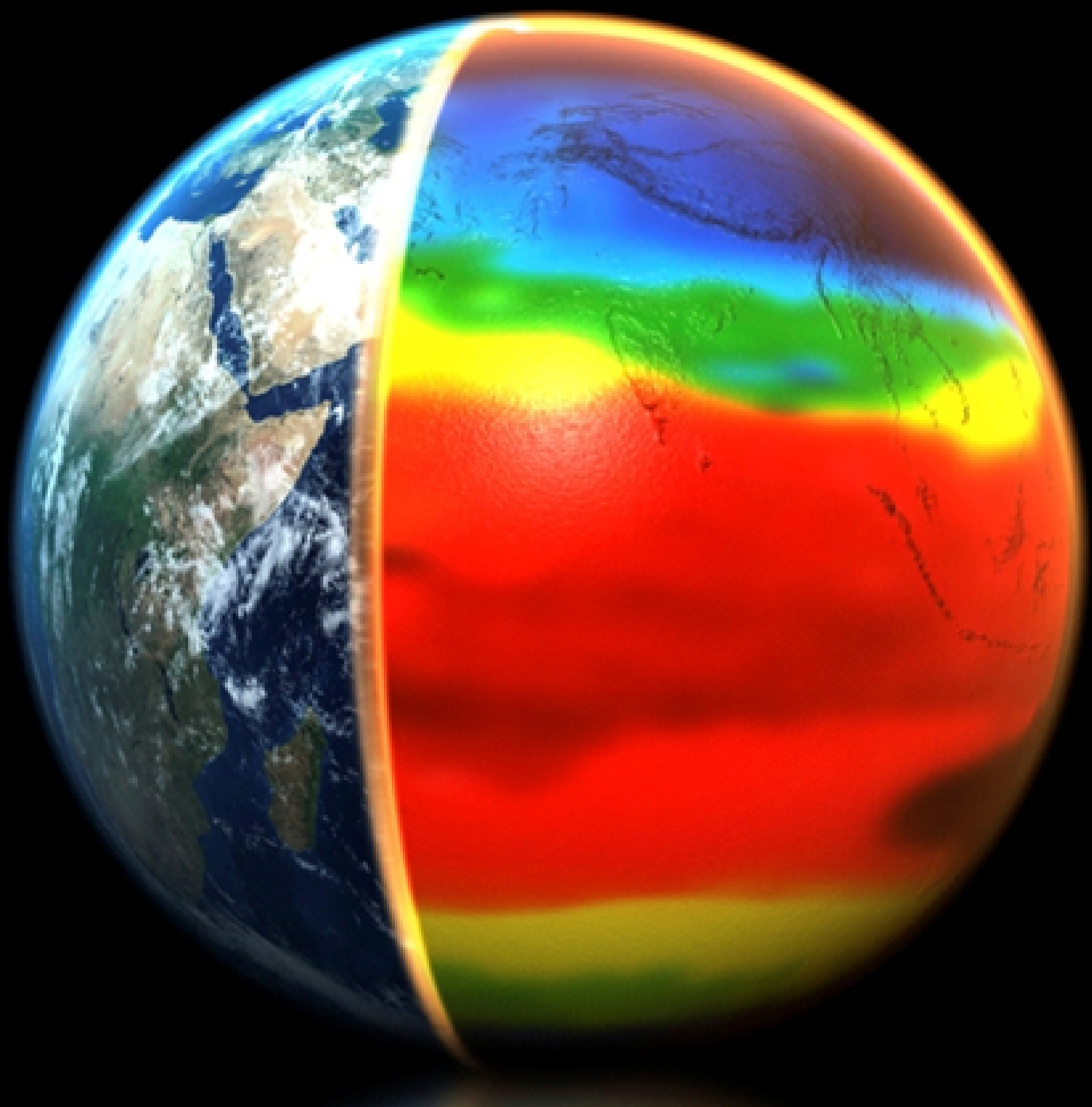
Earth

(History, Composition, Structure, Rotation & Future)



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Introduction

Earth ⊕

"Blue Marble" photograph of Earth,
taken from *Apollo 17*

Designations	
Adjective	earthly, tellurian, telluric, terran, terrestrial.

Orbital characteristics	
Epoch J2000.0	
Aphelion	152,098,232 km 1.01671388 AU
Perihelion	147,098,290 km

	0.98329134 AU
Semi-major axis	149,598,261 km 1.00000261 AU
Eccentricity	0.01671123
Orbital period	365.256363004 days 1.000017421 yr
Average orbital speed	29.78 km/s 107,200 km/h
Mean anomaly	357.51716°
Inclination	7.155° to Sun's equator 1.57869° to invariable plane
Longitude of ascending node	348.73936°
Argument of perihelion	114.20783°
Satellites	1 (the Moon)
Physical characteristics	
Mean radius	6,371.0 km
Equatorial radius	6,378.1 km
Polar radius	6,356.8 km
Flattening	0.0033528
Circumference	40,075.16 km (equatorial) 40,008.00 km (meridional)
Surface area	510,072,000 km^2 148,940,000 km^2 land (29.2 %) 361,132,000 km^2 water (70.8 %)
Volume	1.08321×10^{12} km^3
Mass	5.9736×10^{24} kg
Mean density	5.515 g/cm^3
Equatorial surface gravity	9.780327 m/s^2 0.99732 *g*
Escape velocity	11.186 km/s
Sidereal rotation period	0.99726968 d $23^h\ 56^m\ 4.100^s$
Equatorial rotation velocity	1,674.4 km/h (465.1 m/s)
Axial tilt	23°26'21".4119
Albedo	0.367
Surface temp.	**min** **mean** **max**

Kelvin	184 K	287.2 K	331 K
Celsius	-89.2 °C	14 °C	57.8 °C

Atmosphere	
Surface pressure	101.325 kPa (MSL)
Composition	78.08% nitrogen (N_2) 20.95% oxygen (O_2) 0.93% argon 0.038% carbon dioxide About 1% water vapor (varies with climate)

Earth (or **the Earth**) is the third planet from the Sun, and the densest and fifth-largest of the eight planets in the Solar System. It is also the largest of the Solar System's four terrestrial planets. It is sometimes referred to as the World, the Blue Planet, or by its Latin name, *Terra*.

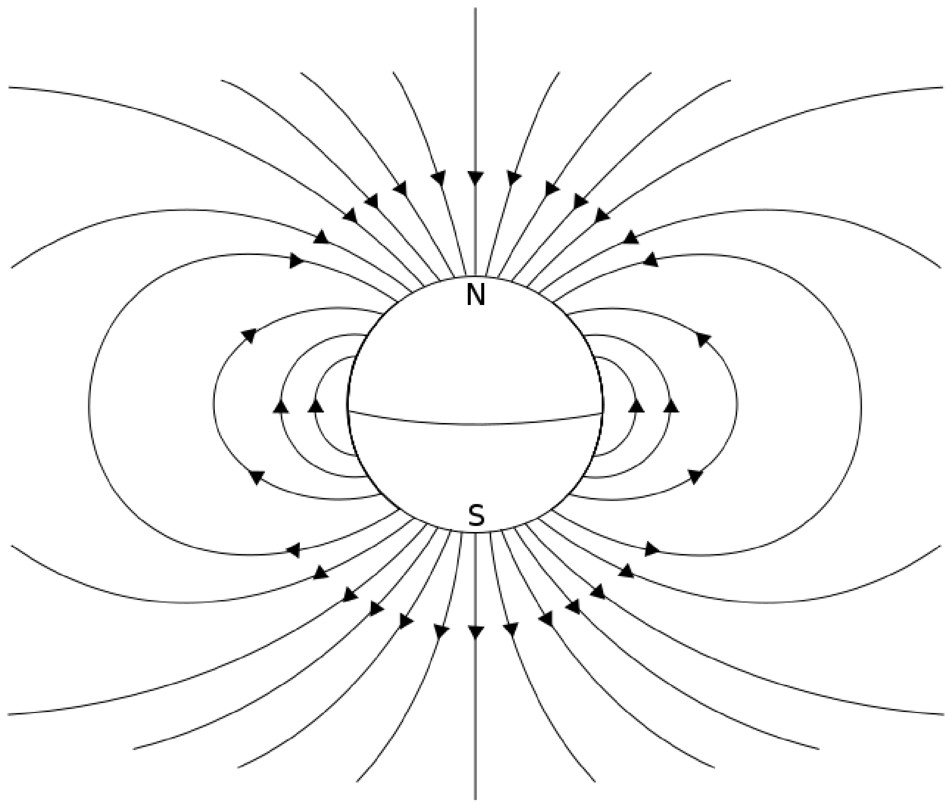
Home to millions of species including humans, Earth is currently the only place where life is known to exist. The planet formed 4.54 billion years ago, and life appeared on its surface within a billion years. Earth's biosphere has significantly altered the atmosphere and other abiotic conditions on the planet, enabling the proliferation of aerobic organisms as well as the formation of the ozone layer which, together with Earth's magnetic field, blocks harmful solar radiation, permitting life on land. The physical properties of the Earth, as well as its geological history and orbit, have allowed life to persist during this period. The planet is expected to continue supporting life for at least another 500 million years.

Earth's outer surface is divided into several rigid segments, or tectonic plates, that migrate across the surface over periods of many millions of years. About 71% of the surface is covered with salt water oceans, the remainder consisting of continents and islands which together have many lakes and other sources of water contributing to the hydrosphere. Liquid water, necessary for all known life, is not known to exist in equilibrium on any other planet's surface. Earth's poles are mostly covered with solid ice (Antarctic ice sheet) or sea ice (Arctic ice cap). The planet's interior remains active, with a thick layer of relatively solid mantle, a liquid outer core that generates a magnetic field, and a solid iron inner core.

Earth interacts with other objects in space, especially the Sun and the Moon. At present, Earth orbits the Sun once for every roughly 366.26 times it rotates about its axis, which is equal to 365.26 solar days, or one sidereal year. The Earth's axis of rotation is tilted 23.4° away from the perpendicular to its orbital plane, producing seasonal variations on the planet's surface with a period of one tropical year (365.24 solar days). Earth's only known natural satellite, the Moon, which began orbiting it about 4.53 billion years ago, provides ocean tides, stabilizes the axial tilt and gradually slows the planet's rotation. Between approximately 3.8 billion and 4.1 billion years ago, numerous asteroid impacts during the Late Heavy Bombardment caused significant changes to the greater surface environment.

Both the mineral resources of the planet, as well as the products of the biosphere, contribute resources that are used to support a global human population. These inhabitants are grouped into about 200 independent sovereign states, which interact through diplomacy, travel, trade, and military action. Human cultures have developed many views of the planet, including personification as a deity, a belief in a flat Earth or in Earth as the center of the universe, and a modern perspective of the world as an integrated environment that requires stewardship.

Magnetic field



The Earth's magnetic field, which approximates a dipole

The Earth's magnetic field is shaped roughly as a magnetic dipole, with the poles currently located proximate to the planet's geographic poles. According to dynamo theory, the field is generated within the molten outer core region where heat creates convection motions of conducting materials, generating electric currents. These in turn produce the Earth's magnetic field. The convection movements in the core are chaotic; the magnetic poles drift and periodically change alignment. This results in field reversals at irregular intervals averaging a few times every million years. The most recent reversal occurred approximately 700,000 years ago.

The field forms the magnetosphere, which deflects particles in the solar wind. The sunward edge of the bow shock is located at about 13 times the radius of the Earth. The collision between the magnetic field and the solar wind forms the Van Allen radiation belts, a pair of concentric, torusshaped regions of energetic charged particles. When the plasma enters the Earth's atmosphere at the magnetic poles, it forms the aurora.

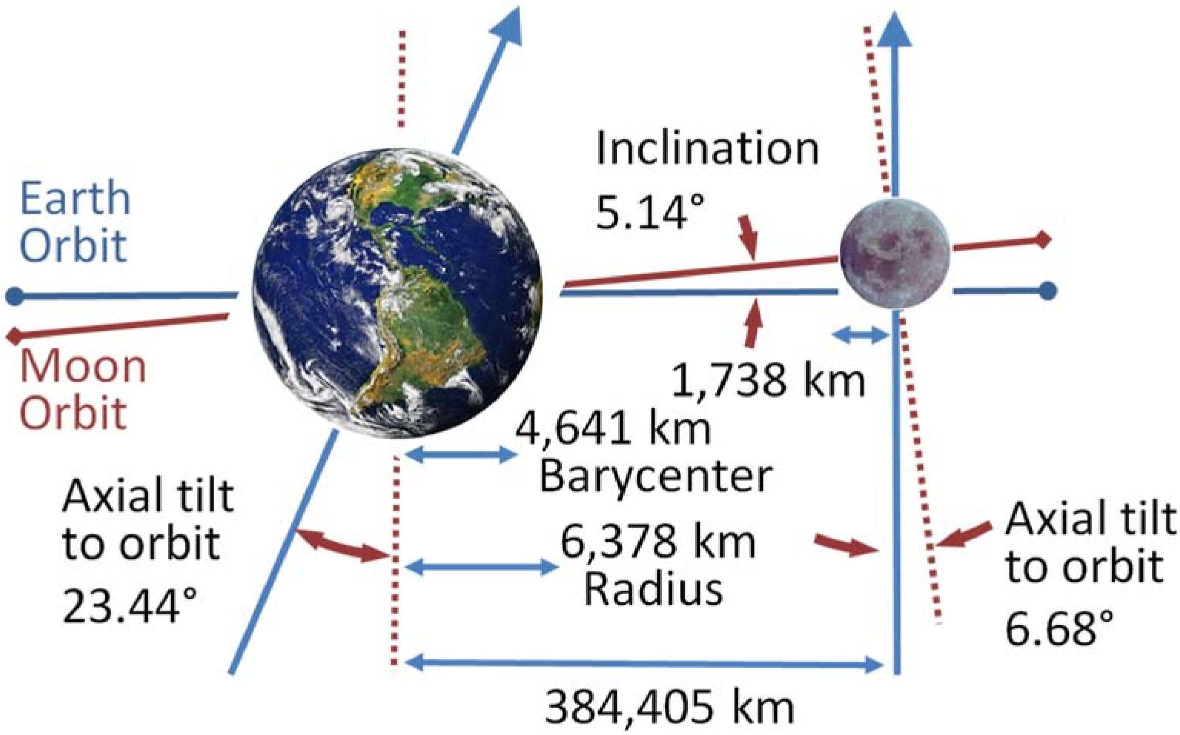
Moon

Characteristics	
Diameter	3,474.8 km
Mass	7.349×10^{22} kg
Semi-major axis	384,400 km
Orbital period	27 d 7 h 43.7 m

The Moon is a relatively large, terrestrial, planet-like satellite, with a diameter about one-quarter of the Earth's. It is the largest moon in the Solar System relative to the size of its planet, although Charon is larger relative to the dwarf planet Pluto. The natural satellites orbiting other planets are called "moons" after Earth's Moon.

The gravitational attraction between the Earth and Moon causes tides on Earth. The same effect on the Moon has led to its tidal locking: its rotation period is the same as the time it takes to orbit the Earth. As a result, it always presents the same face to the planet. As the Moon orbits Earth, different parts of its face are illuminated by the Sun, leading to the lunar phases; the dark part of the face is separated from the light part by the solar terminator.

Because of their tidal interaction, the Moon recedes from Earth at the rate of approximately 38 mm a year. Over millions of years, these tiny modifications—and the lengthening of Earth's day by about 23 µs a year—add up to significant changes. During the Devonian period, for example, (approximately 410 million years ago) there were 400 days in a year, with each day lasting 21.8 hours.



Details of the Earth-Moon system. Besides the radius of each object, the radius to the Earth-Moon barycenter is shown. Photos from NASA. Data from NASA. The Moon's axis is located by Cassini's third law.

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. Some theorists believe that without this stabilization against the torques applied by the Sun and planets to the Earth's equatorial bulge, the rotational axis might be chaotically unstable, exhibiting chaotic changes over millions of years, as appears to be the case for Mars. If Earth's axis of rotation were to approach the plane of the ecliptic, extremely severe weather could result from the resulting extreme seasonal differences. One pole would be pointed directly toward the Sun during *summer* and directly away during *winter*. Planetary scientists who have studied the effect claim that this might kill all large animal and higher plant life. However, this is a controversial subject, and further studies of Mars—whose rotation period and axial tilt are similar to those of Earth, but which lacks a large moon or liquid core—may settle the matter.

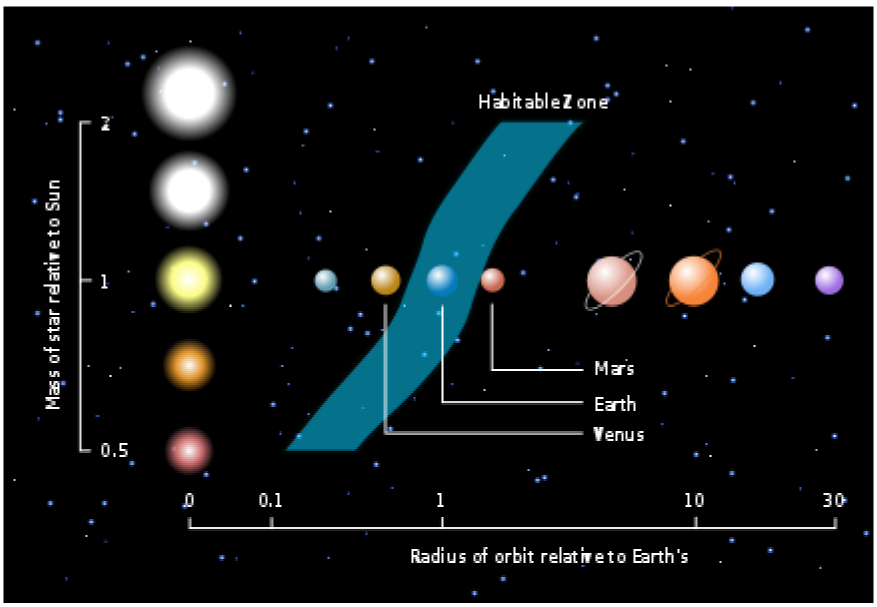
Viewed from Earth, the Moon is just far enough away to have very nearly the same apparent-sized disk as the Sun. The angular size (or solid angle) of these two bodies match because, although the Sun's diameter is about 400 times as large as the Moon's, it is also 400 times more distant. This allows total and annular solar eclipses to occur on Earth.

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 called Theia with the early Earth. This hypothesis explains (among other things) the Moon's relative lack of iron and volatile elements, and the fact that its composition is nearly identical to that of the Earth's crust.

Earth has at least two co-orbital asteroids, 3753 Cruithne and 2002 AA_{29}.

A scale representation of the relative sizes of, and average distance between, Earth and Moon

Habitability



A range of theoretical habitable zones with stars of different mass (our Solar System at center). Scale is logarithmic, and planet sizes are not to scale.

A planet that can sustain life is termed habitable, even if life did not originate there. The Earth provides the (currently understood) requisite conditions of liquid water, an environment where complex organic molecules can assemble, and sufficient energy to sustain metabolism. The distance of the Earth from the Sun, as well as its orbital eccentricity, rate of rotation, axial tilt, geological history, sustaining atmosphere and protective magnetic field all contribute to the conditions believed necessary to originate and sustain life on this planet.

Biosphere

The planet's life forms are sometimes said to form a "biosphere". This biosphere is generally believed to have begun evolving about 3.5 billion years ago. Earth is the only place where life is known to exist. The biosphere is divided into a number of biomes, inhabited by broadly similar plants and animals. On land, biomes are separated primarily by differences in latitude, height above sea level and humidity. Terrestrial biomes lying within the Arctic or Antarctic Circles, at high altitudes or in extremely arid areas are relatively barren of plant and animal life; species diversity reaches a peak in humid lowlands at equatorial latitudes.

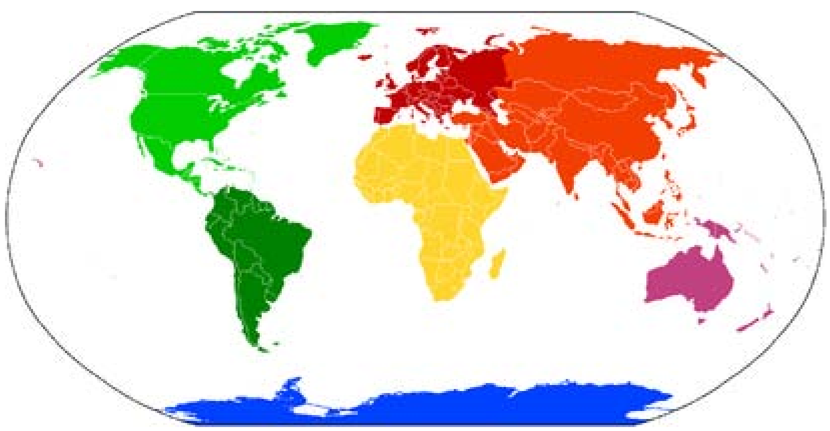
Natural and environmental hazards

Large areas of the Earth's surface are subject to extreme weather such as tropical cyclones, hurricanes, or typhoons that dominate life in those areas. Many places are subject to earthquakes, landslides, tsunamis, volcanic eruptions, tornadoes, sinkholes, blizzards, floods, droughts, and other calamities and disasters.

Many localized areas are subject to human-made pollution of the air and water, acid rain and toxic substances, loss of vegetation (overgrazing, deforestation, desertification), loss of wildlife, species extinction, soil degradation, soil depletion, erosion, and introduction of invasive species.

According to the United Nations, a scientific consensus exists linking human activities to global warming due to industrial carbon dioxide emissions. This is predicted to produce changes such as the melting of glaciers and ice sheets, more extreme temperature ranges, significant changes in weather and a global rise in average sea levels.

