material freely available on Wikipedia