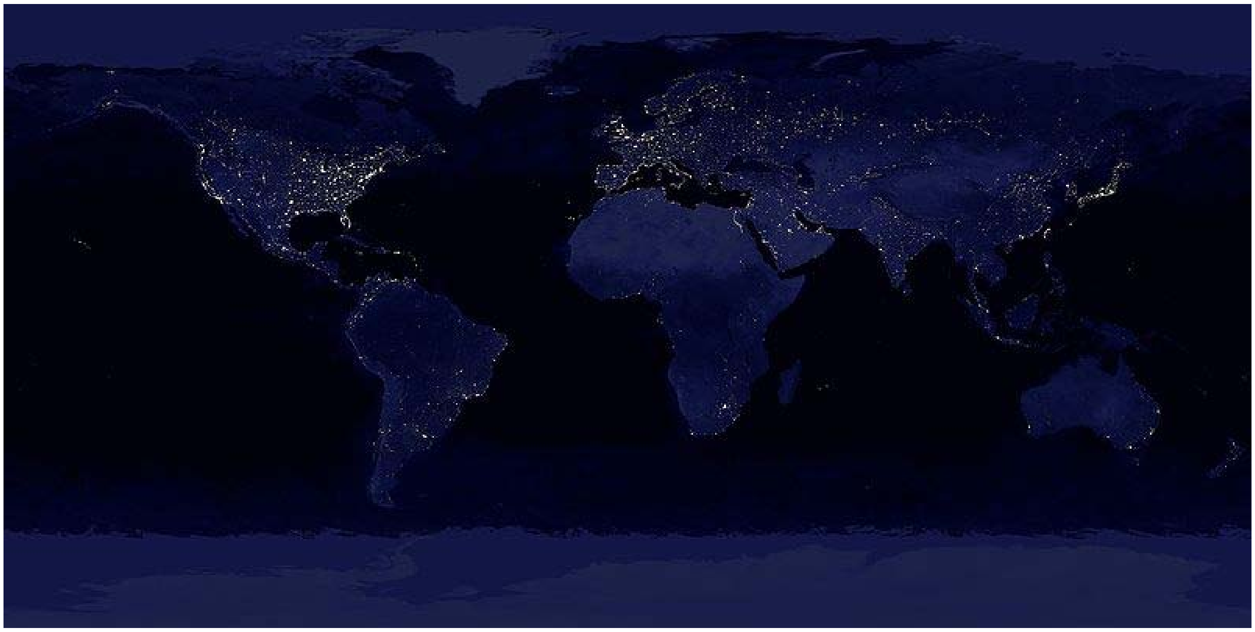
Human geography



Cartography, the study and practice of map making, and vicariously geography, have historically been the disciplines devoted to depicting the Earth. Surveying, the determination of locations and distances, and to a lesser extent navigation, the determination of position and direction, have developed alongside cartography and geography, providing and suitably quantifying the requisite information.

Earth has approximately 6,803,000,000 human inhabitants as of December 12, 2009. Projections indicate that the world's human population will reach seven billion in 2013 and 9.2 billion in 2050. Most of the growth is expected to take place in developing nations. Human population density varies widely around the world, but a majority live in Asia. By 2020, 60% of the world's population is expected to be living in urban, rather than rural, areas.

It is estimated that only one-eighth of the surface of the Earth is suitable for humans to live on—three-quarters is covered by oceans, and half of the land area is either desert (14%), high mountains (27%), or other less suitable terrain. The northernmost permanent settlement in the world is Alert, on Ellesmere Island in Nunavut, Canada. (82°28′N) The southernmost is the Amundsen-Scott South Pole Station, in Antarctica, almost exactly at the South Pole. (90°S)



The Earth at night, a composite of DMSP/OLS ground illumination data on a simulated night-time image of the world. This image is not photographic and many features are brighter than they would appear to a direct observer.

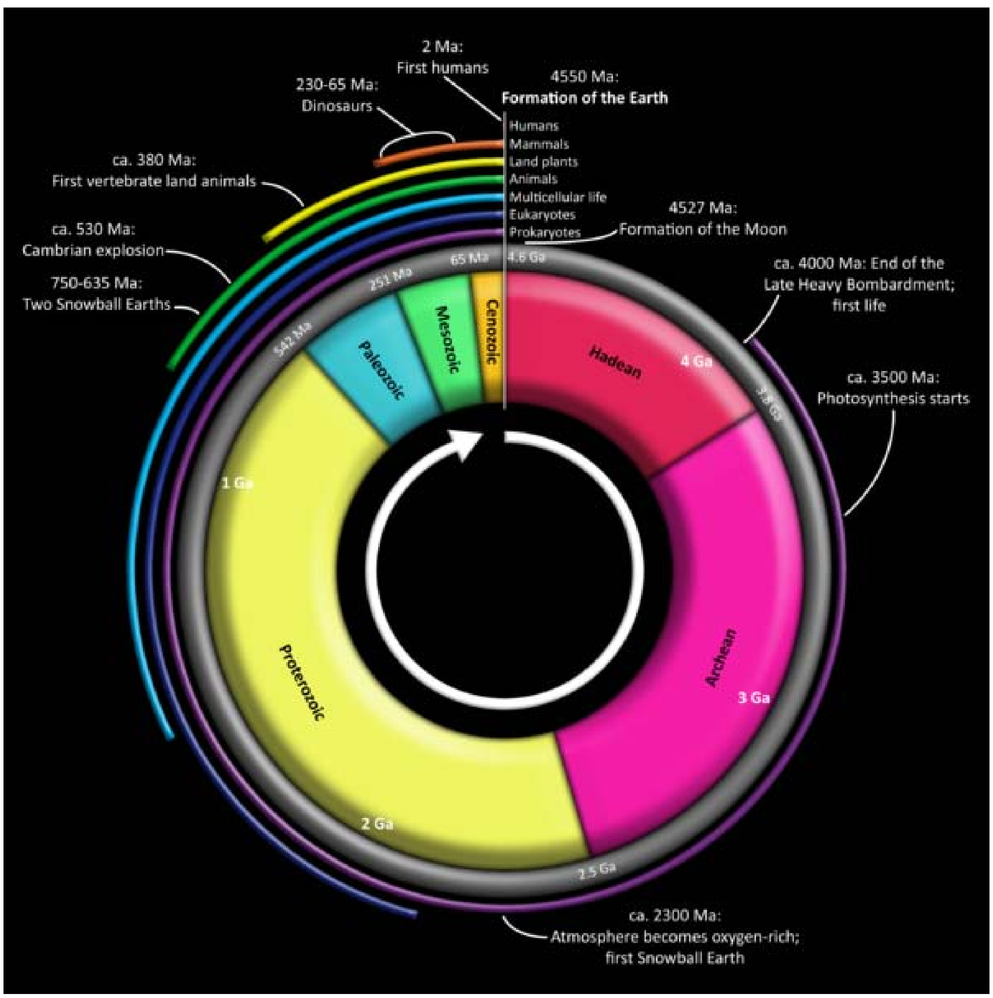
Independent sovereign nations claim the planet's entire land surface, except for some parts of Antarctica and the odd unclaimed area of Bir Tawil between Egypt and Sudan. As of 2007 there are 201 sovereign states, including the 192 United Nations member states. In addition, there are 59 dependent territories, and a number of autonomous areas, territories under dispute and other entities. Historically, Earth has never had a sovereign government with authority over the entire globe, although a number of nation-states have striven for world domination and failed.

The United Nations is a worldwide intergovernmental organization that was created with the goal of intervening in the disputes between nations, thereby avoiding armed conflict. It is not, however, a world government. The U.N. serves primarily as a forum for international diplomacy and international law. When the consensus of the membership permits, it provides a mechanism for armed intervention.

The first human to orbit the Earth was Yuri Gagarin on April 12, 1961. In total, about 400 people visited outer space and reached Earth orbit as of 2004, and, of these, twelve have walked on the Moon. Normally the only humans in space are those on the International Space Station. The station's crew, currently six people, is usually replaced every six months. The furthest humans have travelled from Earth is 400,171 km, achieved during the 1970 Apollo 13 mission.

Chapter- 1

History and Future of the Earth



Geological time put in a diagram called a geological clock, showing the relative lengths of the eons of the Earth's history.

The **history of the Earth** describes the most important events and fundamental stages in the development of the planet Earth from its formation 4.6 billion years ago to the present day. Nearly all branches of natural science have contributed to the understanding of the main events of the Earth's past. The age of Earth is approximately one-third of the age of the universe. Immense geological and biological changes have occurred during that time span.

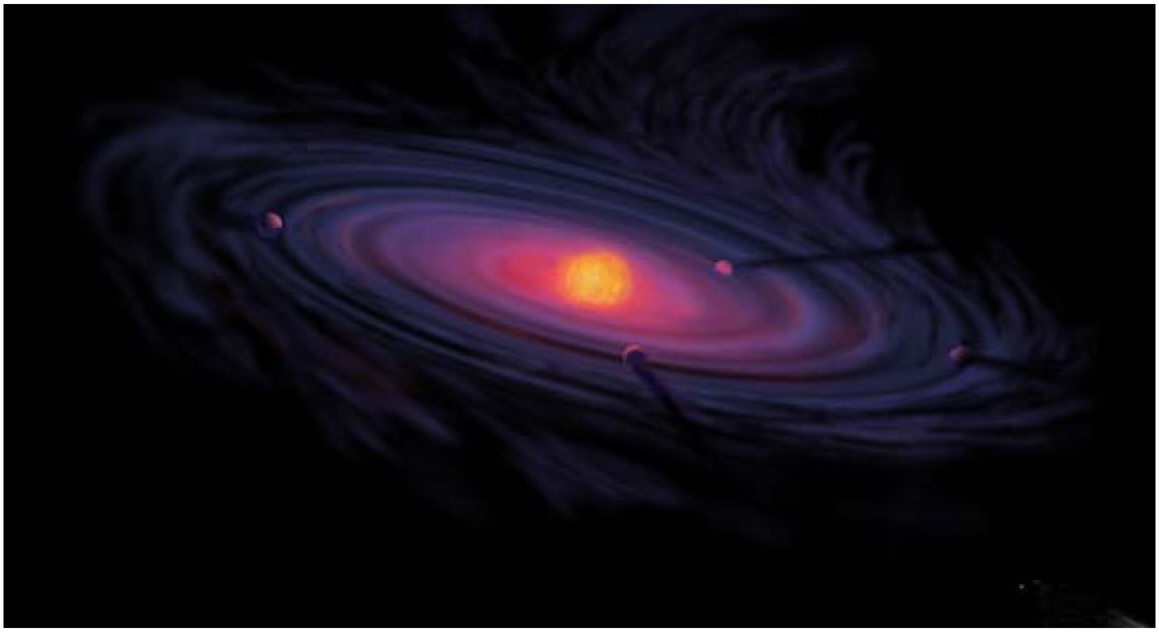
Hadean and Archaean

Starting with the Earth's formation by accretion from the solar nebula 4.54 billion years ago (4.54 Ga), the first eon in the Earth's history is called the Hadean. It lasted until the Archaean eon, which began 3.8 Ga. The oldest rocks found on Earth date to about 4.0 Ga, and the oldest detrital zircon crystals in some rocks have been dated to about 4.4 Ga, close to the formation of the Earth's crust and the Earth itself. Because not much material from this time is preserved, little is known about Hadean times, but scientists hypothesize at an estimated 4.53 Ga, shortly after formation of an initial crust, the proto-Earth was impacted by a smaller protoplanet, which ejected part of the mantle and crust into space and created the Moon.

During the Hadean, the Earth's surface was under a continuous bombardment by meteorites, and volcanism must have been severe due to the large heat flow and geothermal gradient. The detrital zircon crystals dated to 4.4 Ga show evidence of having undergone contact with liquid water, considered as proof that the planet already had oceans or seas at that time. From crater counts on other celestial bodies it is inferred that a period of intense meteorite impacts, called the "Late Heavy Bombardment", began about 4.1 Ga, and concluded around 3.8 Ga, at the end of the Hadean.

By the beginning of the Archaean, the Earth had cooled significantly. It would have been impossible for most present day life forms to exist due to the composition of the Archaean atmosphere, which lacked oxygen and an ozone layer. Nevertheless it is believed that primordial life began to evolve by the early Archaean, with some possible fossil finds dated to around 3.5 Ga. Some researchers, however, speculate that life could have begun during the early Hadean, as far back as 4.4 Ga, surviving the possible Late Heavy Bombardment period in hydrothermal vents below the Earth's surface.

Origin of the solar system



An artist's impression of protoplanetary disk

The Solar System (including the Earth) formed from a large, rotating cloud of interstellar dust and gas called the solar nebula, orbiting the Milky Way's galactic center. It was composed of hydrogen and helium created shortly after the Big Bang 13.7 Ga and heavier elements ejected by supernovas. About 4.6 Ga, the solar nebula began to contract, possibly due to the shock wave of a nearby supernova. Such a shock wave would have also caused the nebula to rotate and gain angular momentum. As the cloud began to accelerate its rotation, gravity and inertia flattened it into a protoplanetary disk oriented perpendicularly to its axis of rotation. Most of the mass concentrated in the middle and began to heat up, but small perturbations due to collisions and the angular momentum of other large debris created the means by which protoplanets up to several kilometres in length began to form, orbiting the nebular center.

The infall of material, increase in rotational speed and the crush of gravity created an enormous amount of kinetic heat at the center. Its inability to transfer that energy away through any other process at a rate capable of relieving the build-up resulted in the disk's center heating up. Ultimately, nuclear fusion of hydrogen into helium began, and eventually, after contraction, a T Tauri star ignited to create the Sun. Meanwhile, as gravity caused matter to condense around the previously perturbed objects outside the gravitational grasp of the new sun, dust particles and the rest of the protoplanetary disk began separating into rings. Successively larger fragments collided with one another and became larger objects, ultimately becoming protoplanets. These included one collection about 150 million kilometers from the center: Earth. The planet formed about 4.54 billion years ago (within an uncertainty of 1%) and was largely completed within 10–20 million years. The solar wind of the newly formed T Tauri star cleared out most of the material in the disk that had not already condensed into larger bodies.

Computer simulations have shown that planets with distances equal to the terrestrial planets in our solar system can be created from a protoplanetary disk. The now widely accepted nebular hypothesis suggests that the same process, which gave rise to the solar system's planets, produces accretion disks around virtually all newly forming stars in the universe, some of which yield planets.

Origin of the Earth's core and first atmosphere

The Proto-Earth grew by accretion, until the inner part of the protoplanet was hot enough to melt the heavy, siderophile metals. Such liquid metals, with now higher densities, began to sink to the Earth's center of mass. This so called iron catastrophe resulted in the separation of a primitive mantle and a (metallic) core only 10 million years after the Earth began to form, producing the layered structure of Earth and setting up the formation of Earth's magnetic field.

During the accretion of material to the protoplanet, a cloud of gaseous silica must have surrounded the Earth, to condense afterwards as solid rocks on the surface. What was left surrounding the planet was an early atmosphere of light (atmophile) elements from the solar nebula, mostly hydrogen and helium, but the solar wind and Earth's heat would have driven off this atmosphere.

This changed when Earth accreted to about 40% its present radius, and gravitational attraction retained an atmosphere which included water.

The giant impact hypothesis

The Earth's relatively large natural satellite, the Moon, is unique. During the Apollo program, rocks from the Moon's surface were brought to Earth. Radiometric dating of these rocks has shown the Moon to be 4527 ± 10 million years old, about 30 to 55 million years younger than other bodies in the solar system. (New evidence suggests the Moon formed even later, 4.48±0.02 Ga, or 70–110 Ma after the start of the Solar System.) Another notable feature is the relatively low density of the Moon, which must mean it does not have a large metallic core, like all other terrestrial bodies in the solar system. The Moon has a bulk composition closely resembling the Earth's mantle and crust together, without the Earth's core. This has led to the giant impact hypothesis, the idea that the Moon was formed during a giant impact of the proto-Earth with another protoplanet by accretion of the material blown off the mantles of the proto-Earth and impactor.

The impactor, sometimes named Theia, is thought to have been a little smaller than the current planet Mars. It could have formed by accretion of matter about 150 million kilometres from the Sun and Earth, at their fourth or fifth Lagrangian point. Its orbit may have been stable at first, but destabilized as Theia's mass increased due to the accretion of matter. Theia oscillated in larger and larger orbits around the Lagrangian point until it finally collided with Earth about 4.533 Ga. Models reveal that when an impactor this size struck the proto-Earth at a low angle and relatively low speed (8–20 km/sec), much material from the mantles and crusts of the proto-Earth and the impactor was ejected into space, where much of it stayed in orbit around the Earth. This material would eventually form the Moon. However, the metallic cores of the impactor would have sunk through the Earth's mantle to fuse with the Earth's core, depleting the Moon of metallic material. The giant impact hypothesis thus explains the Moon's abnormal composition. The ejecta in orbit around the Earth could have condensed into a single body within a couple of weeks. Under the influence of its own gravity, the ejected material became a more spherical body: the Moon.

The radiometric ages show the Earth existed already for at least 10 million years before the impact, enough time to allow for differentiation of the Earth's primitive mantle and core. Then, when the impact occurred, only material from the mantle was ejected, leaving the Earth's core of heavy siderophile elements untouched.

The impact had some important consequences for the young Earth. It released an enormous amount of energy, causing both the Earth and Moon to be completely molten. Immediately after the impact, the Earth's mantle was vigorously convecting, the surface was a large magma ocean. The planet's first atmosphere must have been completely blown away by the impact. The impact is also thought to have changed Earth’s axis to produce the large 23.5° axial tilt that is responsible for Earth’s seasons (a simple, ideal model of the planets’ origins would have axial tilts of 0° with no recognizable seasons). It may also have sped up Earth’s rotation.

Origin of the oceans and atmosphere

Because the Earth lacked an atmosphere immediately after the giant impact, cooling must have occurred quickly. Within 150 million years, a solid crust with a basaltic composition must have formed. The felsic continental crust of today did not yet exist. Within the Earth, further differentiation could only begin when the mantle had at least partly solidified again. Nevertheless, during the early Archaean (about 3.0 Ga) the mantle was still much hotter than today, probably around 1600°C. This means the fraction of partially molten material was still much larger than today.

Steam escaped from the crust, and more gases were released by volcanoes, completing the second atmosphere. Additional water was imported by bolide collisions, probably from asteroids ejected from the outer asteroid belt under the influence of Jupiter's gravity.

The large amount of water on Earth can never have been produced by volcanism and degassing alone. It is assumed the water was derived from impacting comets that contained ice. Though most comets are today in orbits farther away from the Sun than Neptune, computer simulations show they were originally far more common in the inner parts of the solar system. However, most of the water on Earth was probably derived from small impacting protoplanets, objects comparable with today's small icy moons of the outer planets. Impacts of these objects can have enriched the terrestrial planets (Mercury, Venus, the Earth and Mars) with water, carbon dioxide, methane, ammonia, nitrogen and other volatiles. If all water on Earth was derived from comets alone, millions of comet impacts would be required to support this theory. Computer simulations illustrate that this is not an unreasonable number.

As the planet cooled, clouds formed. Rain created the oceans. Recent evidence suggests the oceans may have begun forming by 4.2 Ga, or as early as 4.4 Ga. In any event, by the start of the Archaean eon the Earth was already covered with oceans. The new atmosphere probably contained water vapor, carbon dioxide, nitrogen, and smaller amounts of other gases. As the output of the Sun was only 70% of the current amount, significant amounts of greenhouse gas in the atmosphere most likely prevented the surface water from freezing. Free oxygen would have been bound by hydrogen or minerals on the surface. Volcanic activity was intense and, without an ozone layer to hinder its entry, ultraviolet radiation flooded the surface.

Lithified stromatolites on the shores of Lake Thetis (Western Australia). Stromatolites are formed by colonies of single celled organisms like cyanobacteria or chlorophyta. These colonies of algae entrap sedimentary grains, thus forming the draped sedimentary layers of a stromatolite. Archaean stromatolites are the first direct fossil traces of life on Earth, even though little preserved fossilized cells have been found inside them. The Archaean and Proterozoic oceans could have been full of algal mats like these.

The first continents

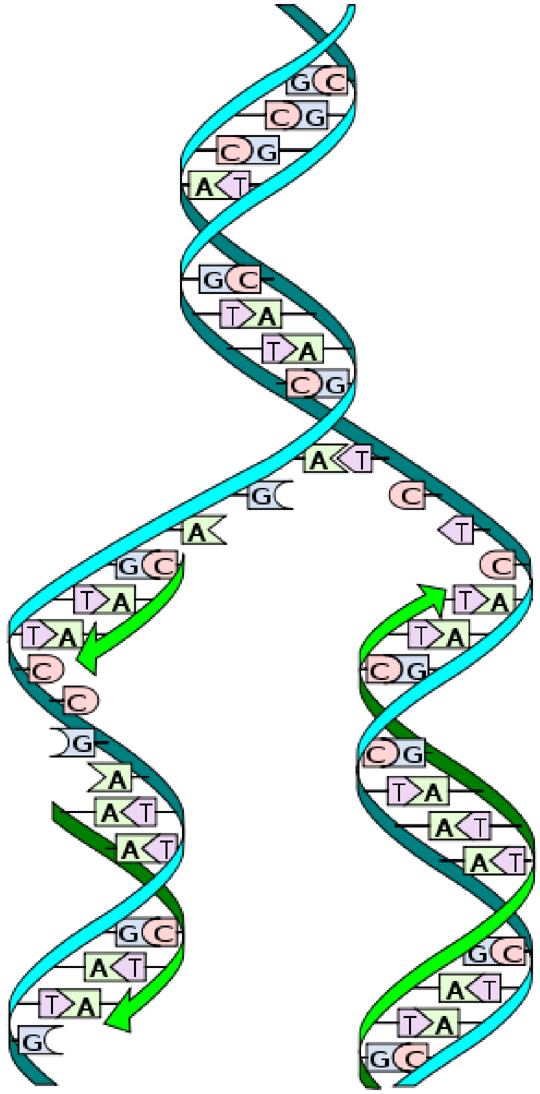
Mantle convection, the process that drives plate tectonics today, is a result of heat flow from the core to the Earth's surface. It involves the creation of rigid tectonic plates at mid-oceanic ridges. These plates are destroyed by subduction into the mantle at subduction zones. The inner Earth was warmer during the Hadean and Archaean eons, so convection in the mantle must have been faster. When a process similar to present day plate tectonics did occur, this would have gone faster too. Most geologists believe that during the Hadean and Archaean, subduction zones were more common, and therefore tectonic plates were smaller.

The initial crust, formed when the Earth's surface first solidified, totally disappeared from a combination of this fast Hadean plate tectonics and the intense impacts of the Late Heavy Bombardment. It is, however, assumed that this crust must have been basaltic in composition, like today's oceanic crust, because little crustal differentiation had yet taken place. The first larger pieces of continental crust, which is a product of differentiation of lighter elements during partial melting in the lower crust, appeared at the end of the Hadean, about 4.0 Ga. What is left of these first small continents are called cratons. These pieces of late Hadean and early Archaean crust form the cores around which today's continents grew.

The oldest rocks on Earth are found in the North American craton of Canada. They are tonalites from about 4.0 Ga. They show traces of metamorphism by high temperature, but also sedimentary grains that have been rounded by erosion during transport by water, showing rivers and seas existed then.

Cratons consist primarily of two alternating types of terranes. The first are so called greenstone belts, consisting of low grade metamorphosed sedimentary rocks. These "greenstones" are similar to the sediments today found in oceanic trenches, above subduction zones. For this reason, greenstones are sometimes seen as evidence for subduction during the Archaean. The second type is a complex of felsic magmatic rocks. These rocks are mostly tonalite, trondhjemite or granodiorite, types of rock similar in composition to granite (hence such terranes are called TTG-terranes). TTG-complexes are seen as the relicts of the first continental crust, formed by partial melting in basalt. The alternation between greenstone belts and TTG-complexes is interpreted as a tectonic situation in which small proto-continents were separated by a thorough network of subduction zones.

Origin of life



The replicator in virtually all known life is deoxyribonucleic acid. DNA is far more complex than the original replicator and its replication systems are highly elaborate.

The details of the origin of life are unknown, but the basic principles have been established. There are two schools of thought about the origin of life. One suggests that organic components arrived on Earth from space, while the other argues that they originated on Earth. Nevertheless, both schools suggest similar mechanisms by which life initially arose.

If life arose on Earth, the timing of this event is highly speculative—perhaps it arose around 4 Ga. It is possible that, as a result of repeated formation and destruction of oceans during that time period caused by high energy asteroid bombardment, life may have arisen and extinguished more than once.

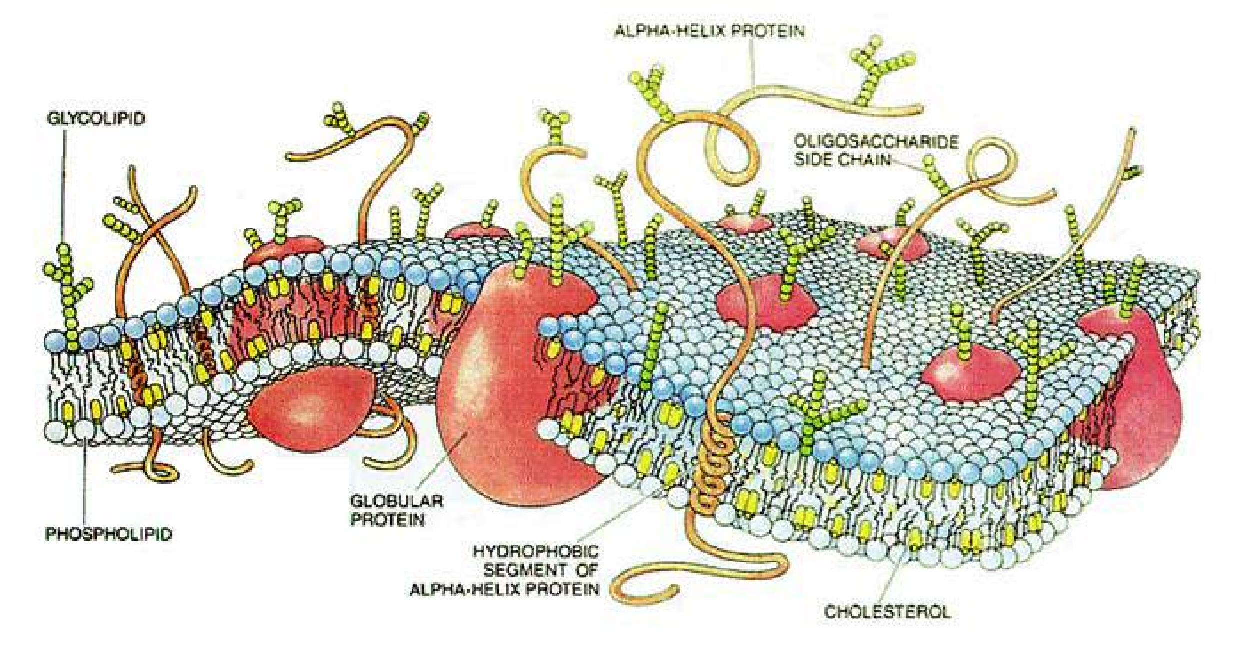
In the energetic chemistry of early Earth, a molecule gained the ability to make copies of itself — a replicator. (More accurately, it promoted the chemical reactions which produced a copy of itself.) The replication was not always accurate: some copies were slightly different from their parent.

If the change destroyed the copying ability of the molecule, the molecule did not produce any copies, and the line "died out". On the other hand, a few rare changes might have made the molecule replicate faster or better: those "strains" would become more numerous and "successful". This is an early example of evolution on abiotic material. The variations present in matter and molecules combined with the universal tendency for systems to move towards a lower energy state allowed for an early method of natural selection. As choice raw materials ("food") became depleted, strains which could utilize different materials, or perhaps halt the development of other strains and steal their resources, became more numerous.

The nature of the first replicator is unknown because its function was long since superseded by life's current replicator, DNA. Several models have been proposed explaining how a replicator might have developed. Different replicators have been posited, including organic chemicals such as modern proteins, nucleic acids, phospholipids, crystals, or even quantum systems. There is currently no way to determine whether any of these models closely fits the origin of life on Earth.

One of the older theories, one which has been worked out in some detail, will serve as an example of how this might occur. The high energy from volcanoes, lightning, and ultraviolet radiation could help drive chemical reactions producing more complex molecules from simple compounds such as methane and ammonia. Among these were many of the simpler organic compounds, including nucleobases and amino acids, which are the building blocks of life. As the amount and concentration of this "organic soup" increased, different molecules reacted with one another. Sometimes more complex molecules would result—perhaps clay provided a framework to collect and concentrate organic material.

Certain molecules could speed up a chemical reaction. All this continued for a long time, with reactions occurring at random, until by chance it produced a replicator molecule. In any case, at some point, the function of the replicator was superseded by DNA; all known life (except some viruses and prions) use DNA as their replicator, in an almost identical manner.



A small section of a cell membrane. This modern cell membrane is far more sophisticated than the original simple phospholipid bilayer (the small blue spheres with two tails). Proteins and carbohydrates serve various functions in regulating the passage of material through the membrane and in reacting to the environment.

Modern life has its replicating material packaged inside a cellular membrane. It is easier to understand the origin of the cell membrane than the origin of the replicator, because a cell membrane is made of phospholipid molecules, which often form a bilayer spontaneously when placed in water. Under certain conditions, many such spheres can be formed.

The prevailing theory is that the membrane formed after the replicator, which perhaps by then was RNA (the RNA world hypothesis), along with its replicating apparatus and other biomolecules. Initial protocells may have simply burst when they grew too large; the scattered contents may then have recolonized other “bubbles”. Proteins that stabilized the membrane, or that later assisted in an orderly division, would have promoted the proliferation of those cell lines.

RNA is a likely candidate for an early replicator, because it can both store genetic information and catalyze reactions. At some point DNA took over the genetic storage role from RNA, and proteins known as enzymes took over the catalysis role, leaving RNA to transfer information, synthesize proteins and regulate the process. There is increasing belief that these early cells evolved in association with undersea volcanic vents known as *black smokers* or even hot, deep rocks.

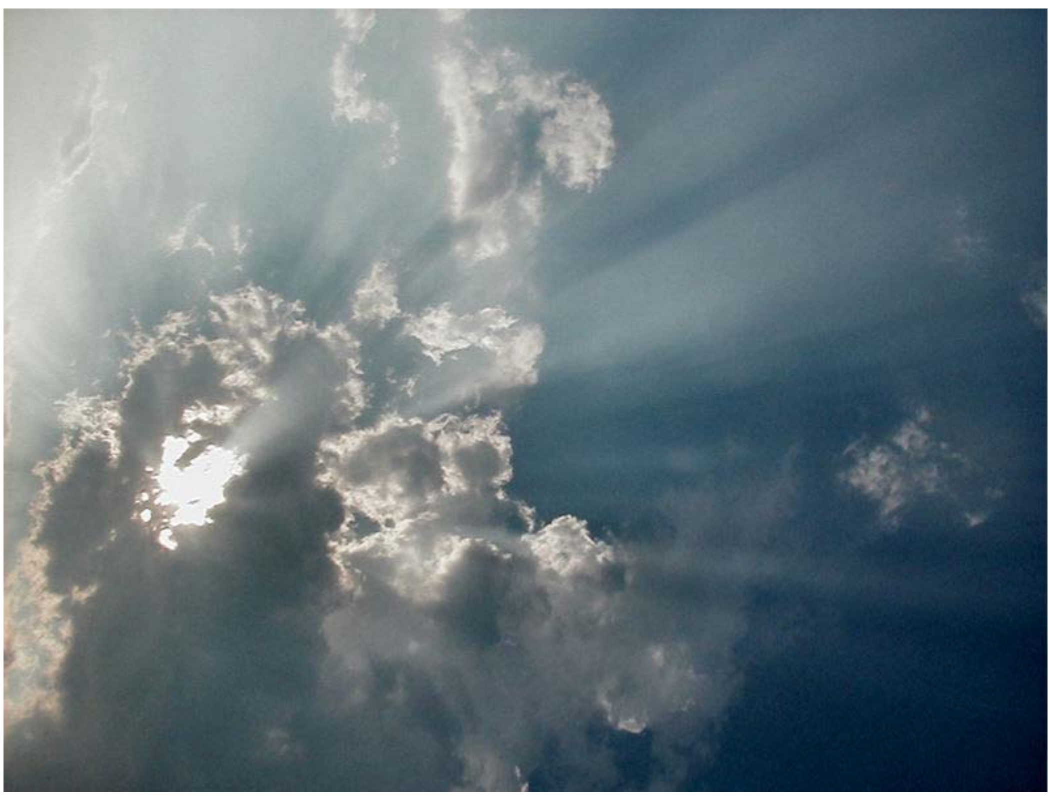
It is believed that of this multiplicity of protocells, only one line survived. Current phylogentic evidence suggests that the last universal common ancestor lived during the early Archean eon, perhaps roughly 3.5 Ga or earlier. This “LUCA” cell is the ancestor of all life on Earth today. It was probably a prokaryote, possessing a cell membrane and probably ribosomes, but lacking a nucleus or membrane-bound organelles such as mitochondria or chloroplasts.

Like all modern cells, it used DNA as its genetic code, RNA for information transfer and protein synthesis, and enzymes to catalyze reactions. Some scientists believe that instead of a single organism being the last universal common ancestor, there were populations of organisms exchanging genes in lateral gene transfer.

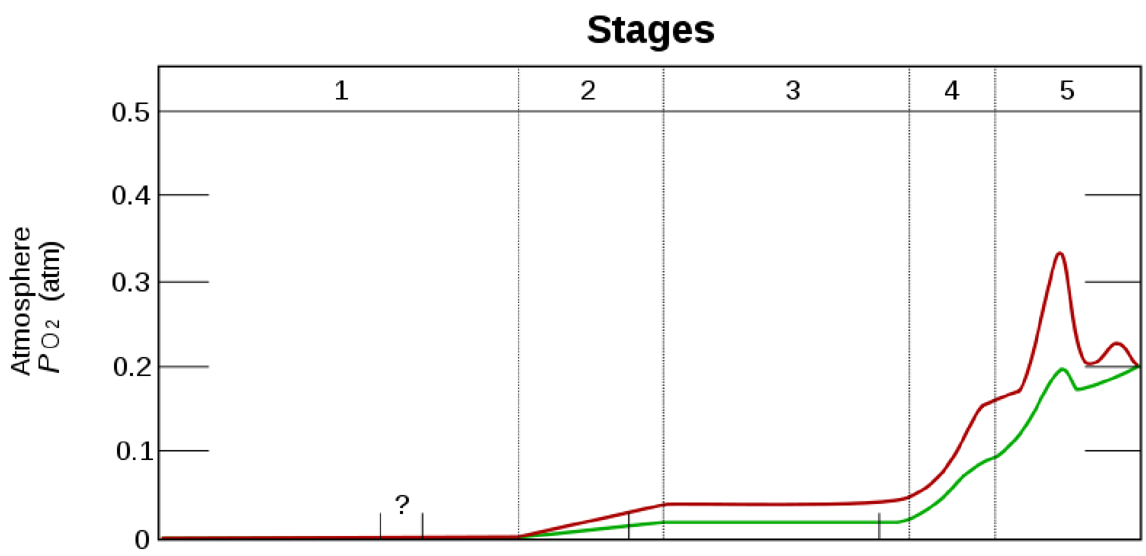
Proterozoic eon

The Proterozoic is the eon of Earth's history that lasted from 2.5 Ga to 542 Ma. In this time span, the cratons grew into continents with modern sizes. For the first time plate tectonics took place in a modern sense. The change to an oxygen-rich atmosphere was a crucial development. Life developed from prokaryotes into eukaryotes and multicellular forms. The Proterozoic saw a couple of severe ice ages called snowball Earths. After the end of the last Snowball Earth about 600 Ma, the evolution of life on Earth accelerated. About 580 Ma, the Ediacara biota formed the prelude for the Cambrian Explosion.

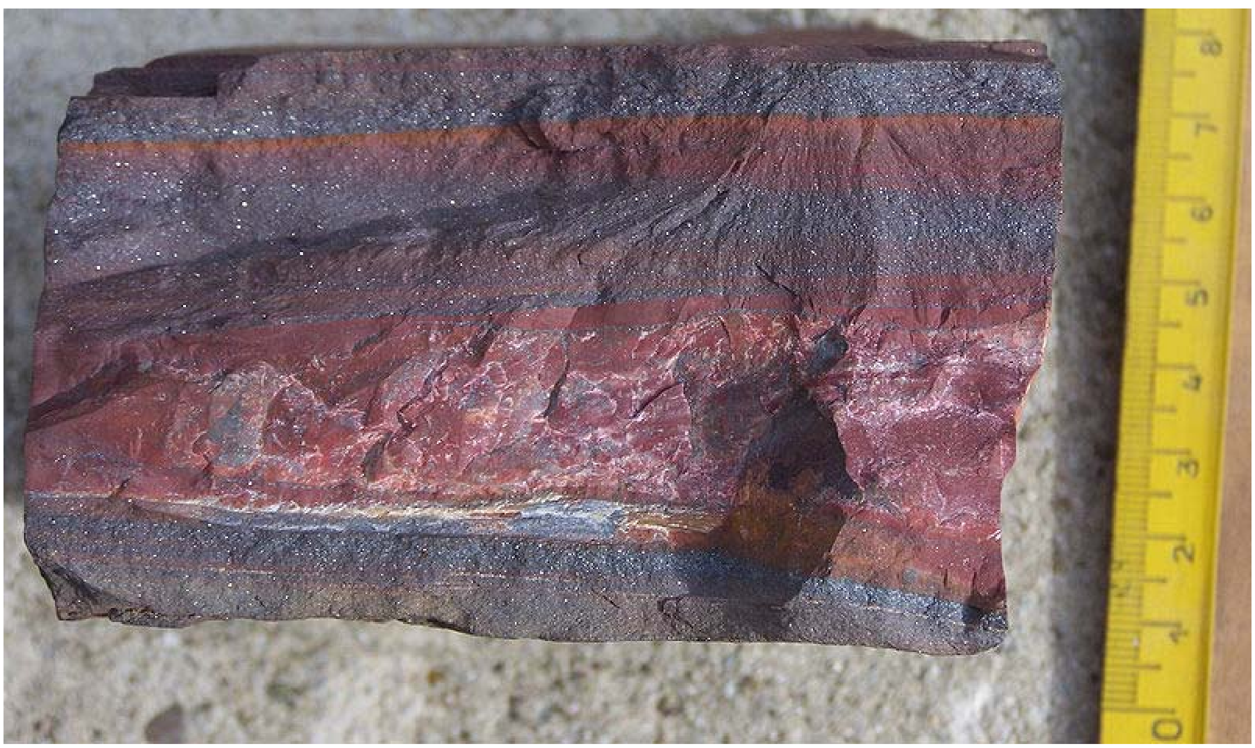
The oxygen revolution



The harnessing of the sun's energy led to several major changes in life on Earth



Graph showing range of estimated partial pressure of atmospheric oxygen through geologic time



A banded iron formation from the 3.15 Ga Moories Group, Barberton Greenstone Belt, South Africa. Red layers represent the times when oxygen was available, gray layers were formed in anoxic circumstances.

The first cells were likely heterotrophs, using surrounding organic molecules (including those from other cells) as raw material and an energy source. As the food supply diminished, a new strategy evolved in some cells. Instead of relying on the diminishing amounts of free-existing organic molecules, these cells adopted sunlight as an energy source. Estimates vary, but by about 3 Ga, something similar to modern oxygenic photosynthesis had probably developed, which made the sun's energy available not only to autotrophs but also to the heterotrophs that consumed them. This type of photosynthesis, which became by far the most common, used the abundant carbon dioxide and water as raw materials and, with the energy of sunlight, produced energy-rich organic molecules (carbohydrates).

Moreover, oxygen was released as a waste product of the photosynthesis. At first, it became bound up with limestone, iron, and other minerals. There is substantial proof of this in iron-oxide rich layers in geological strata that correspond with this period. The reaction of the minerals with oxygen would have turned the oceans green. When most of the exposed readily reacting minerals were oxidized, oxygen finally began to accumulate in the atmosphere. Though each cell only produced a minute amount of oxygen, the combined metabolism of many cells over a vast time transformed Earth's atmosphere to its current state. Among the oldest examples of oxygen-producing lifeforms are fossil stromatolites. This was Earth's third atmosphere.

Some of the oxygen was stimulated by incoming ultraviolet radiation to form ozone, which collected in a layer near the upper part of the atmosphere. The ozone layer absorbed, and still absorbs, a significant amount of the ultraviolet radiation that once had passed through the atmosphere. It allowed cells to colonize the surface of the ocean and eventually the land: without the ozone layer, ultraviolet radiation bombarding the surface would have caused unsustainable levels of mutation in exposed cells.

Photosynthesis had another, major, and world-changing impact. Oxygen was toxic; probably much life on Earth died out as its levels rose in what is known as the "oxygen catastrophe". Resistant forms survived and thrived, and some developed the ability to use oxygen to increase their metabolism and obtain more energy from the same food.

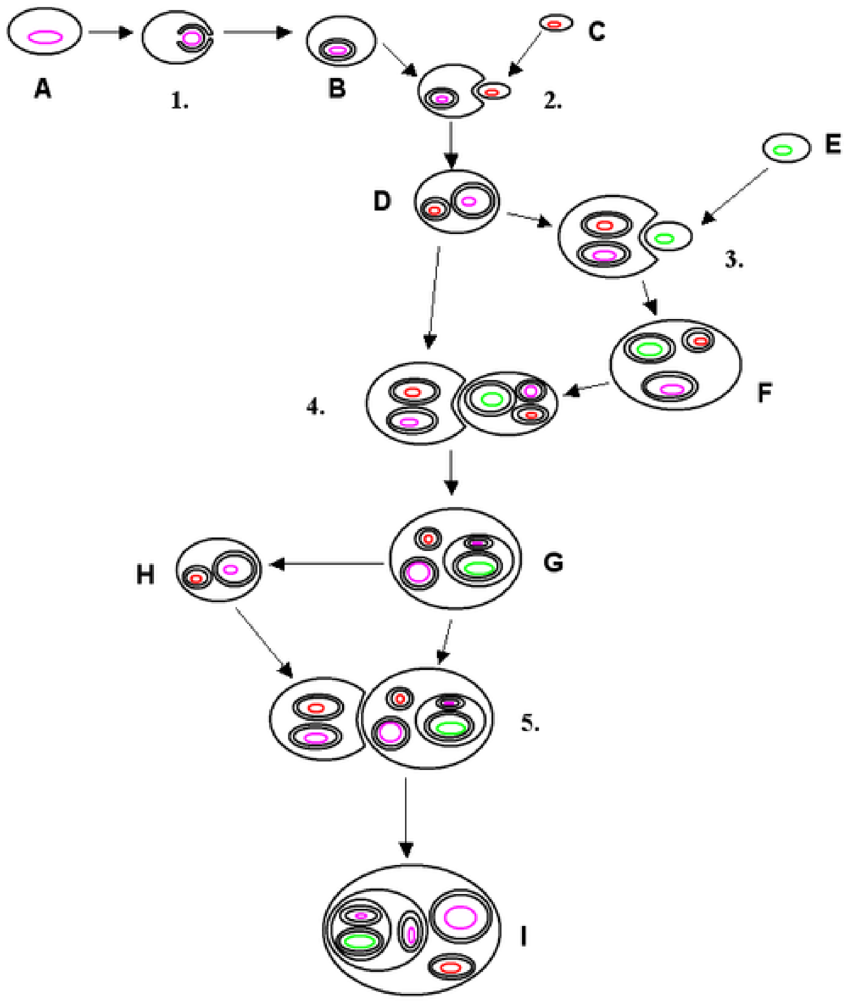
Snowball Earth and the origin of the ozone layer

An oxygen-rich atmosphere had two principal advantages for life. Organisms not using oxygen for their metabolism, such as anaerobe bacteria, base their metabolism on fermentation. The abundance of oxygen makes respiration possible, a much more effective energy source for life than fermentation. The second advantage of an oxygen-rich atmosphere is that oxygen forms ozone in the higher atmosphere, causing the emergence of the Earth's ozone layer. The ozone layer protects the Earth's surface from ultraviolet radiation, which is harmful for life. Without the ozone layer, the development of more complex life later on would probably have been impossible.

The natural evolution of the Sun made it progressively more luminous during the Archaean and Proterozoic eons; the Sun's luminosity increases 6% every billion years. As a result, the Earth began to receive more heat from the Sun in the Proterozoic eon. However, the Earth did not get warmer. Instead, the geological record seems to suggest it cooled dramatically during the early Proterozoic. Glacial deposits found in all cratons show that about 2.3 Ga, the Earth underwent its first big ice age (the Makganyene ice age). Some scientists suggest this and following Proterozoic ice ages were so severe that the planet was totally frozen over from the poles to the equator, a hypothesis called Snowball Earth. Not all geologists agree with this scenario and older, Archaean ice ages have been postulated, but the ice age 2.3 Ga is the first such event for which the evidence is widely accepted.

The ice age around 2.3 Ga could have been directly caused by the increased oxygen concentration in the atmosphere, which caused the decrease of methane (CH_4) in the atmosphere. Methane is a strong greenhouse gas, but with oxygen it reacts to form CO_2, a less effective greenhouse gas. When free oxygen became available in the atmosphere, the concentration of methane could have decreased dramatically, enough to counter the effect of the increasing heat flow from the Sun.

Proterozoic development of life

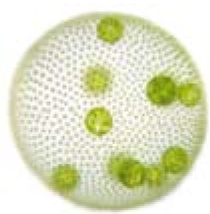


Some of the pathways by which the various endosymbionts might have arisen

Modern taxonomy classifies life into three domains. The time of the origin of these domains is uncertain. The Bacteria domain probably first split off from the other forms of life (sometimes called Neomura), but this supposition is controversial. Soon after this, by 2 Ga, the Neomura split into the Archaea and the Eukarya. Eukaryotic cells (Eukarya) are larger and more complex than prokaryotic cells (Bacteria and Archaea), and the origin of that complexity is only now becoming known.

Around this time, the first proto-mitochondrion was formed. A bacterial cell related to today's *Rickettsia*, which had learned how to metabolize oxygen, entered a larger prokaryotic cell, which lacked that capability. Perhaps the large cell attempted to ingest the smaller one but failed (possibly due to the evolution of prey defenses). The smaller cell may have tried to parasitize the larger one. In any case, the smaller cell survived inside the larger cell. Using oxygen, it metabolized the larger cell's waste products and derived more energy. Some of this excess energy was returned to the host. The smaller cell replicated inside the larger one. Soon, a stable symbiosis developed between the large cell and the smaller cells inside it. Over time, the host cell acquired some of the genes of the smaller cells, and the two kinds became dependent on each other: the larger cell could not survive without the energy produced by the smaller ones, and these in turn could not survive without the raw materials provided by the larger cell. The whole cell is now considered a single organism, and the smaller cells are classified as organelles called mitochondria.

A similar event occurred with photosynthetic cyanobacteria entering large heterotrophic cells and becoming chloroplasts. Probably as a result of these changes, a line of cells capable of photosynthesis split off from the other eukaryotes more than 1 billion years ago. There were probably several such inclusion events, as the figure at right suggests. Besides the well-established endosymbiotic theory of the cellular origin of mitochondria and chloroplasts, it has been suggested that cells led to peroxisomes, spirochetes led to cilia and flagella, and that perhaps a DNA virus led to the cell nucleus, though none of these theories is widely accepted.

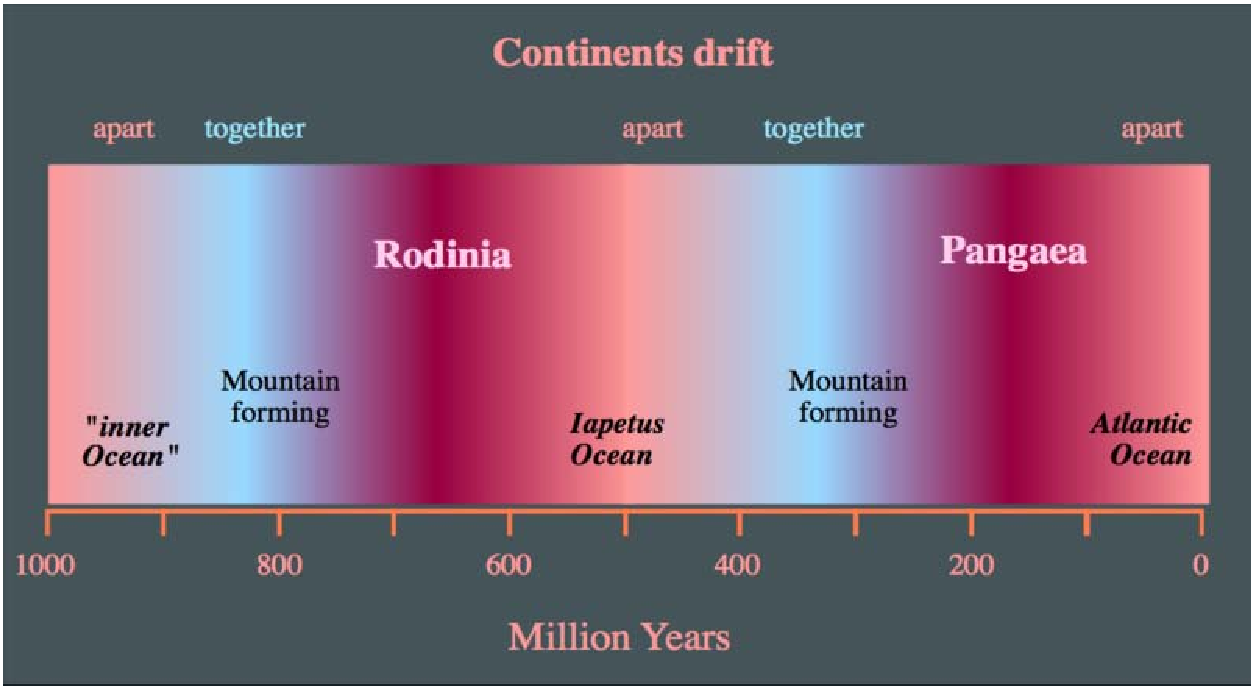


Green algae of the genus *Volvox* are believed to be similar to the first multicellular plants.

Archaeans, bacteria, and eukaryotes continued to diversify and to become more complex and better adapted to their environments. Each domain repeatedly split into multiple lineages, although little is known about the history of the archaea and bacteria. Around 1.1 Ga, the supercontinent Rodinia was assembling. The plant, animal, and fungi lines had all split, though they still existed as solitary cells. Some of these lived in colonies, and gradually some division of labor began to take place; for instance, cells on the periphery might have started to assume different roles from those in the interior. Although the division between a colony with specialized cells and a multicellular organism is not always clear, around 1 billion years ago the first multicellular plants emerged, probably green algae. Possibly by around 900 Ma true multicellularity had also evolved in animals.

At first it probably resembled today's sponges, which have totipotent cells that allow a disrupted organism to reassemble itself. As the division of labor was completed in all lines of multicellular organisms, cells became more specialized and more dependent on each other; isolated cells would die.

Rodinia and other supercontinents



Wilson cycle timeline from 1 Ga, depicting Rodinia and Pangaea supercontinent formation and separation

When the theory of Plate tectonics was developed around 1960, geologists began to reconstruct the movements and positions of the continents in the past. This appeared relatively easy until about 250 million years ago, when all continents were united in what is called the "supercontinent" Pangaea. Before that time, reconstructions cannot rely on apparent similarities in coastlines or ages of oceanic crust, but only on geologic observations and paleomagnetic data.

Throughout the history of the Earth, there have been times when the continental mass came together to form a supercontinent, followed by the break-up of the supercontinent and new continents moving apart again. This repetition of tectonic events is called a Wilson cycle. The further back in time, the scarcer and harder to interpret the data get. It is at least clear that, about 1000 to 830 Ma, most continental mass was united in the supercontinent Rodinia. It is highly probable Rodinia was not the first supercontinent, and many earlier supercontinents have been proposed. This means plate tectonic processes similar to today's must have been active during the Proterozoic.

After the break-up of Rodinia about 800 Ma, it is possible the continents joined again around 550 Ma. The hypothetical supercontinent is sometimes referred to as Pannotia or Vendia. The evidence for it is a phase of continental collision known as the Pan-African orogeny, which joined the continental masses of current-day Africa, South-America, Antarctica and Australia. It is extremely likely, however, that the aggregation of continental masses was not completed, since a continent called Laurentia (roughly equivalent to current-day North America) had already started breaking off around 610 Ma. It is at least certain that by the end of the Proterozoic eon, most of the continental mass lay united in a position around the south pole.

Late Proterozoic climate and life

A 580 million year old fossil of *Spriggina floundensi*, an animal from the Ediacaran period. Such life forms could have been ancestors to the many new forms that origined in the Cambrian Explosion.

The end of the Proterozoic saw at least two Snowball Earths, so severe that the surface of the oceans may have been completely frozen. This happened about 710 and 640 Ma, in the Cryogenian period. These severe glaciations are less easy to explain than the early Proterozoic Snowball Earth. Most paleoclimatologists think the cold episodes had something to do with the formation of the supercontinent Rodinia. Because Rodinia was centered on the equator, rates of chemical weathering increased and carbon dioxide (CO_2) was taken from the atmosphere. Because CO_2 is an important greenhouse gas, climates cooled globally.

In the same way, during the Snowball Earths most of the continental surface was in permafrost, which decreased chemical weathering again, leading to the end of the glaciations. An alternative hypothesis is that enough carbon dioxide escaped through volcanic outgassing that the resulting greenhouse effect raised global temperatures. Increased volcanic activity resulted from the break-up of Rodinia at about the same time.

The Cryogenian period was followed by the Ediacaran period, which was characterized by a rapid development of new multicellular lifeforms. If there is a connection between the end of the severe ice ages and the increase in diversity of life, is not clear, but it does not seem coincidental. The new forms of life, called Ediacara biota, were larger and more diverse than ever. Most scientists think some of them may have been the precursors of the new life forms of the following Cambrian period. Though the taxonomy of most Ediacaran life forms is unclear, some are proposed to have been ancestors of groups of modern life. Important developments were the origin of muscular and neural cells. None of the Ediacaran fossils had hard body parts like skeletons. These first appear after the boundary between the Proterozoic and Phanerozoic eons or Ediacaran and Cambrian periods.

Paleozoic era

The Paleozoic era (meaning: *era of old life forms*) was the first era of the Phanerozoic eon, lasting from 542 to 251 Ma. During the Paleozoic, many modern groups of life came into existence. Life colonized the land, first plants, then animals. Life usually evolved slowly. At times, however, there are sudden radiations of new species or mass extinctions. These bursts of evolution were often caused by unexpected changes in the environment resulting from natural disasters such as volcanic activity, meteorite impacts or climate changes.

The continents formed at the break-up of Pannotia and Rodinia at the end of the Proterozoic would slowly move together again during the Paleozoic. This would eventually result in phases of mountain building that created the supercontinent Pangaea in the late Paleozoic.

Cambrian explosion

Apparently, the rate of the evolution of life accelerated in the Cambrian period (542-488 Ma). The sudden emergence of many new species, phyla, and forms in this period is called the Cambrian Explosion. The biological formenting in the Cambrian Explosion was unpreceded before and since that time. Whereas the Ediacaran life forms appear yet primitive and not easy to put in any modern group, at the end of the Cambrian most modern phyla were already present. The development of hard body parts such as shells, skeletons or exoskeletons in animals like molluscs, echinoderms, crinoids and arthropods (a well-known group of arthropods from the lower Paleozoic are the trilobites) made the preservation and fossilisation of such life forms easier than those of their Proterozoic ancestors. For this reason, much more is known about life in and after the Cambrian than about that of older periods. The boundary between the Cambrian and Ordovician (the following period, 488-444 Ma) is characterized by a large mass-extinction, in which some of the new groups disappeared altogether. Some of these Cambrian groups appear complex but are quite different from modern life; examples are *Anomalocaris* and *Haikouichthys*.

During the Cambrian, the first vertebrate animals, among them the first fishes, had appeared. A creature that could have been the ancestor of the fishes, or was probably closely related to it, was *Pikaia*. It had a primitive notochord, a structure that could have developed into a vertebral column later. The first fishes with jaws (Gnathostomata) appeared during the Ordovician. The colonisation of new niches resulted in massive body sizes. In this way, fishes with increasing sizes evolved during the early Paleozoic, such as the titanic placoderm *Dunkleosteus*, which could grow 7 meters long.

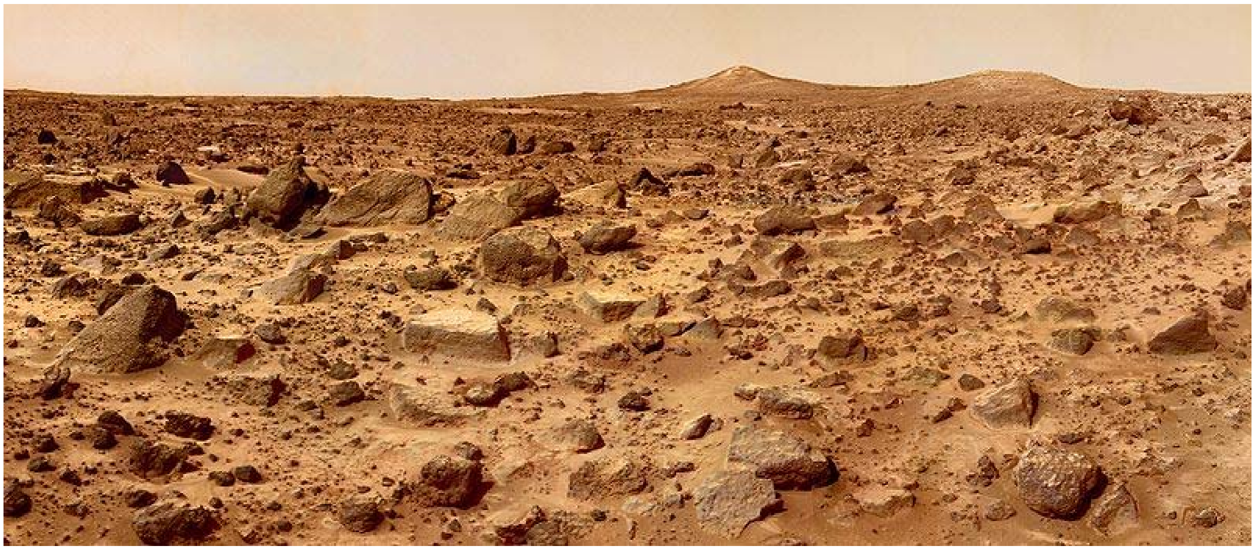
Paleozoic tectonics, paleogeography and climate

At the end of the Proterozoic, the supercontinent Pannotia had broken apart in the smaller continents Laurentia, Baltica, Siberia and Gondwana. During periods when continents move apart, more oceanic crust is formed by volcanic activity. Because young volcanic crust is relatively hotter and less dense than old oceanic crust, the ocean floors will rise during such periods. This causes the sea level to rise. Therefore, in the first half of the Paleozoic, large areas of the continents were below sea level.

Early Paleozoic climates were warmer than today, but the end of the Ordovician saw a short ice age during which glaciers covered the south pole, where the huge continent Gondwana was situated. Traces of glaciation from this period are only found on former Gondwana. During the Late Ordovician ice age, a number of mass extinctions took place, in which many brachiopods, trilobites, Bryozoa and corals disappeared. These marine species could probably not contend with the decreasing temperature of the sea water. After the extinctions new species evolved, more diverse and better adapted. They would fill the niches left by the extinct species.

The continents Laurentia and Baltica collided between 450 and 400 Ma, during the Caledonian Orogeny, to form Laurussia. Traces of the mountain belt which resulted from this collision can be found in Scandinavia, Scotland and the northern Appalachians. In the Devonian period (416-359 Ma) Gondwana and Siberia began to move towards Laurussia. The collision of Siberia with Laurussia caused the Uralian Orogeny, the collision of Gondwana with Laurussia is called the Variscan or Hercynian Orogeny in Europe or the Alleghenian Orogeny in North America. The latter phase took place during the Carboniferous period (359-299 Ma) and resulted in the formation of the last supercontinent, Pangaea.

Colonization of land

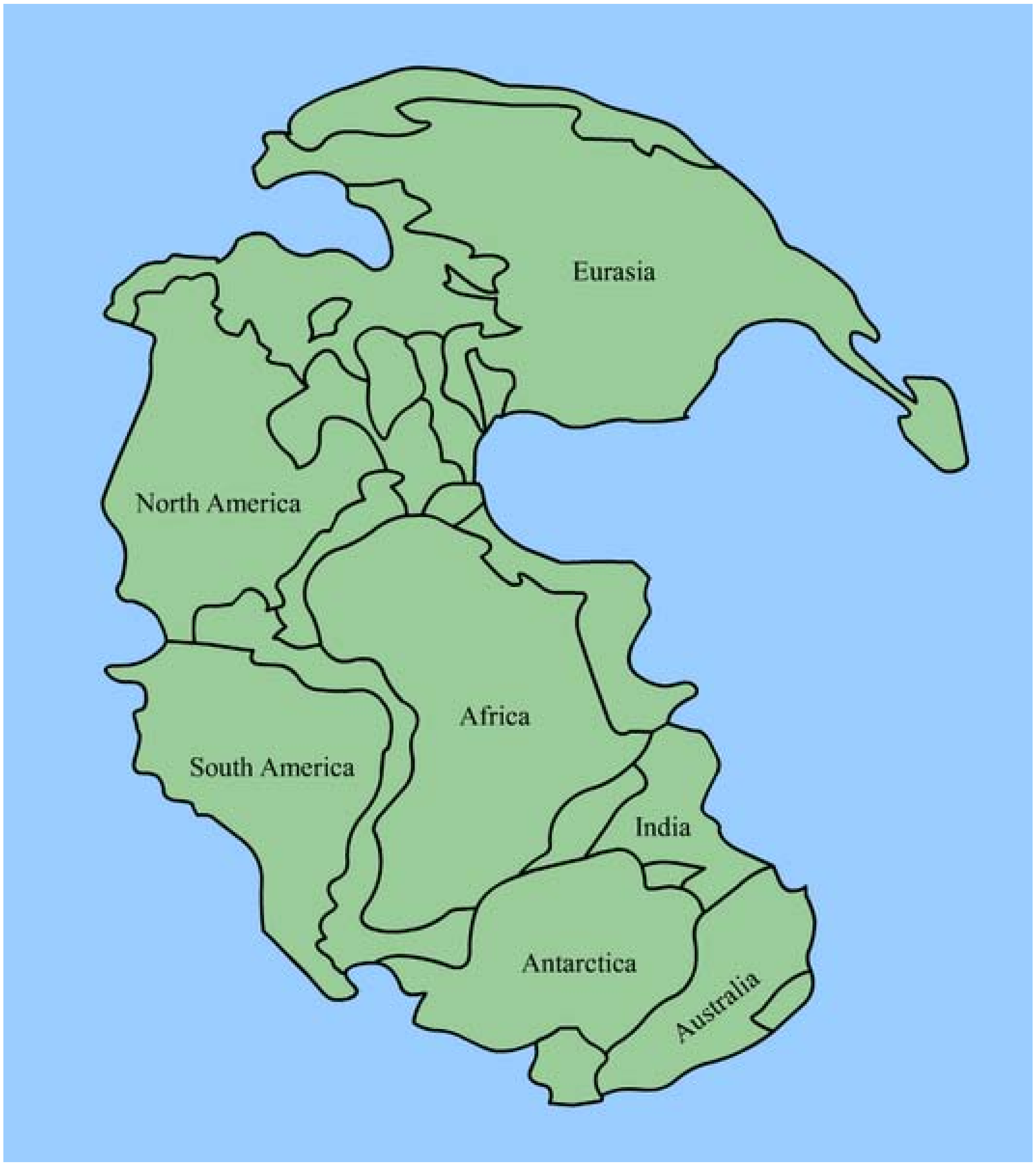


For most of Earth's history, there were no multicellular organisms on land. Parts of the surface may have vaguely resembled this view of Mars.

Oxygen accumulation from photosynthesis resulted in the formation of an ozone layer that absorbed much of Sun's ultraviolet radiation, meaning unicellular organisms that reached land were less likely to die, and prokaryotes began to multiply and become better adapted to survival out of the water. Prokaryotes had probably colonized the land as early as 2.6 Ga even before the origin of the eukaryotes. For a long time, the land remained barren of multicellular organisms. The supercontinent Pannotia formed around 600 Ma and then broke apart a short 50 million years later. Fish, the earliest vertebrates, evolved in the oceans around 530 Ma. A major extinction event occurred near the end of the Cambrian period, which ended 488 Ma.

Several hundred million years ago, plants (probably resembling algae) and fungi started growing at the edges of the water, and then out of it. The oldest fossils of land fungi and plants date to 480–460 Ma, though molecular evidence suggests the fungi may have colonized the land as early as 1000 Ma and the plants 700 Ma. Initially remaining close to the water's edge, mutations and variations resulted in further colonization of this new environment. The timing of the first animals to leave the oceans is not precisely known: the oldest clear evidence is of arthropods on land around 450 Ma, perhaps thriving and becoming better adapted due to the vast food source provided by the terrestrial plants. There is also some unconfirmed evidence that arthropods may have appeared on land as early as 530 Ma.

At the end of the Ordovician period, 440 Ma, additional extinction events occurred, perhaps due to a concurrent ice age. Around 380 to 375 Ma, the first tetrapods evolved from fish. It is thought that perhaps fins evolved to become limbs which allowed the first tetrapods to lift their heads out of the water to breathe air. This would allow them to live in oxygen-poor water or pursue small prey in shallow water. They may have later ventured on land for brief periods. Eventually, some of them became so well adapted to terrestrial life that they spent their adult lives on land, although they hatched in the water and returned to lay their eggs. This was the origin of the amphibians. About 365 Ma, another period of extinction occurred, perhaps as a result of global cooling. Plants evolved seeds, which dramatically accelerated their spread on land, around this time (by approximately 360 Ma).



Pangaea, the most recent supercontinent, existed from 300 to 180 Ma. The outlines of the modern continents and other land masses are indicated on this map.

Some 20 million years later (340 Ma), the amniotic egg evolved, which could be laid on land, giving a survival advantage to tetrapod embryos. This resulted in the divergence of amniotes from amphibians. Another 30 million years (310 Ma) saw the divergence of the synapsids (including mammals) from the sauropsids (including birds and reptiles). Other groups of organisms continued to evolve, and lines diverged—in fish, insects, bacteria, and so on—but less is known of the details. The most recent hypothesized supercontinent, called Pangaea, formed 300 Ma.

Mesozoic

The most severe extinction event to date took place 250 Ma, at the boundary of the Permian and Triassic periods; 95% of life on Earth died out. That started the Mesozoic era (meaning middle life) that spanned 187 million years, possibly due to the Siberian Traps volcanic event. The discovery of the Wilkes Land crater in Antarctica may indicate a connection with the Permian-Triassic extinction, but the age of that crater is not known. Among other speculative theories, it has been suggested that what is now the Gulf of Mexico was created by a large bolide impact event at that time. Life persevered, and around 230 Ma, dinosaurs split off from their reptilian ancestors. An extinction event between the Triassic and Jurassic periods 200 Ma spared many of the dinosaurs, and they soon became dominant among the vertebrates. Though some of the mammalian lines began to separate during this period, existing mammals were probably all small animals resembling shrews.

By 180 Ma, Pangaea broke up into Laurasia and Gondwana. The boundary between avian and non-avian dinosaurs is not clear, but *Archaeopteryx*, traditionally considered one of the first birds, lived around 150 Ma. The earliest evidence for the angiosperms evolving flowers is during the Cretaceous period, some 20 million years later (132 Ma). Competition with birds drove many pterosaurs to extinction and the dinosaurs were probably already in decline when, 65 Ma, a 10-kilometre (6.2 mi) meteorite probably struck Earth just off the Yucatán Peninsula where the Chicxulub crater is today. This ejected vast quantities of particulate matter and vapor into the air that occluded sunlight, inhibiting photosynthesis. Most large animals, including the non-avian dinosaurs, became extinct, marking the end of the Cretaceous period and Mesozoic era. Thereafter, in the Paleocene epoch, mammals rapidly diversified, grew larger, and became the dominant vertebrates. Perhaps a couple of million years later (around 63 Ma), the last common ancestor of primates lived. By the late Eocene epoch, 34 Ma, some terrestrial mammals had returned to the oceans to become animals such as *Basilosaurus* which eventually led to dolphins and baleen whales.

Cenozoic era (Recent life)

Human evolution

Australopithecus africanus, an early hominid

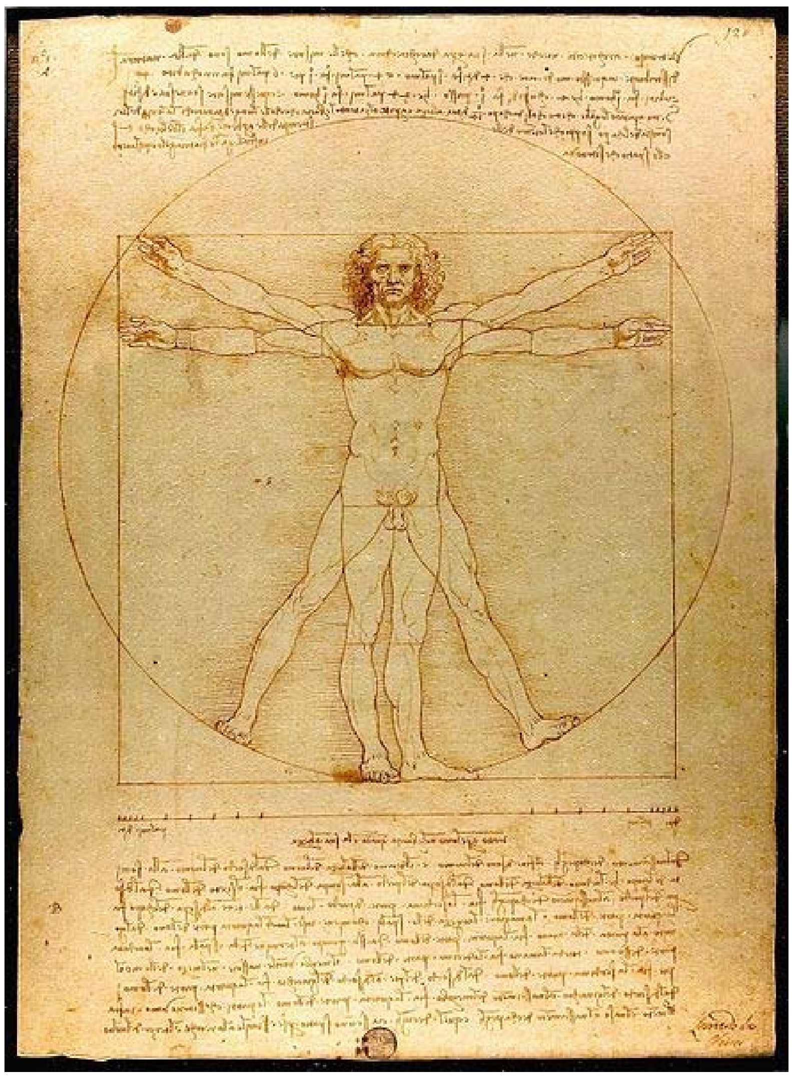
A small African ape living around six Ma was the last animal whose descendants would include both modern humans and their closest relatives, the bonobo and chimpanzees. Only two branches of its family tree have surviving descendants. Very soon after the split, for reasons that are still debated, apes in one branch developed the ability to walk upright. Brain size increased rapidly, and by 2 Ma, the first animals classified in the genus *Homo* had appeared. Of course, the line between different species or even genera is somewhat arbitrary as organisms continuously change over generations. Around the same time, the other branch split into the ancestors of the common chimpanzee and the ancestors of the bonobo as evolution continued simultaneously in all life forms.

The ability to control fire probably began in *Homo erectus* (or *Homo ergaster*), probably at least 790,000 years ago but perhaps as early as 1.5 Ma. In addition, it has sometimes suggested that the use and discovery of controlled fire may even predate *Homo erectus*. Fire was possibly used by the early Lower Paleolithic (Oldowan) hominid *Homo habilis* or strong australopithecines such as *Paranthropus.*

It is more difficult to establish the origin of language; it is unclear whether *Homo erectus* could speak or if that capability had not begun until *Homo sapiens*. As brain size increased, babies were born earlier, before their heads grew too large to pass through the pelvis. As a result, they exhibited more plasticity, and thus possessed an increased capacity to learn and required a longer period of dependence. Social skills became more complex, language became more sophisticated, and tools became more elaborate. This contributed to further cooperation and intellectual development. Modern humans (*Homo sapiens*) are believed to have originated somewhere around 200,000 years ago or earlier in Africa; the oldest fossils date back to around 160,000 years ago.

The first humans to show signs of spirituality are the Neanderthals (usually classified as a separate species with no surviving descendants); they buried their dead, often apparently with food or tools. However, evidence of more sophisticated beliefs, such as the early Cro-Magnon cave paintings (probably with magical or religious significance) did not appear until some 32,000 years ago. Cro-Magnons also left behind stone figurines such as Venus of Willendorf, probably also signifying religious belief. By 11,000 years ago, *Homo sapiens* had reached the southern tip of South America, the last of the uninhabited continents (except for Antarctica, which remained undiscovered until 1820 AD). Tool use and communication continued to improve, and interpersonal relationships became more intricate.

Civilization



Vitruvian Man by Leonardo da Vinci epitomizes the advances in art and science seen during the Renaissance.

Throughout more than 90% of its history, *Homo sapiens* lived in small bands as nomadic hunter-gatherers. As language became more complex, the ability to remember and communicate information resulted in a new replicator: the meme. Ideas could be exchanged quickly and passed down the generations.

Cultural evolution quickly outpaced biological evolution, and history proper began. Somewhere between 8500 and 7000 BC, humans in the Fertile Crescent in Middle East began the systematic husbandry of plants and animals: agriculture. This spread to neighboring regions, and developed independently elsewhere, until most *Homo sapiens* lived sedentary lives in permanent settlements as farmers.

Not all societies abandoned nomadism, especially those in isolated areas of the globe poor in domesticable plant species, such as Australia. However, among those civilizations that did adopt agriculture, the relative stability and increased productivity provided by farming allowed the population to expand.

Agriculture had a major impact; humans began to affect the environment as never before. Surplus food allowed a priestly or governing class to arise, followed by increasing division of labor. This led to Earth's first civilization at Sumer in the Middle East, between 4000 and 3000 BC. Additional civilizations quickly arose in ancient Egypt, at the Indus River valley and in China.

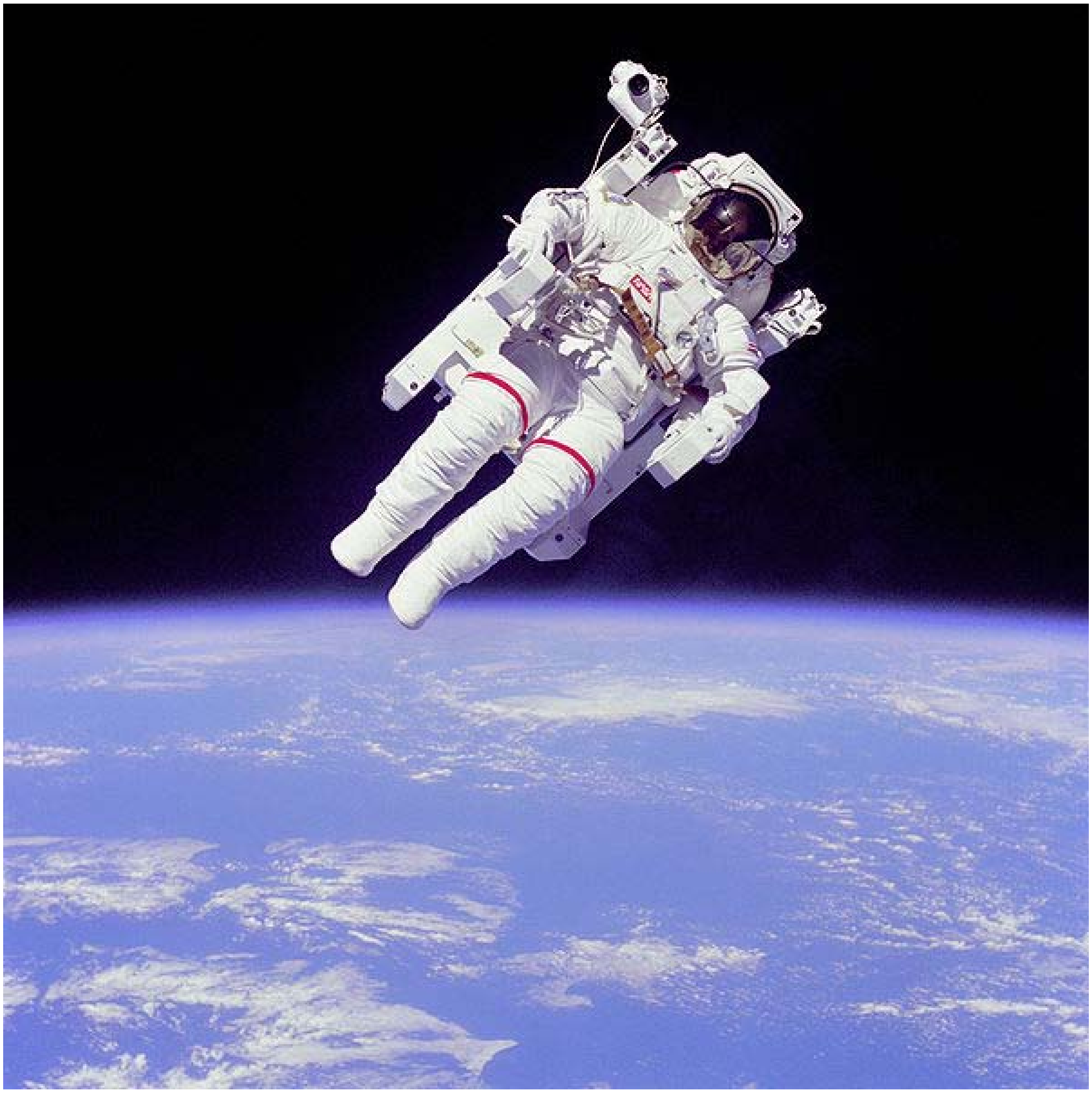
Starting around 3000 BC, Hinduism, one of the oldest religions still practiced today, began to take form. Others soon followed. The invention of writing enabled complex societies to arise: record-keeping and libraries served as a storehouse of knowledge and increased the cultural transmission of information. Humans no longer had to spend all their time working for survival—curiosity and education drove the pursuit of knowledge and wisdom.

Various disciplines, including science (in a primitive form), arose. New civilizations sprang up, traded with one another, and fought for territory and resources. Empires soon began to develop. By around 500 BC, there were empires in the Middle East, Iran, India, China, and Greece, on nearly equal footing; at times one empire expanded, only to decline or be driven back later.

In the fourteenth century, the Renaissance began in Italy with advances in religion, art, and science. European civilization began to change beginning in 1500, leading to the scientific and industrial revolutions. That continent began to exert political and cultural dominance over human societies around the planet. From 1914 to 1918 and 1939 to 1945, nations around the world were embroiled in world wars.

Established following World War I, the League of Nations was a first step in establishing international institutions to settle disputes peacefully. After failing to prevent World War II, it was replaced by the United Nations. In 1992, several European nations joined in the European Union. As transportation and communication improved, the economies and political affairs of nations around the world have become increasingly intertwined. This globalization has often produced both conflict and collaboration.

Recent events



Four and a half billion years after the planet's formation, Earth's life broke free of the biosphere. For the first time in history, Earth was viewed from space.

Change has continued at a rapid pace from the mid-1940s to today. Technological developments include nuclear weapons, computers, genetic engineering, and nanotechnology. Economic globalization spurred by advances in communication and transportation technology has influenced everyday life in many parts of the world. Cultural and institutional forms such as democracy, capitalism, and environmentalism have increased influence. Major concerns and problems such as disease, war, poverty, violent radicalism, and recently, human-caused climate change have risen as the world population increases.

In 1957, the Soviet Union launched the first artificial satellite into orbit and, soon afterward, Yuri Gagarin became the first human in space. Neil Armstrong, an American, was the first to set foot on another astronomical object, the Moon. Unmanned probes have been sent to all the known planets in the solar system, with some (such as Voyager) having left the solar system. The Soviet Union and the United States were the earliest leaders in space exploration in the 20th Century. Five space agencies, representing over fifteen countries, have worked together to build the International Space Station. Aboard it, there has been a continuous human presence in space since 2000.

Geological history of Earth

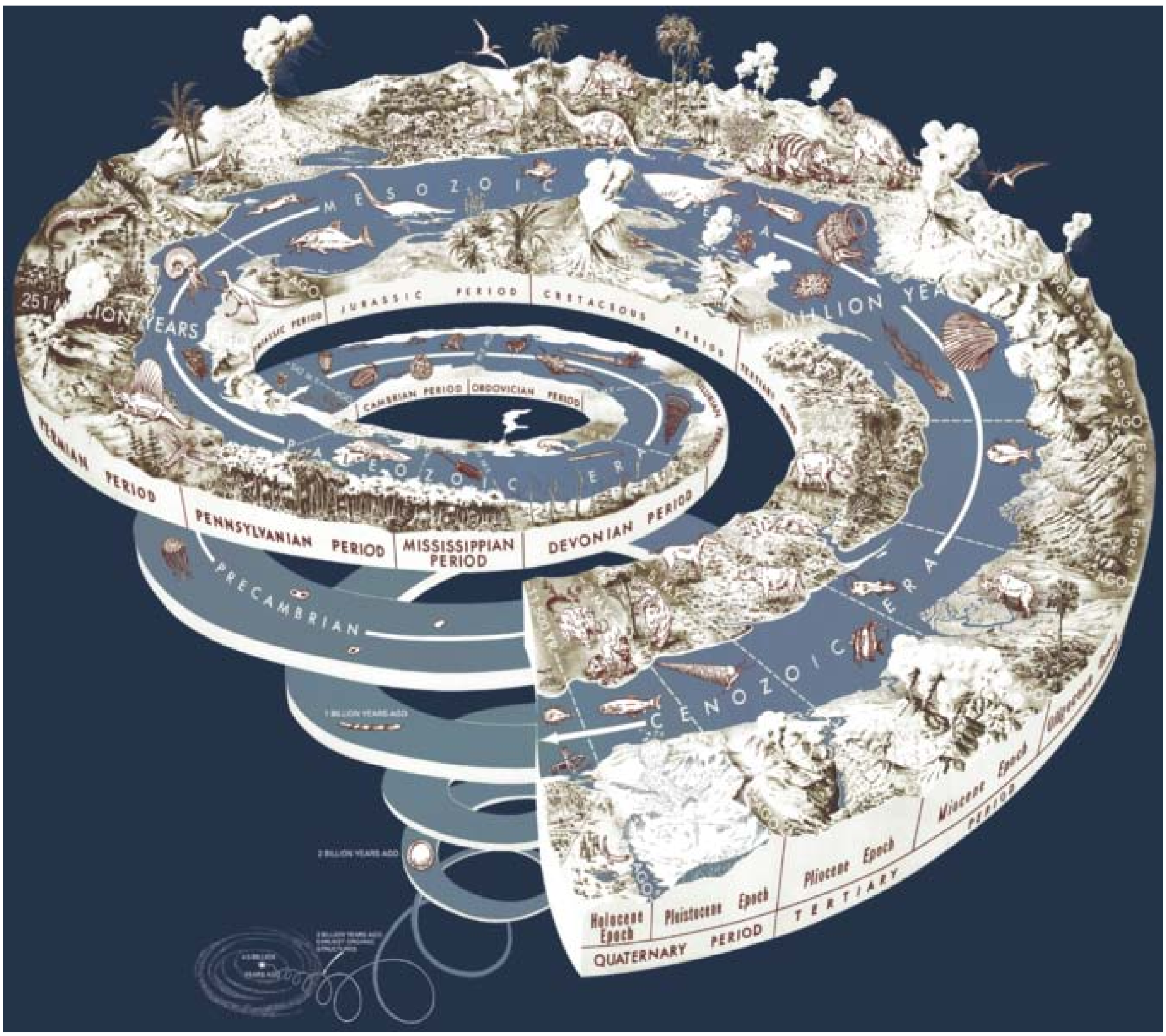


Diagram of geological time scale

The **geological history of Earth** began 4.567 billion years ago when the planets of the Solar System were formed out of the solar nebula, a disk-shaped mass of dust and gas left over from the formation of the Sun. Initially molten, the outer layer of the planet Earth cooled to form a solid crust when water began accumulating in the atmosphere. The Moon formed soon afterwards, possibly as the result of a Mars-sized object with about 10% of the Earth's mass, known as Theia, impacting the Earth in a glancing blow. Some of this object's mass merged with the Earth and a portion was ejected into space, but enough material survived to form an orbiting moon.

Outgassing and volcanic activity produced the primordial atmosphere. Condensing water vapor, augmented by ice delivered by comets, produced the oceans.

As the surface continually reshaped itself over hundreds of millions of years, continents formed and broke up. The continents migrated across the surface, occasionally combining to form a supercontinent. Roughly 750 Ma (million years ago), the earliest-known supercontinent Rodinia, began to break apart. The continents later recombined to form Pannotia, 600–540 Ma, then finally Pangaea, which broke apart 180 Ma.

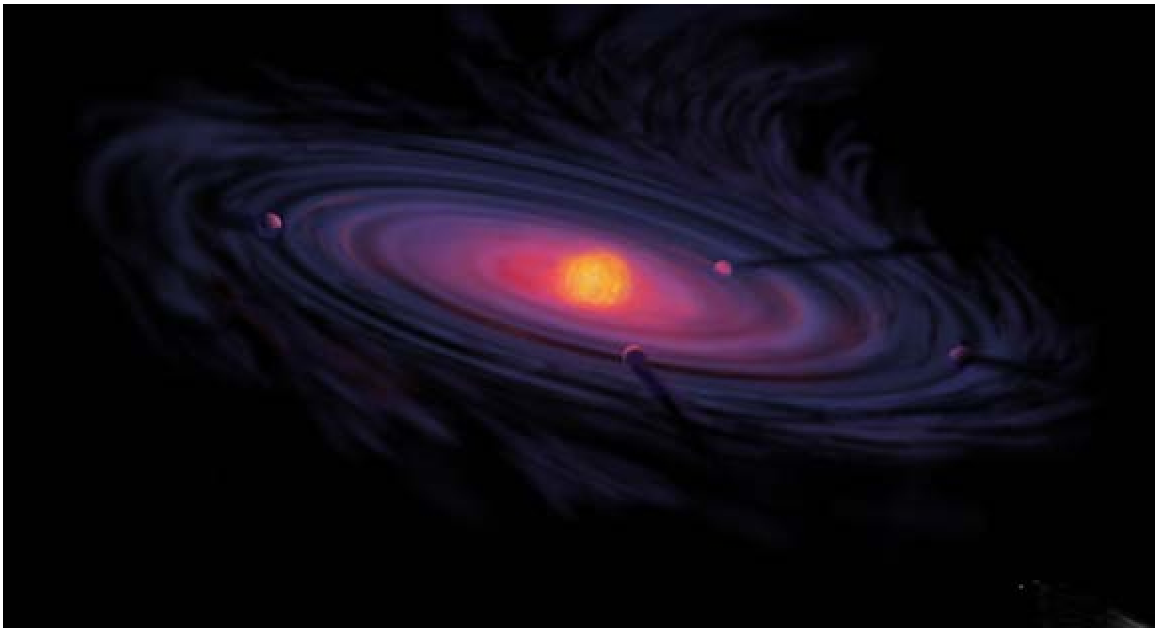
The present pattern of ice ages began about 40 Ma, then intensified during the Pleistocene about 3 Ma. The polar regions have since undergone repeated cycles of glaciation and thaw, repeating every 40,000–100,000 years. The last glacial period of the current ice age ended about 10,000 years ago.

The geological history of the Earth can be broadly classified into two periods: the Precambrian supereon and the Phanerozoic eon.

Precambrian

Precambrian includes approximately 90% of geologic time. It extends from 4.6 billion years ago to the beginning of the Cambrian Period (about 570 Ma). It includes three eons, the Hadean, Archean, and Proterozoic Eons.

Hadean Eon



Artist's conception of a protoplanetary disc

During Hadean time (4.6–3.8 Ga), the Solar System was forming, probably within a large cloud of gas and dust around the sun, called an accretion disc. The Hadean Eon isn't formally recognized, but it essentially marks the era before there were any rocks. The oldest dated zircons date from about 4400 Ma (million years ago) - very close to the hypothesized time of the Earth's formation.

During the Hadean period the Late Heavy Bombardment occurred (approximately 3800 to 4100 Ma) during which a large number of impact craters are believed to have formed on the Moon, and by inference on Earth, Mercury, Venus and Mars as well.

Archean Eon

The Earth of the early Archean (3,800-2,500 Ma) may have had a different tectonic style. During this time, the Earth's crust cooled enough that rocks and continental plates began to form. Some scientists think because the Earth was hotter, that plate tectonic activity was more vigorous than it is today, resulting in a much greater rate of recycling of crustal material. This may have prevented cratonisation and continent formation until the mantle cooled and convection slowed down. Others argue that the subcontinental lithospheric mantle is too buoyant to subduct and that the lack of Archean rocks is a function of erosion and subsequent tectonic events.

In contrast to the Proterozoic, Archean rocks are often heavily-metamorphized deep-water sediments, such as graywackes, mudstones, volcanic sediments and banded iron formations. Greenstone belts are typical Archean formations, consisting of alternating high- and low-grade metamorphic rocks. The high-grade rocks were derived from volcanic island arcs, while the low-grade metamorphic rocks represent deep-sea sediments eroded from the neighboring island arcs and deposited in a forearc basin. In short, greenstone belts represent sutured protocontinents.

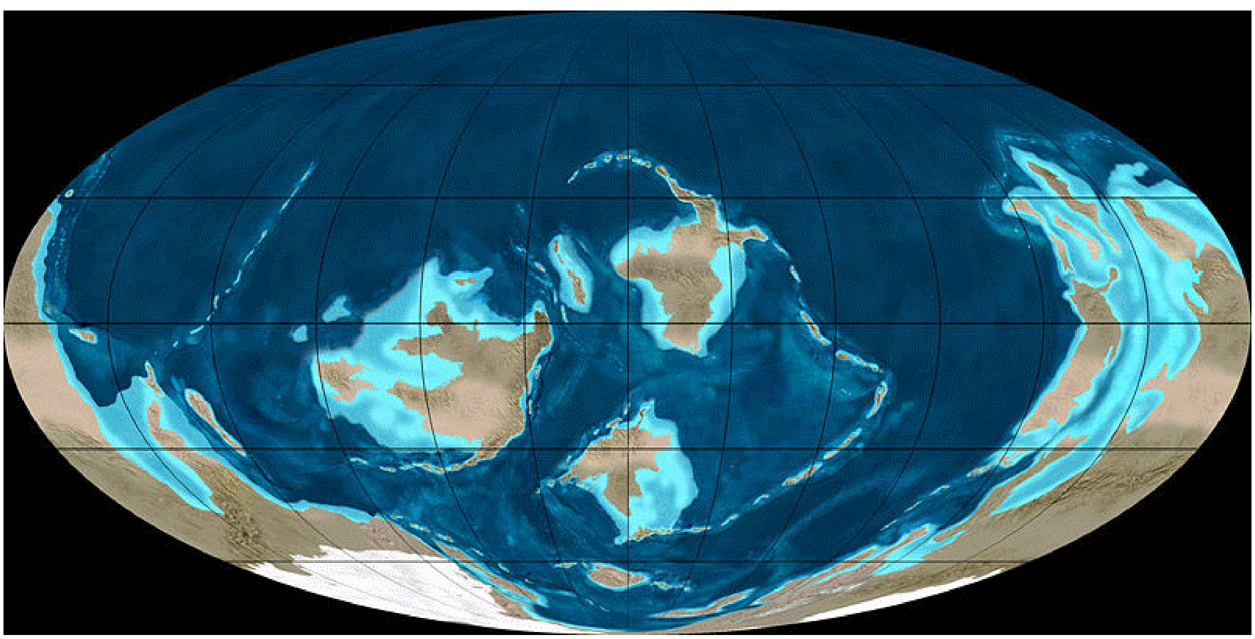
By 3.5 billion years ago, the Earth's magnetic field was established. The solar wind flux was about 100 times the value of the modern Sun, so the presence of the magnetic field helped prevent the planet's atmosphere from being stripped away, which is what likely happened to the atmosphere of Mars. However, the field strength was lower than at present and the magnetosphere was about half the modern radius.

Proterozoic Eon

The geologic record of the **Proterozoic** (2,500-570 Ma) is much better than that for the preceding Archean. In contrast to the deep-water deposits of the Archean, the Proterozoic features many strata that were laid down in extensive shallow epicontinental seas; furthermore, many of these rocks are less metamorphosed than Archean-age ones, and plenty are unaltered. Study of these rocks show that the eon featured massive, rapid continental accretion (unique to the Proterozoic), supercontinent cycles, and wholly-modern orogenic activity.

The first-known glaciations occurred during the Proterozoic, one began shortly after the beginning of the eon, while there were at least four during the Neoproterozoic, climaxing with the Snowball Earth of the Varangian glaciation.

Phanerozoic Eon



Earth's palaeogeographic reconstruction beginning from early Cambrian period

The **Phanerozoic** Eon is the current eon in the geologic timescale. It covers roughly 545 million years. During this period continents drifted about, eventually collected into a single landmass known as Pangea and then split up into the current continental landmasses.

The Phanerozoic is divided into three eras — the Paleozoic, the Mesozoic and the Cenozoic.

Paleozoic Era

The **Paleozoic** spanned from roughly 542 Ma to roughly 251 Ma and is subdivided into six geologic periods; from oldest to youngest they are the Cambrian, Ordovician, Silurian, Devonian, Carboniferous and Permian. Geologically, the Paleozoic starts shortly after the breakup of a supercontinent called Pannotia and at the end of a global ice age. Throughout the early Palaeozoic, the Earth's landmass was broken up into a substantial number of relatively small continents. Toward the end of the era the continents gathered together into a supercontinent called Pangaea, which included most of the Earth's land area.

Cambrian Period

The **Cambrian** is a major division of the geologic timescale that begins about 542 ± 1.0 Ma. Cambrian continents are thought to have resulted from the breakup of a Neoproterozoic supercontinent called Pannotia. The waters of the Cambrian period appear to have been widespread and shallow. Continental drift rates may have been anomalously high. Laurentia, Baltica and Siberia remained independent continents following the break-up of the supercontinent of Pannotia. Gondwana started to drift toward the South Pole. Panthalassa covered most of the southern hemisphere, and minor oceans included the Proto-Tethys Ocean, Iapetus Ocean and Khanty Ocean.

Ordovician Period

The **Ordovician** period started at a major extinction event called the Cambrian-Ordovician extinction events some time about 488.3 ± 1.7 Ma. During the Ordovician the southern continents were collected into a single continent called Gondwana. Gondwana started the period in the equatorial latitudes and, as the period progressed, drifted toward the South Pole. Early in the Ordovician the continents Laurentia, Siberia and Baltica were still independent continents (since the break-up of the supercontinent Pannotia earlier), but Baltica began to move toward Laurentia later in the period, causing the Iapetus Ocean to shrink between them. Also, Avalonia broke free from Gondwana and began to head north toward Laurentia. The Rheic Ocean was formed as a result of this. By the end of the period, Gondwana had neared or approached the pole and was largely glaciated.

The Ordovician came to a close in a series of extinction events that, taken together, comprise the second-largest of the five major extinction events in Earth's history in terms of percentage of genera that went extinct. The only larger one was the Permian-Triassic extinction event. The extinctions occurred approximately 444-447 Ma and mark the boundary between the Ordovician and the following Silurian Period.

The most-commonly accepted theory is that these events were triggered by the onset of an ice age, in the Hirnantian faunal stage that ended the long, stable greenhouse conditions typical of the Ordovician. The ice age was probably not as long-lasting as once thought; study of oxygen isotopes in fossil brachiopods shows that it was probably no longer than 0.5 to 1.5 million years. The event was preceded by a fall in atmospheric carbon dioxide (from 7000ppm to 4400ppm) which selectively affected the shallow seas where most organisms lived. As the southern supercontinent Gondwana drifted over the South Pole, ice caps formed on it. Evidence of these ice caps have been detected in Upper Ordovician rock strata of North Africa and then-adjacent northeastern South America, which were south-polar locations at the time.

Silurian Period

The **Silurian** is a major division of the geologic timescale that started about 443.7 ± 1.5 Ma. During the Silurian, Gondwana continued a slow southward drift to high southern latitudes, but there is evidence that the Silurian ice caps were less extensive than those of the late Ordovician glaciation. The melting of ice caps and glaciers contributed to a rise in sea levels, recognizable from the fact that Silurian sediments overlie eroded Ordovician sediments, forming an unconformity. Other cratons and continent fragments drifted together near the equator, starting the formation of a second supercontinent known as Euramerica. The vast ocean of Panthalassa covered most of the northern hemisphere. Other minor oceans include Proto-Tethys, Paleo-Tethys, Rheic Ocean, a seaway of Iapetus Ocean (now in between Avalonia and Laurentia), and newly-formed Ural Ocean.

Devonian Period

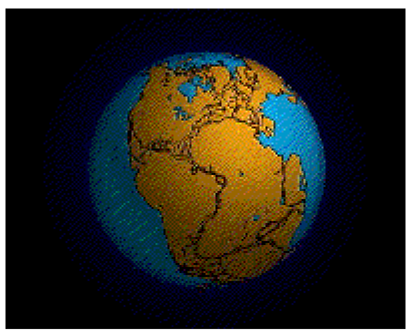
The **Devonian** spanned roughly from 416 to 359 Ma. The period was a time of great tectonic activity, as Laurasia and Gondwanaland drew closer together. The continent Euramerica (or Laurussia) was created in the early Devonian by the collision of Laurentia and Baltica, which rotated into the natural dry zone along the Tropic of Capricorn. In these near-deserts, the Old Red Sandstone sedimentary beds formed, made red by the oxidized iron (hematite) characteristic of drought conditions. Near the equator Pangaea began to consolidate from the plates containing North America and Europe, further raising the northern Appalachian Mountains and forming the Caledonian Mountains in Great Britain and Scandinavia. The southern continents remained tied together in the supercontinent of Gondwana. The remainder of modern Eurasia lay in the Northern Hemisphere. Sea levels were high worldwide, and much of the land lay submerged under shallow seas. The deep, enormous Panthalassa (the "universal ocean") covered the rest of the planet. Other minor oceans were Paleo-Tethys, Proto-Tethys, Rheic Ocean and Ural Ocean (which was closed during the collision with Siberia and Baltica).

Carboniferous Period

The **Carboniferous** extends from about 359.2 ± 2.5 Ma, to about 299.0 ± 0.8 Ma.

A global drop in sea level at the end of the Devonian reversed early in the Carboniferous; this created the widespread epicontinental seas and carbonate deposition of the Mississippian. There was also a drop in south polar temperatures; southern Gondwanaland was glaciated throughout the period, though it is uncertain if the ice sheets were a holdover from the Devonian or not. These conditions apparently had little effect in the deep tropics, where lush coal swamps flourished within 30 degrees of the northernmost glaciers. A mid-Carboniferous drop in sea-level precipitated a major marine extinction, one that hit crinoids and ammonites especially hard. This sea-level drop and the associated unconformity in North America separate the Mississippian period from the Pennsylvanian period.

The Carboniferous was a time of active mountain building, as the supercontinent Pangea came together. The southern continents remained tied together in the supercontinent Gondwana, which collided with North America-Europe (Laurussia) along the present line of eastern North America. This continental collision resulted in the Hercynian orogeny in Europe, and the Alleghenian orogeny in North America; it also extended the newly-uplifted Appalachians southwestward as the Ouachita Mountains. In the same time frame, much of present eastern Eurasian plate welded itself to Europe along the line of the Ural mountains. During the Late Carboniferous Pangaea was shaped like an "O". There were two major oceans in the Carboniferous the Panthalassa and Paleo-Tethys, which was inside the "O" in the Carboniferous Pangaea. Other minor oceans were shrinking and eventually closed the Rheic Ocean (closed by the assembly of South and North America), the small, shallow Ural Ocean (which was closed by the collision of Baltica, and Siberia continents, creating the Ural Mountains) and Proto-Tethys Ocean.



Pangaea separation animation

Permian Period

The **Permian** extends from about 299.0 ± 0.8 Ma (ICS 2004) to 251.0 ± 0.4 Ma.

During the Permian all the Earth's major land masses, except portions of East Asia, were collected into a single supercontinent known as Pangaea. Pangaea straddled the equator and extended toward the poles, with a corresponding effect on ocean currents in the single great ocean (*Panthalassa*, the *universal sea*), and the Paleo-Tethys Ocean, a large ocean that was between Asia and Gondwana. The Cimmeria continent rifted away from Gondwana and drifted north to Laurasia, causing the Paleo-Tethys to shrink. A new ocean was growing on its southern end, the Tethys Ocean, an ocean that would dominate much of the Mesozoic Era. Large continental landmasses create climates with extreme variations of heat and cold ("continental climate") and monsoon conditions with highly seasonal rainfall patterns. Deserts seem to have been widespread on Pangaea.

Mesozoic Era

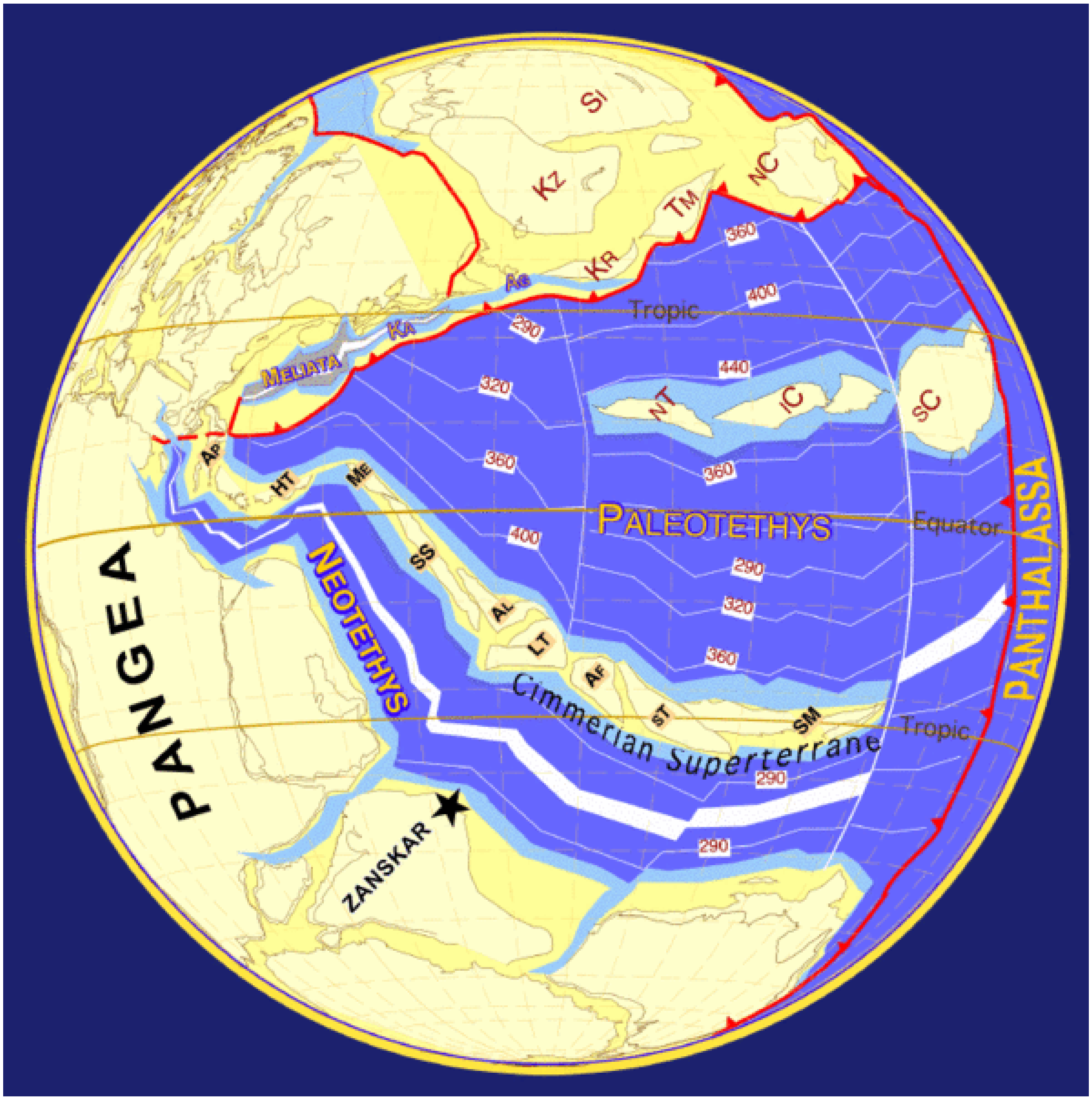


Plate tectonics- 249 MA (million years ago)

Plate tectonics- 290 MA (million years ago)

The **Mesozoic** extended roughly from 251 Ma to 65 Ma.

After the vigorous convergent plate mountain-building of the late Paleozoic, Mesozoic tectonic deformation was comparatively mild. Nevertheless, the era featured the dramatic rifting of the supercontinent Pangaea. Pangaea gradually split into a northern continent, Laurasia, and a southern continent, Gondwana. This created the passive continental margin that characterizes most of the Atlantic coastline (such as along the U.S. East Coast) today.

Triassic Period

The **Triassic** period extends from about 251 ± 0.4 to 199.6 ± 0.6 Ma. During the Triassic, almost all the Earth's land mass was concentrated into a single supercontinent centered more or less on the equator, called Pangaea ("all the land"). This took the form of a giant "Pac-Man" with an east-facing "mouth" constituting the Tethys sea, a vast gulf that opened farther westward in the mid-Triassic, at the expense of the shrinking Paleo-Tethys Ocean, an ocean that existed during the Paleozoic.

The remainder was the world-ocean known as Panthalassa ("all the sea"). All the deep-ocean sediments laid down during the Triassic have disappeared through subduction of oceanic plates; thus, very little is known of the Triassic open ocean. The supercontinent Pangaea was rifting during the Triassic—especially late in the period—but had not yet separated. The first nonmarine sediments in the rift that marks the initial break-up of Pangea—which separated New Jersey from Morocco—are of Late Triassic age; in the U.S., these thick sediments comprise the Newark Supergroup. Because of the limited shoreline of one super-continental mass, Triassic marine deposits are globally relatively rare; despite their prominence in Western Europe, where the Triassic was first studied. In North America, for example, marine deposits are limited to a few exposures in the west. Thus Triassic stratigraphy is mostly based on organisms living in lagoons and hypersaline environments, such as *Estheria* crustaceans and terrestrial vertebrates.

Jurassic Period

The **Jurassic** period extends from about 199.6 ± 0.6 Ma to 145.4 ± 4.0 Ma. During the early Jurassic, the supercontinent Pangaea broke up into the northern supercontinent Laurasia and the southern supercontinent Gondwana; the Gulf of Mexico opened in the new rift between North America and what is now Mexico's Yucatan Peninsula. The Jurassic North Atlantic Ocean was relatively narrow, while the South Atlantic did not open until the following Cretaceous Period, when Gondwana itself rifted apart. The Tethys Sea closed, and the Neotethys basin appeared. Climates were warm, with no evidence of glaciation. As in the Triassic, there was apparently no land near either pole, and no extensive ice caps existed. The Jurassic geological record is good in western Europe, where extensive marine sequences indicate a time when much of the continent was submerged under shallow tropical seas; famous locales include the Jurassic Coast World Heritage Site and the renowned late Jurassic *lagerstätten* of Holzmaden and Solnhofen. In contrast, the North American Jurassic record is the poorest of the Mesozoic, with few outcrops at the surface. Though the epicontinental Sundance Sea left marine deposits in parts of the northern plains of the United States and Canada during the late Jurassic, most exposed sediments from this period are continental, such as the alluvial deposits of the Morrison Formation. The first of several massive batholiths were emplaced in the northern Cordillera beginning in the mid-Jurassic, marking the Nevadan orogeny. Important Jurassic exposures are also found in Russia, India, South America, Japan, Australasia and the United Kingdom.

Cretaceous Period

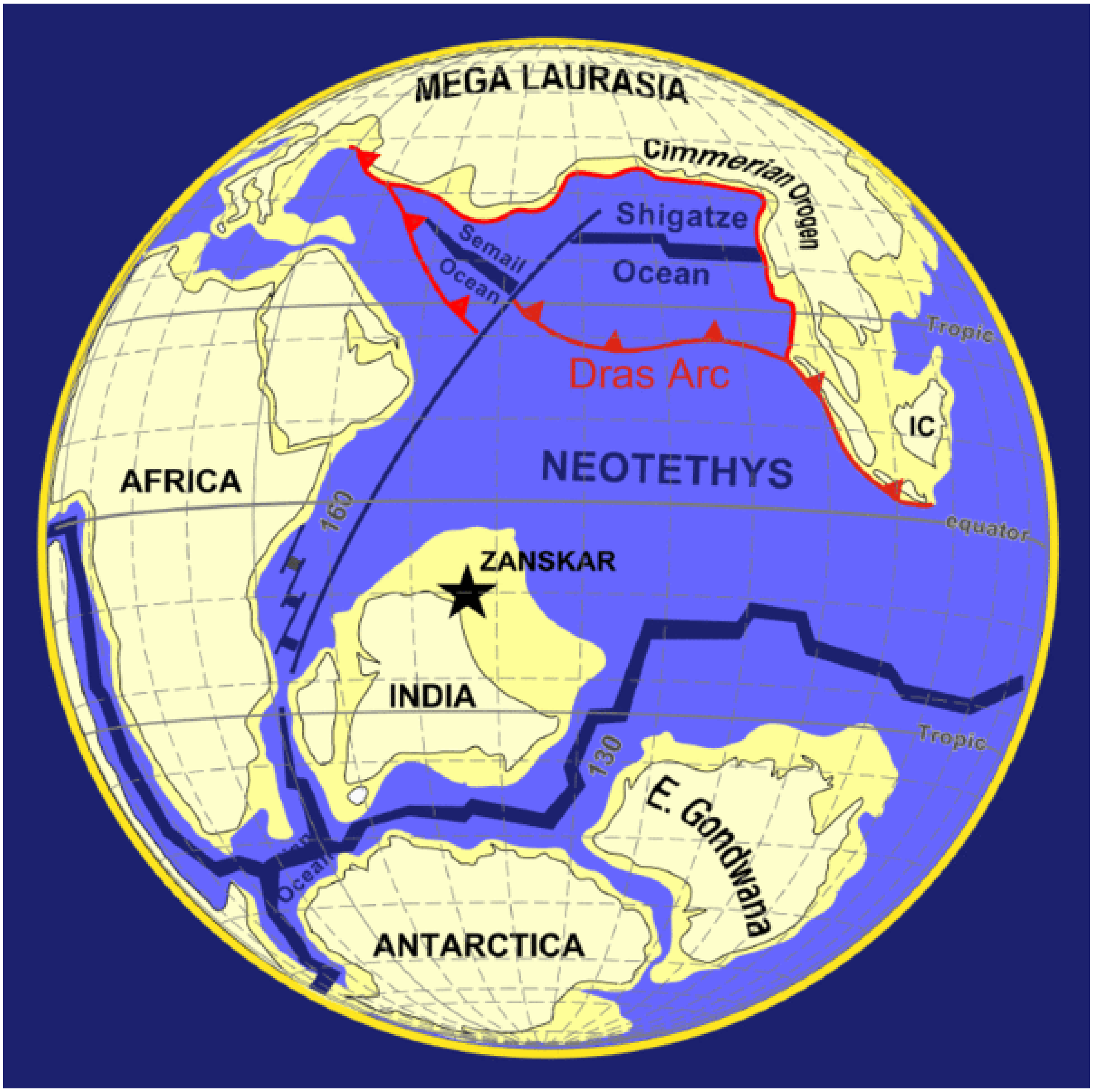


Plate tectonics- 100 Ma, Cretaceous period

The **Cretaceous** period extends from about 145.5 ± 4.0 Ma to about 65.5 ± 0.3 Ma.

During the Cretaceous, the late Paleozoic-early Mesozoic supercontinent of Pangaea completed its breakup into present day continents, although their positions were substantially different at the time. As the Atlantic Ocean widened, the convergent-margin orogenies that had begun during the Jurassic continued in the North American Cordillera, as the Nevadan orogeny was followed by the Sevier and Laramide orogenies. Though Gondwana was still intact in the beginning of the Cretaceous, Gondwana itself broke up as South America, Antarctica and Australia rifted away from Africa (though India and Madagascar remained attached to each other); thus, the South

Atlantic and Indian Oceans were newly formed. Such active rifting lifted great undersea mountain chains along the welts, raising eustatic sea levels worldwide.

To the north of Africa the Tethys Sea continued to narrow. Broad shallow seas advanced across central North America (the Western Interior Seaway) and Europe, then receded late in the period, leaving thick marine deposits sandwiched between coal beds. At the peak of the Cretaceous transgression, one-third of Earth's present land area was submerged. The Cretaceous is justly famous for its chalk; indeed, more chalk formed in the Cretaceous than in any other period in the Phanerozoic. Mid-ocean ridge activity—or rather, the circulation of seawater through the enlarged ridges—enriched the oceans in calcium; this made the oceans more saturated, as well as increased the bioavailability of the element for calcareous nannoplankton. These widespread carbonates and other sedimentary deposits make the Cretaceous rock record especially fine. Famous formations from North America include the rich marine fossils of Kansas's Smoky Hill Chalk Member and the terrestrial fauna of the late Cretaceous Hell Creek Formation. Other important Cretaceous exposures occur in Europe and China. In the area that is now India, massive lava beds called the Deccan Traps were laid down in the very late Cretaceous and early Paleocene.

Cenozoic Era

The **Cenozoic** era covers the 65.5 million years since the Cretaceous-Tertiary extinction event. The Cenozoic era is ongoing. By the end of the Mesozoic era, the continents had rifted into nearly their present form. Laurasia became North America and Eurasia, while Gondwana split into South America, Africa, Australia, Antarctica and the Indian subcontinent, which collided with the Asian plate. This impact gave rise to the Himalayas. The Tethys Sea, which had separated the northern continents from Africa and India, began to close up, forming the Mediterranean sea.

Paleogene Period

The **Paleogene** (alternatively **Palaeogene**) period is a unit of geologic time that began 65.5 ± 0.3 and ended 23.03 ± 0.05 Ma and comprises the first part of the Cenozoic era. This period consists of the Paleocene, Eocene and Oligocene Epochs.

Paleocene Epoch

The **Paleocene**, lasted from 65.5 ± 0.3 Ma to 55.8 ± 0.2 Ma.

In many ways, the Paleocene continued processes that had begun during the late Cretaceous Period. During the Paleocene, the continents continued to drift toward their present positions. Supercontinent Laurasia had not yet separated into three continents. Europe and Greenland were still connected. North America and Asia were still intermittently joined by a land bridge, while Greenland and North America were beginning to separate. The Laramide orogeny of the late Cretaceous continued to uplift the Rocky Mountains in the American west, which ended in the succeeding epoch. South and North America remained separated by equatorial seas (they joined during the Neogene); the components of the former southern supercontinent Gondwanaland continued to split apart, with Africa, South America, Antarctica and Australia pulling away from each other. Africa was heading north toward Europe, slowly closing the Tethys Ocean, and India began its migration to Asia that would lead to a tectonic collision and the formation of the Himalayas.

Eocene Epoch

During the **Eocene** (55.8 ± 0.2 - 33.9 ± 0.1 Ma), the continents continued to drift toward their present positions. At the beginning of the period, Australia and Antarctica remained connected, and warm equatorial currents mixed with colder Antarctic waters, distributing the heat around the world and keeping global temperatures high. But when Australia split from the southern continent around 45 Ma, the warm equatorial currents were deflected away from Antarctica, and an isolated cold water channel developed between the two continents. The Antarctic region cooled down, and the ocean surrounding Antarctica began to freeze, sending cold water and ice floes north, reinforcing the cooling. The northern supercontinent of Laurasia began to break up, as Europe, Greenland and North America drifted apart. In western North America, mountain building started in the Eocene, and huge lakes formed in the high flat basins among uplifts. In Europe, the Tethys Sea finally vanished, while the uplift of the Alps isolated its final remnant, the Mediterranean, and created another shallow sea with island archipelagos to the north. Though the North Atlantic was opening, a land connection appears to have remained between North America and Europe since the faunas of the two regions are very similar. India continued its journey away from Africa and began its collision with Asia, folding the Himalayas into existence.

Oligocene Epoch

The **Oligocene** epoch extends from about 34 Ma to 23 Ma. During the Oligocene the continents continued to drift toward their present positions.

Antarctica continued to become more isolated and finally developed a permanent ice cap. Mountain building in western North America continued, and the Alps started to rise in Europe as the African plate continued to push north into the Eurasian plate, isolating the remnants of Tethys Sea. A brief marine incursion marks the early Oligocene in Europe. There appears to have been a land bridge in the early Oligocene between North America and Europe since the faunas of the two regions are very similar. During sometime in the Oligocene, South America was finally detached from Antarctica and drifted north toward North America. It also allowed the Antarctic Circumpolar Current to flow, rapidly cooling the continent.

Neogene Period

Neogene Period is a unit of geologic time starting 23.03 ± 0.05 Ma. The Neogene Period follows the Paleogene Period. Under the current proposal of the International Commission on Stratigraphy (ICS), the Neogene would consist of the Miocene, Pliocene, Pleistocene and Holocene epochs and continue until the present.

Miocene Epoch

The **Miocene** extends from about 23.03 to 5.332 Ma.

During the Miocene continents continued to drift toward their present positions. Of the modern geologic features, only the land bridge between South America and North America was absent, although South America was approaching the western subduction zone in the Pacific Ocean, causing both the rise of the Andes and a southward extension of the Meso-American peninsula. India continued to collide with Asia, creating more mountain ranges. The Tethys Seaway continued to shrink and then disappeared as Africa collided with Eurasia in the Turkish-Arabian region between 19 and 12 Ma (ICS 2004). Subsequent uplift of mountains in the western Mediterranean region and a global fall in sea levels combined to cause a temporary drying up of the Mediterranean Sea (known as the Messinian salinity crisis) near the end of the Miocene.

Pliocene Epoch

The **Pliocene** extends from 5.332 Ma to 1.806 Ma. During the Pliocene continents continued to drift toward their present positions, moving from positions possibly as far as 250 kilometres (155 mi) from their present locations to positions only 70 km from their current locations.

South America became linked to North America through the Isthmus of Panama during the Pliocene, bringing a nearly-complete end to South America's distinctive marsupial faunas. The formation of the Isthmus had major consequences on global temperatures, since warm equatorial ocean currents were cut off and an Atlantic cooling cycle began, with cold Arctic and Antarctic waters dropping temperatures in the now-isolated Atlantic Ocean. Africa's collision with Europe formed the Mediterranean Sea, cutting off the remnants of the Tethys Ocean. Sea level changes exposed the land-bridge between Alaska and Asia. Near the end of the Pliocene, about 2.58 Ma (the start the of the Quaternary Period), the current ice age began.

Pleistocene Epoch

The **Pleistocene** extends from 1,808,000 to 11,550 years before present. The modern continents were essentially at their present positions during the Pleistocene, the plates upon which they sit probably having moved no more than 100 kilometres (62 mi) relative to each other since the beginning of the period.

Holocene Epoch

The **Holocene** epoch began approximately 11,550 calendar years before present) and continues to the present. During the Holocene, continental motions have been less than a kilometer.

However, ice melt caused world sea levels to rise about 35 metres (115 ft) in the early part of the Holocene. In addition, many areas above about 40 degrees north latitude had been depressed by the weight of the Pleistocene glaciers and rose as much as 180 metres (591 ft) over the late Pleistocene and Holocene, and are still rising today. The sea level rise and temporary land depression allowed temporary marine incursions into areas that are now far from the sea. Holocene marine fossils are known from Vermont, Quebec, Ontario and Michigan. Other than higher latitude temporary marine incursions associated with glacial depression, Holocene fossils are found primarily in lakebed, floodplain and cave deposits. Holocene marine deposits along low-latitude coastlines are rare because the rise in sea levels during the period exceeds any likely upthrusting of non-glacial origin. Post-glacial rebound in Scandinavia resulted in the emergence of coastal areas around the Baltic Sea, including much of Finland. The region continues to rise, still causing weak earthquakes across Northern Europe. The equivalent event in North America was the rebound of Hudson Bay, as it shrank from its larger, immediate post-glacial Tyrrell Sea phase, to near its present boundaries.

Evolutionary History of life

The **evolutionary history of life** on Earth traces the processes by which living and fossil organisms evolved. It stretches from the origin of life on Earth, thought to be over 3,500 million years ago, to the present day. The similarities between all present day organisms indicate the presence of a common ancestor from which all known species have diverged through the process of evolution.

Microbial mats of coexisting bacteria and archaea were the dominant form of life in the early Archean and many of the major steps in early evolution are thought to have taken place within them. The evolution of oxygenic photosynthesis, around 3,500 million years ago, eventually led to the oxygenation of the atmosphere, beginning around 2,400 million years ago. The earliest evidence of eukaryotes (complex cells with organelles), dates from 1,850 million years ago, and while they may have been present earlier, their diversification accelerated when they started using oxygen in their metabolism. Later, around 1,700 million years ago, multicellular organisms began to appear, with differentiated cells performing specialised functions.

The earliest land plants date back to around 450 million years ago, though evidence suggests that algal scum formed on the land as early as 1,200 million years ago. Land plants were so successful that they are thought to have contributed to the late Devonian extinction event. Invertebrate animals appear during the Vendian period, while vertebrates originated about 525 million years ago during the Cambrian explosion.

During the Permian period, synapsids, including the ancestors of mammals, dominated the land, but the Permian–Triassic extinction event 251 million years ago came close to wiping out all complex life. During the recovery from this catastrophe, archosaurs became the most abundant land vertebrates, displacing therapsids in the mid-Triassic. One archosaur group, the dinosaurs, dominated the Jurassic and Cretaceous periods, with the ancestors of mammals surviving only as small insectivores. After the Cretaceous–Tertiary extinction event 65 million years ago killed off the non-avian dinosaurs mammals increased rapidly in size and diversity. Such mass extinctions may have accelerated evolution by providing opportunities for new groups of organisms to diversify.

Fossil evidence indicates that flowering plants appeared and rapidly diversified in the Early Cretaceous, between 130 million years ago and 90 million years ago, probably helped by coevolution with pollinating insects. Flowering plants and marine phytoplankton are still the dominant producers of organic matter. Social insects appeared around the same time as flowering plants. Although they occupy only small parts of the insect "family tree", they now form over half the total mass of insects. Humans evolved from a lineage of upright-walking apes whose earliest fossils date from over 6 million years ago. Although early members of this lineage had chimp-sized brains, there are signs of a steady increase in brain size after about 3 million years ago.

Earliest history of Earth

The oldest meteorite fragments found on Earth are about 4,540 million years old, this, coupled primarily with the dating of ancient lead deposits, has put the estimated age of Earth at around that time. About 40 million years later a planetoid struck the Earth, throwing into orbit the material that formed the Moon.

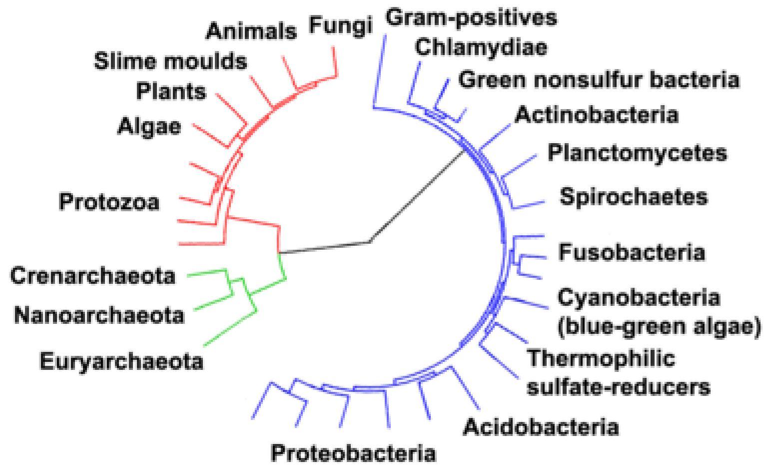
Until recently the oldest rocks found on Earth were about 3,800 million years old, leading scientists to believe for decades that Earth's surface had been molten until then. Accordingly, they named this part of Earth's history the Hadean eon, whose name means "hellish". However analysis of zircons formed 4,400 to 4,000 million years ago indicates that Earth's crust solidified about 100 million years after the planet's formation and that the planet quickly acquired oceans and an atmosphere, which may have been capable of supporting life.

Evidence from the Moon indicates that from 4,000 to 3,800 million years ago it suffered a Late Heavy Bombardment by debris that was left over from the formation of the Solar system, and the Earth should have experienced an even heavier bombardment due to its stronger gravity. While there is no direct evidence of conditions on Earth 4,000 to 3,800 million years ago, there is no reason to think that the Earth was not also affected by this late heavy bombardment. This event may well have stripped away any previous atmosphere and oceans; in this case gases and water from comet impacts may have contributed to their replacement, although volcanic outgassing on Earth would have contributed at least half.

Earliest evidence for life on Earth

The earliest identified organisms were minute and relatively featureless, their fossils look like small rods, which are very difficult to tell apart from structures that arise through abiotic physical processes. The oldest undisputed evidence of life on Earth, interpreted as fossilized bacteria, dates to 3,000 million years ago. Other finds in rocks dated to about 3,500 million years ago have been interpreted as bacteria, with geochemical evidence also seeming to show the presence of life 3,800 million years ago. However these analyses were closely scrutinized, and non-biological processes were found which could produce all of the "signatures of life" that had been reported. While this does not prove that the structures found had a non-biological origin, they cannot be taken as clear evidence for the presence of life. Currently, the oldest unchallenged evidence for life is geochemical signatures from rocks deposited 3,400 million years ago, although these statements have not been thoroughly examined by critics.

Origins of life on Earth



Evolutionary tree showing the divergence of modern species from their common ancestor in the center. The three domains are colored, with bacteria blue, archaea green, and eukaryotes red.

Biologists reason that all living organisms on Earth must share a single last universal ancestor, because it would be virtually impossible that two or more separate lineages could have independently developed the many complex biochemical mechanisms common to all living organisms. As previously mentioned the earliest organisms for which fossil evidence is available are bacteria, cells far too complex to have arisen directly from non-living materials. The lack of fossil or geochemical evidence for earlier organisms has left plenty of scope for hypotheses, which fall into two main groups: 1) that life arose spontaneously on Earth or 2) that it was "seeded" from elsewhere in the universe.

Life "seeded" from elsewhere

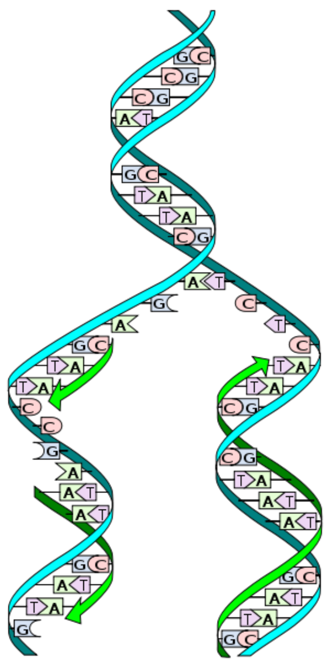
The idea that life on Earth was "seeded" from elsewhere in the universe dates back at least to the fifth century BCE. In the twentieth century it was proposed by the physical chemist Svante Arrhenius, by the astronomers Fred Hoyle and Chandra Wickramasinghe, and by molecular biologist Francis Crick and chemist Leslie Orgel. There are three main versions of the "seeded from elsewhere" hypothesis: from elsewhere in our Solar system via fragments knocked into space by a large meteor impact, in which case the only credible source is Mars; by alien visitors, possibly as a result of accidental contamination by micro-organisms that they brought with them; and from outside the Solar system but by natural means. Experiments suggest that some micro-organisms can survive the shock of being catapulted into space and some can survive exposure to radiation for several days, but there is no proof that they can survive in space for much longer periods. Scientists are divided over the likelihood of life arising independently on Mars, or on other planets in our galaxy.

Independent emergence on Earth

Life on earth is based on carbon and water. Carbon provides stable frameworks for complex chemicals and can be easily extracted from the environment, especially from carbon dioxide. The only other element with similar chemical properties, silicon, forms much less stable structures and, because most of its compounds are solids, would be more difficult for organisms to extract. Water is an excellent solvent and has two other useful properties: the fact that ice floats enables aquatic organisms to survive beneath it in winter; and its molecules have electrically negative and positive ends, which enables it to form a wider range of compounds than other solvents can. Other good solvents, such as ammonia, are liquid only at such low temperatures that chemical reactions may be too slow to sustain life, and lack water's other advantages. Organisms based on alternative biochemistry may however be possible on other planets.

Research on how life might have emerged unaided from non-living chemicals focuses on three possible starting points: self-replication, an organism's ability to produce offspring that are very similar to itself; metabolism, its ability to feed and repair itself; and external cell membranes, which allow food to enter and waste products to leave, but exclude unwanted substances. Research on abiogenesis still has a long way to go, since theoretical and empirical approaches are only beginning to make contact with each other.

Replication first: RNA world



The replicator in virtually all known life is deoxyribonucleic acid. DNA's structure and replication systems are far more complex than those of the original replicator.

Even the simplest members of the three modern domains of life use DNA to record their "recipes" and a complex array of RNA and protein molecules to "read" these instructions and use them for growth, maintenance and self-replication. This system is far too complex to have emerged directly from non-living materials. The discovery that some RNA molecules can catalyze both their own replication and the construction of proteins led to the hypothesis of earlier life-forms based entirely on RNA. These ribozymes could have formed an RNA world in which there were individuals but no species, as mutations and horizontal gene transfers would have meant that the offspring in each generation were quite likely to have different genomes from those that their parents started with. RNA would later have been replaced by DNA, which is more stable and therefore can build longer genomes, expanding the range of capabilities a single organism can have. Ribozymes remain as the main components of ribosomes, modern cells' "protein factories".

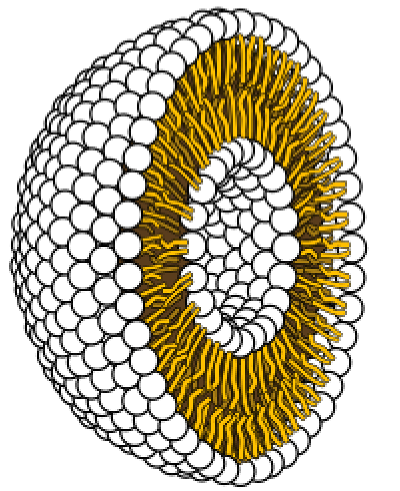
Although short self-replicating RNA molecules have been artificially produced in laboratories, doubts have been raised about where natural non-biological synthesis of RNA is possible. The earliest "ribozymes" may have been formed of simpler nucleic acids such as PNA, TNA or GNA, which would have been replaced later by RNA.

In 2003 it was proposed that porous metal sulfide precipitates would assist RNA synthesis at about 100 °C (212 °F) and ocean-bottom pressures near hydrothermal vents. In this hypothesis lipid membranes would be the last major cell components to appear and until then the proto-cells would be confined to the pores.

Metabolism first: Iron-sulfur world

A series of experiments starting in 1997 showed that early stages in the formation of proteins from inorganic materials including carbon monoxide and hydrogen sulfide could be achieved by using iron sulfide and nickel sulfide as catalysts. Most of the steps required temperatures of about 100 °C (212 °F) and moderate pressures, although one stage required 250 °C (482 °F) and a pressure equivalent to that found under 7 kilometres (4.3 mi) of rock. Hence it was suggested that self-sustaining synthesis of proteins could have occurred near hydrothermal vents.

Membranes first: Lipid world



water-attracting heads of lipid molecules

It has been suggested that double-walled "bubbles" of lipids like those that form the external membranes of cells may have been an essential first step. Experiments that simulated the conditions of the early Earth have reported the formation of lipids, and these can spontaneously form liposomes, double-walled "bubbles", and then reproduce themselves. Although they are not intrinsically information-carriers as nucleic acids are, they would be subject to natural selection for longevity and reproduction. Nucleic acids such as RNA might then have formed more easily within the liposomes than they would have outside.

The clay theory

RNA is complex and there are doubts about whether it can be produced non-biologically in the wild. Some clays, notably montmorillonite, have properties that make them plausible accelerators for the emergence of an RNA world: they grow by self-replication of their crystalline pattern; they are subject to an analog of natural selection, as the clay "species" that grows fastest in a particular environment rapidly becomes dominant; and they can catalyze the formation of RNA molecules. Although this idea has not become the scientific consensus, it still has active supporters.

Research in 2003 reported that montmorillonite could also accelerate the conversion of fatty acids into "bubbles", and that the "bubbles" could encapsulate RNA attached to the clay. These "bubbles" can then grow by absorbing additional lipids and then divide. The formation of the earliest cells may have been aided by similar processes.

A similar hypothesis presents self-replicating iron-rich clays as the progenitors of nucleotides, lipids and amino acids.

Environmental and evolutionary impact of microbial mats

Modern stromatolites in Shark Bay, Western Australia

Microbial mats are multi-layered, multi-species colonies of bacteria and other organisms that are generally only a few millimeters thick, but still contain a wide range of chemical environments, each of which favors a different set of micro-organisms. To some extent each mat forms its own food chain, as the by-products of each group of micro-organisms generally serve as "food" for adjacent groups.

Stromatolites are stubby pillars built as microbes in mats slowly migrate upwards to avoid being smothered by sediment deposited on them by water. There has been vigorous debate about the validity of alleged fossils from before 3,000 million years ago, with critics arguing that so-called stromatolites could have been formed by non-biological processes. In 2006 another find of stromatolites was reported from the same part of Australia as previous ones, in rocks dated to 3,500 million years ago.

In modern underwater mats the top layer often consists of photosynthesizing cyanobacteria which create an oxygen-rich environment, while the bottom layer is oxygen-free and often dominated by hydrogen sulfide emitted by the organisms living there. It is estimated that the appearance of oxygenic photosynthesis by bacteria in mats increased biological productivity by a factor of between 100 and 1,000. The reducing agent used by oxygenic photosynthesis is water, which is much more plentiful than the geologically-produced reducing agents required by the earlier non-oxygenic photosynthesis. From this point onwards life itself produced significantly more of the resources it needed than did geochemical processes. Oxygen is toxic to organisms that are not adapted to it, but greatly increases the metabolic efficiency of oxygen-adapted organisms. Oxygen became a significant component of Earth's atmosphere about 2,400 million years ago. Although eukaryotes may have been present much earlier, the oxygenation of the atmosphere was a prerequisite for the evolution of the most complex eukaryotic cells, from which all multicellular organisms are built. The boundary between oxygen-rich and oxygen-free layers in microbial mats would have moved upwards when photosynthesis shut down overnight, and then downwards as it resumed on the next day. This would have created selection pressure for organisms in this intermediate zone to acquire the ability to tolerate and then to use oxygen, possibly via endosymbiosis, where one organism lives inside another and both of them benefit from their association.

Cyanobacteria have the most complete biochemical "toolkits" of all the mat-forming organisms. Hence they are the most self-sufficient of the mat organisms and were well-adapted to strike out on their own both as floating mats and as the first of the phytoplankton, providing the basis of most marine food chains.

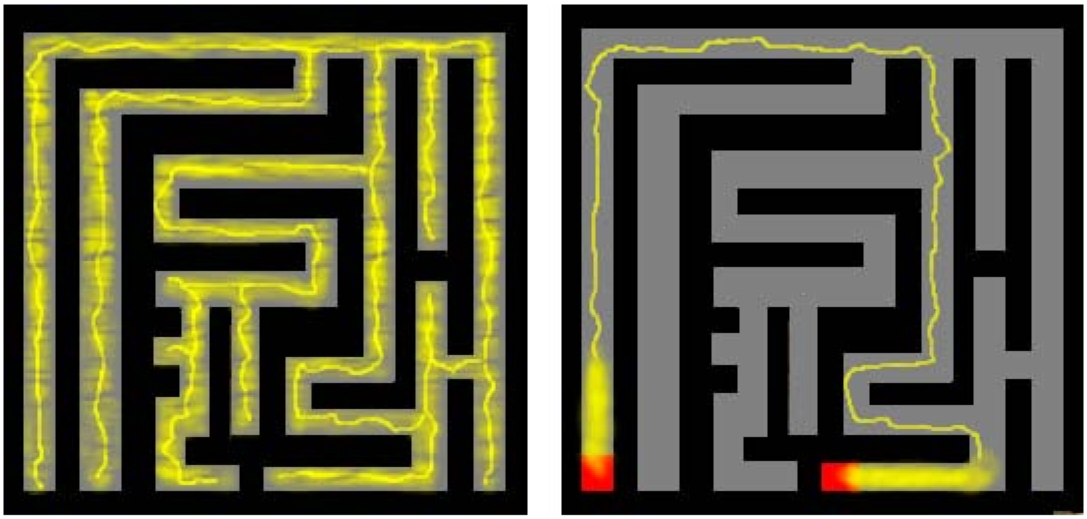
Diversification of eukaryotes

Eukaryotes may have been present long before the oxygenation of the atmosphere, but most modern eukaryotes require oxygen, which their mitochondria use to fuel the production of ATP, the internal energy supply of all known cells. In the 1970s it was proposed and, after much debate, widely accepted that eukaryotes emerged as a result of a sequence of endosymbioses between "procaryotes". For example: a predatory micro-organism invaded a large procaryote, probably an archaean, but the attack was neutralized, and the attacker took up residence and evolved into the first of the mitochondria; one of these chimeras later tried to swallow a photosynthesizing cyanobacterium, but the victim survived inside the attacker and the new combination became the ancestor of plants; and so on. After each endosymbiosis began, the partners would have eliminated unproductive duplication of genetic functions by re-arranging their genomes, a process which sometimes involved transfer of genes between them. Another hypothesis proposes that mitochondria were originally sulfur- or hydrogen-metabolising endosymbionts, and became oxygen-consumers later. On the other hand mitochondria might have been part of eukaryotes' original equipment.

There is a debate about when eukaryotes first appeared: the presence of steranes in Australian shales may indicate that eukaryotes were present 2,700 million years ago; however an analysis in 2008 concluded that these chemicals infiltrated the rocks less than 2,200 million years ago and prove nothing about the origins of eukaryotes. Fossils of the alga *Grypania* have been reported in 1,850 million-year-old rocks (originally dated to 2,100 million years ago but later revised), and indicates that eukaryotes with organelles had already evolved. A diverse collection of fossil algae were found in rocks dated between 1,500 million years ago and 1,400 million years ago. The earliest known fossils of fungi date from 1,430 million years ago.

Multicellular organisms and sexual reproduction

Multicellularity



A slime mold solves a maze. The mold (yellow) explored and filled the maze (left). When the researchers placed sugar (red) at two separate points, the mold concentrated most of its mass there and left only the most efficient connection between the two points (right).

The simplest definitions of "multicellular", for example "having multiple cells", could include colonial cyanobacteria like Nostoc. Even a professional biologist's definition such as "having the same genome but different types of cell" would still include some genera of the green alga Volvox, which have cells that specialize in reproduction. Multicellularity evolved independently in organisms as diverse as sponges and other animals, fungi, plants, brown algae, cyanobacteria, slime moulds and myxobacteria. For the sake of brevity here we focuses on the organisms that show the greatest specialization of cells and variety of cell types, although this approach to the evolution of complexity could be regarded as "rather anthropocentric".

The initial advantages of multicellularity may have included: increased resistance to predators, many of which attacked by engulfing; the ability to resist currents by attaching to a firm surface; the ability to reach upwards to filter-feed or to obtain sunlight for photosynthesis; the ability to create an internal environment that gives protection against the external one; and even the opportunity for a group of cells to behave "intelligently" by sharing information. These features would also have provided opportunities for other organisms to diversify, by creating more varied environments than flat microbial mats could.

Multicellularity with differentiated cells is beneficial to the organism as a whole but disadvantageous from the point of view of individual cells, most of which lose the opportunity to reproduce themselves. In an asexual multicellular organism, rogue cells which retain the ability to reproduce may take over and reduce the organism to a mass of undifferentiated cells. Sexual reproduction eliminates such rogue cells from the next generation and therefore appears to be a prerequisite for complex multicellularity.

The available evidence indicates that eukaryotes evolved much earlier but remained inconspicuous until a rapid diversification around 1,000 million years ago. The only respect in which eukaryotes clearly surpass bacteria and archaea is their capacity for variety of forms, and sexual reproduction enabled eukaryotes to exploit that advantage by producing organisms with multiple cells that differed in form and function.

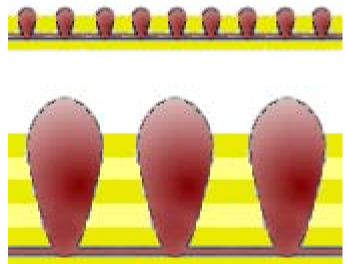
Evolution of sexual reproduction

The defining characteristic of sexual reproduction is recombination, in which each of the offspring receives 50% of its genetic inheritance from each of the parents. Bacteria also exchange DNA by bacterial conjugation, the benefits of which include resistance to antibiotics and other toxins, and the ability to utilize new metabolites. However conjugation is not a means of reproduction, and is not limited to members of the same species – there are cases where bacteria transfer DNA to plants and animals.

The disadvantages of sexual reproduction are well-known: the genetic reshuffle of recombination may break up favorable combinations of genes; and since males do not directly increase the number of offspring in the next generation, an asexual population can out-breed and displace in as little as 50 generations a sexual population that is equal in every other respect. Nevertheless the great majority of animals, plants, fungi and protists reproduce sexually. There is strong evidence that sexual reproduction arose early in the history of eukaryotes and that the genes controlling it have changed very little since then. How sexual reproduction evolved and survived is an unsolved puzzle.

The Red Queen Hypothesis suggests that sexual reproduction provides protection against parasites, because it is easier for parasites to evolve means of overcoming the defenses of genetically identical clones than those of sexual species that present moving targets, and there is some experimental evidence for this. However there is still doubt about whether it would explain the survival of sexual species if multiple similar clone species were present, as one of the clones may survive the attacks of parasites for long enough to out-breed the sexual species.

The Mutation Deterministic Hypothesis assumes that each organism has more than one harmful mutation and the combined effects of these mutations are more harmful than the sum of the harm done by each individual mutation. If so, sexual recombination of genes will reduce the harm that bad mutations do to offspring and at the same time eliminate some bad mutations from the gene pool by isolating them in individuals that perish quickly because they have an above-average number of bad mutations. However the evidence suggests that the MDH's assumptions are shaky, because many species have on average less than one harmful mutation per individual and no species that has been investigated shows evidence of synergy between harmful mutations.



Horodyskia apparently re-arranged itself into fewer but larger main masses as the sediment grew deeper round its base.

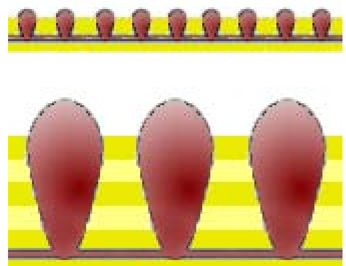
The random nature of recombination causes the relative abundance of alternative traits to vary from one generation to another. This genetic drift is insufficient on its own to make sexual reproduction advantageous, but a combination of genetic drift and natural selection may be sufficient. When chance produces combinations of good traits, natural selection gives a large advantage to lineages in which these traits become genetically linked. On the other hand the benefits of good traits are neutralized if they appear along with bad traits. Sexual recombination gives good traits the opportunities to become linked with other good traits, and mathematical models suggest this may be more than enough to offset the disadvantages of sexual reproduction. Other combinations of hypotheses that are inadequate on their own are also being examined.

The following hypotheses attempt to explain how and why sex evolved:

- It may have enabled organisms to repair genetic damage. The most primitive form of sex may have been one organism repairing damaged DNA by replicating an undamaged strand from a similar organism.
- Sexual reproduction may have originated from selfish parasitic genetic elements propagating themselves by transfer to new hosts.
- It may have evolved from cannibalism, where some of the victim's DNA was incorporated into the cannibal organism.
- Sexual reproduction may have evolved from ancient haloarchaea through a combination of jumping genes, and swapping plasmids.
- Or it may have evolved as a form of vaccination in which infected hosts exchanged weakened symbiotic copies of parasitic DNA as protection against more virulent versions. The meiosis stage of sexual reproduction may then have evolved as a way of removing the symbiotes.

Bacteria also exchange DNA by bacterial conjugation, the benefits of which include resistance to antibiotics and other toxins, and the ability to utilize new metabolites. However conjugation is not a means of reproduction and is not limited to members of the same species, and there are cases where bacteria transfer DNA to plants and animals. Nevertheless it may be an example of the "selfish genetic element" hypothesis, as it transfers DNA by means of such a "selfish gene", the F-plasmid.

Fossil evidence for multicellularity and sexual reproduction



Horodyskia may have been an early metazoan, or a colonial foraminiferan

The Francevillian Group Fossil, dated to 2,100 million years ago, is the earliest known fossil organism that is clearly multicellular. They may have had differentiated cells. Another early multicellular fossil, *Qingshania*, dated to 1,700 million years ago, appears to consist of virtually identical cells. The red alga called *Bangiomorpha*, dated at 1,200 million years ago, is the earliest known organism which certainly has differentiated, specialized cells, and is also the oldest known sexually-reproducing organism. The 1,430 million-year-old fossils interpreted as fungi appear to have been multicellular with differentiated cells. The "string of beads" organism *Horodyskia*, found in rocks dated from 1,500 million years ago to 900 million years ago, may have been an early metazoan; however it has also been interpreted as a colonial foraminiferan.

Emergence of animals

Animals are multicellular eukaryotes and are distinguished from plants, algae, and fungi by lacking cell walls. All animals are motile, if only at certain life stages. All animals except sponges have bodies differentiated into separate tissues, including muscles, which move parts of the animal by contracting, and nerve tissue, which transmits and processes signals.

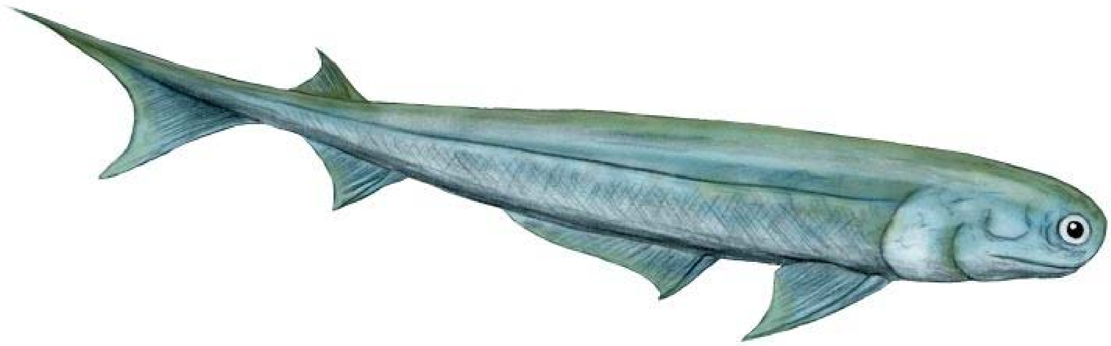
The earliest widely-accepted animal fossils are rather modern-looking cnidarians (the group that includes jellyfish, sea anemones and hydras), possibly from around 580 million years ago, although fossils from the Doushantuo Formation can only be dated approximately. Their presence implies that the cnidarian and bilaterian lineages had already diverged.

The Ediacara biota, which flourished for the last 40 million years before the start of the Cambrian, were the first animals more than a very few centimeters long. Many were flat and had a "quilted" appearance, and seemed so strange that there was a proposal to classify them as a separate kingdom, Vendozoa. Others, however, been interpreted as early molluscs (*Kimberella*), echinoderms (*Arkarua*), and arthropods (*Spriggina*, *Parvancorina*). There is still debate about the classification of these specimens, mainly because the diagnostic features which allow taxonomists to classify more recent organisms, such as similarities to living organisms, are generally absent in the Ediacarans. However there seems little doubt that *Kimberella* was at least a triploblastic bilaterian animal, in other words significantly more complex than cnidarians.

The small shelly fauna are a very mixed collection of fossils found between the Late Ediacaran and Mid Cambrian periods. The earliest, *Cloudina*, shows signs of successful defense against predation and may indicate the start of an evolutionary arms race. Some tiny Early Cambrian shells almost certainly belonged to molluscs, while the owners of some "armor plates", *Halkieria* and *Microdictyon*, were eventually identified when more complete specimens were found in Cambrian lagerstätten that preserved soft-bodied animals.

Opabinia made the largest single contribution to modern interest in the Cambrian explosion

In the 1970s there was already a debate about whether the emergence of the modern phyla was "explosive" or gradual but hidden by the shortage of Pre-Cambrian animal fossils. A re-analysis of fossils from the Burgess Shale lagerstätte increased interest in the issue when it revealed animals, such as *Opabinia*, which did not fit into any known phylum. At the time these were interpreted as evidence that the modern phyla had evolved very rapidly in the "Cambrian explosion" and that the Burgess Shale's "weird wonders" showed that the Early Cambrian was a uniquely experimental period of animal evolution. Later discoveries of similar animals and the development of new theoretical approaches led to the conclusion that many of the "weird wonders" were evolutionary "aunts" or "cousins" of modern groups – for example that *Opabinia* was a member of the lobopods, a group which includes the ancestors of the arthropods, and that it may have been closely related to the modern tardigrades. Nevertheless there is still much debate about whether the Cambrian explosion was really explosive and, if so, how and why it happened and why it appears unique in the history of animals.



Acanthodians were among the earliest vertebrates with jaws

Most of the animals at the heart of the Cambrian explosion debate are protostomes, one of the two main groups of complex animals. One deuterostome group, the echinoderms, many of which have hard calcite "shells", are fairly common from the Early Cambrian small shelly fauna onwards. Other deuterostome groups are soft-bodied, and most of the significant Cambrian deuterostome fossils come from the Chengjiang fauna, a lagerstätte in China. The Chengjiang fossils *Haikouichthys* and *Myllokunmingia* appear to be true vertebrates, and *Haikouichthys* had distinct vertebrae, which may have been slightly mineralized. Vertebrates with jaws, such as the Acanthodians, first appeared in the Late Ordovician.

Colonization of land

Adaptation to life on land is a major challenge: all land organisms need to avoid drying-out and all those above microscopic size have to resist gravity; respiration and gas exchange systems have to change; reproductive systems cannot depend on water to carry eggs and sperm towards each other. Although the earliest good evidence of land plants and animals dates back to the Ordovician period (488 to 444 million years ago), modern land ecosystems only appeared in the late Devonian, about 385 to 359 million years ago.

Evolution of soil

Before the colonization of land, soil, a combination of mineral particles and decomposed organic matter, did not exist. Land surfaces would have been either bare rock or unstable sand produced by weathering. Water and any nutrients in it would have drained away very quickly.

Lichens growing on concrete

Films of cyanobacteria, which are not plants but use the same photosynthesis mechanisms, have been found in modern deserts, and only in areas that are unsuitable for vascular plants. This suggests that microbial mats may have been the first organisms to colonize dry land, possibly in the Precambrian. Mat-forming cyanobacteria could have gradually evolved resistance to desiccation as they spread from the seas to tidal zones and then to land. Lichens, which are symbiotic combinations of a fungus (almost always an ascomycete) and one or more photosynthesizers (green algae or cyanobacteria), are also important colonizers of lifeless environments, and their ability to break down rocks contributes to soil formation in situations where plants cannot survive. The earliest known ascomycete fossils date from 423 to 419 million years ago in the Silurian.

Soil formation would have been very slow until the appearance of burrowing animals, which mix the mineral and organic components of soil and whose feces are a major source of the organic components. Burrows have been found in Ordovician sediments, and are attributed to annelids ("worms") or arthropods.

Plants and the Late Devonian wood crisis

Reconstruction of *Cooksonia*, a vascular plant from the Silurian

Fossilized trees from the Mid-Devonian Gilboa fossil forest

In aquatic algae, almost all cells are capable of photosynthesies and are nearly independent. Life on land required plants to become internally more complex and specialized: photosynthesis was most efficient at the top; roots were required in order to extract water from the ground; the parts in between became supports and transport systems for water and nutrients.

Spores of land plants, possibly rather like liverworts, have been found in Mid Ordovician rocks dated to about 476 million years ago. In Mid Silurian rocks 430 million years ago there are fossils of actual plants including clubmosses such as *Baragwanathia*; most were under 10 centimetres (3.9 in) high, and some appear closely related to vascular plants, the group that includes trees.

By the Late Devonian 370 million years ago, trees such as *Archaeopteris* were so abundant that they changed river systems from mostly braided to mostly meandering, because their roots bound the soil firmly. In fact they caused a "Late Devonian wood crisis", because:

- They removed more carbon dioxide from the atmosphere, reducing the greenhouse effect and thus causing an ice age in the Carboniferous period. In later ecosystems the carbon dioxide "locked up" in wood is returned to the atmosphere by decomposition of dead wood. However the earliest fossil evidence of fungi that can decompose wood also comes from the Late Devonian.
- The increasing depth of plants' roots led to more washing of nutrients into rivers and seas by rain. This caused algal blooms whose high consumption of oxygen caused anoxic events in deeper waters, increasing the extinction rate among deep-water animals.

Land invertebrates

Animals had to change their feeding and excretory systems, and most land animals developed internal fertilization of their eggs. The difference in refractive index between water and air required changes in their eyes. On the other hand in some ways movement and breathing became easier, and the better transmission of high-frequency sounds in air encouraged the development of hearing.

Some trace fossils from the Cambrian-Ordovician boundary about 490 million years ago are interpreted as the tracks of large amphibious arthropods on coastal sand dunes, and may have been made by euthycarcinoids, which are thought to be evolutionary "aunts" of myriapods. Other trace fossils from the Late Ordovician a little over 445 million years ago probably represent land invertebrates, and there is clear evidence of numerous arthropods on coasts and alluvial plains shortly before the Silurian-Devonian boundary, about 415 million years ago, including signs that some arthropods ate plants. Arthropods were well pre-adapted to colonise land, because their existing jointed exoskeletons provided protection against desiccation, support against gravity and a means of locomotion that was not dependent on water.

The fossil record of other major invertebrate groups on land is poor: none at all for non-parasitic flatworms, nematodes or nemerteans; some parasitic nematodes have been fossilized in amber; annelid worm fossils are known from the Carboniferous, but they may still have been aquatic animals; the earliest fossils of gastropods on land date from the Late Carboniferous, and this group may have had to wait until leaf litter became abundant enough to provide the moist conditions they need.

The earliest confirmed fossils of flying insects date from the Late Carboniferous, but it is thought that insects developed the ability to fly in the Early Carboniferous or even Late Devonian. This gave them a wider range of ecological niches for feeding and breeding, and a means of escape from predators and from unfavorable changes in the environment. About 99% of modern insect species fly or are descendants of flying species.

Land vertebrates

Acanthostega changed views about the early evolution of tetrapods

Tetrapods, vertebrates with four limbs, evolved from other rhipidistians over a relatively short timespan during the Late Devonian, between 370 million years ago and 360 million years ago. From the 1950s to the early 1980s it was thought that tetrapods evolved from fish that had already acquired the ability to crawl on land, possibly in order to go from a pool that was drying out to one that was deeper. However in 1987 nearly-complete fossils of *Acanthostega* from about 363 million years ago showed that this Late Devonian transitional animal had legs and both lungs and gills, but could never have survived on land: its limbs and its wrist and ankle joints were too weak to bear its weight; its ribs were too short to prevent its lungs from being squeezed flat by its weight; its fish-like tail fin would have been damaged by dragging on the ground. The current hypothesis is that *Acanthostega*, which was about 1 metre (3.3 ft) long, was a wholly aquatic predator that hunted in shallow water. Its skeleton differed from that of most fish, in ways that enabled it to raise its head to breathe air while its body remained submerged, including: its jaws show modifications that would have enabled it to gulp air; the bones at the back of its skull are locked together, providing strong attachment points for muscles that raised its head; the head is not joined to the shoulder girdle and it has a distinct neck.

The Devonian proliferation of land plants may help to explain why air-breathing would have been an advantage: leaves falling into streams and rivers would have encouraged the growth of aquatic vegetation; this would have attracted grazing invertebrates and small fish that preyed on them; they would have been attractive prey but the environment was unsuitable for the big marine predatory fish; air-breathing would have been necessary because these waters would have been short of oxygen, since warm water holds less dissolved oxygen than cooler marine water and since the decomposition of vegetation would have used some of the oxygen.

Later discoveries revealed earlier transitional forms between *Acanthostega* and completely fish-like animals. Unfortunately there is then a gap of about 30 million years between the fossils of ancestral tetrapods and Mid Carboniferous fossils of vertebrates that look well-adapted for life on land. Some of these look like early relatives of modern amphibians, most of which need to keep their skins moist and to lay their eggs in water, while others are accepted as early relatives of the amniotes, whose water-proof skins and eggs enable them to live and breed far from water.

Dinosaurs, birds and mammals

Amniotes, whose eggs can survive in dry environments, probably evolved in the Late Carboniferous period, between 330 million years ago and 314 million years ago. The earliest fossils of the two surviving amniote groups, synapsids and sauropsids, date from around 313 million years ago. The synapsid pelycosaurs and their descendants the therapsids are the most common land vertebrates in the best-known Permian fossil beds, between 229 million years ago and 251 million years ago. However at the time these were all in temperate zones at middle latitudes, and there is evidence that hotter, drier environments nearer the Equator were dominated by sauropsids and amphibians.

The Permian-Triassic extinction wiped out almost all land vertebrates, as well as the great majority of other life. During the slow recovery from this catastrophe, estimated to be 30M years, a previously obscure sauropsid group became the most abundant and diverse terrestrial vertebrates: a few fossils of archosauriformes ("shaped like archosaurs") have been found in Late Permian rocks, but by the Mid Triassic archosaurs were the dominant land vertebrates. Dinosaurs distinguished themselves from other archosaurs in the Late Triassic, and became the dominant land vertebrates of the Jurassic and Cretaceous periods, between 199 million years ago and 65 million years ago.

During the Late Jurassic, birds evolved from small, predatory theropod dinosaurs. The first birds inherited teeth and long, bony tails from their dinosaur ancestors, but some developed horny, toothless beaks by the very Late Jurassic and short pygostyle tails by the Early Cretaceous.

While the archosaurs and dinosaurs were becoming more dominant in the Triassic, the mammaliform successors of the therapsids could only survive as small, mainly nocturnal insectivores. This apparent set-back may actually have promoted the evolution of mammals, for example nocturnal life may have accelerated the development of endothermy ("warm-bloodedness") and hair or fur. By 195 million years ago in the Early Jurassic there were animals that were very nearly mammals. Unfortunately there is a gap in the fossil record throughout the Mid Jurassic. However fossil teeth discovered in Madagascar indicate that true mammals existed at least 167 million years ago. After dominating land vertebrate niches for about 150 million years, the dinosaurs perished 65 million years ago in the Cretaceous–Tertiary extinction along with many other groups of organisms. Mammals throughout the time of the dinosaurs had been restricted to a narrow range of taxa, sizes and shapes, but increased rapidly in size and diversity after the extinction, with bats taking to the air within 13 million years, and cetaceans to the sea within 15 million years.

Flowering plants

The 250,000 to 400,000 species of flowering plants outnumber all other ground plants combined, and are the dominant vegetation in most terrestrial ecosystems. There is fossil evidence that flowering plants diversified rapidly in the Early Cretaceous, between 130 million years ago and 90 million years ago, and that their rise was associated with that of pollinating insects. Among modern flowering plants Magnolias are thought to be close to the common ancestor of the group. However paleontologists have not succeeded in identifying the earliest stages in the evolution of flowering plants.

Social insects

The social insects are remarkable because the great majority of individuals in each colony are sterile. This appears contrary to basic concepts of evolution such as natural selection and the selfish gene. In fact there are very few eusocial insect species: only 15 out of approximately 2,600 living families of insects contain eusocial species, and it seems that eusociality has evolved independently only 12 times among arthropods, although some eusocial lineages have diversified into several families. Nevertheless social insects have been spectacularly successful; for example although ants and termites account for only about 2% of known insect species, they form over 50% of the total mass of insects. Their ability to control a territory appears to be the foundation of their success.

These termite mounds have survived a bush fire

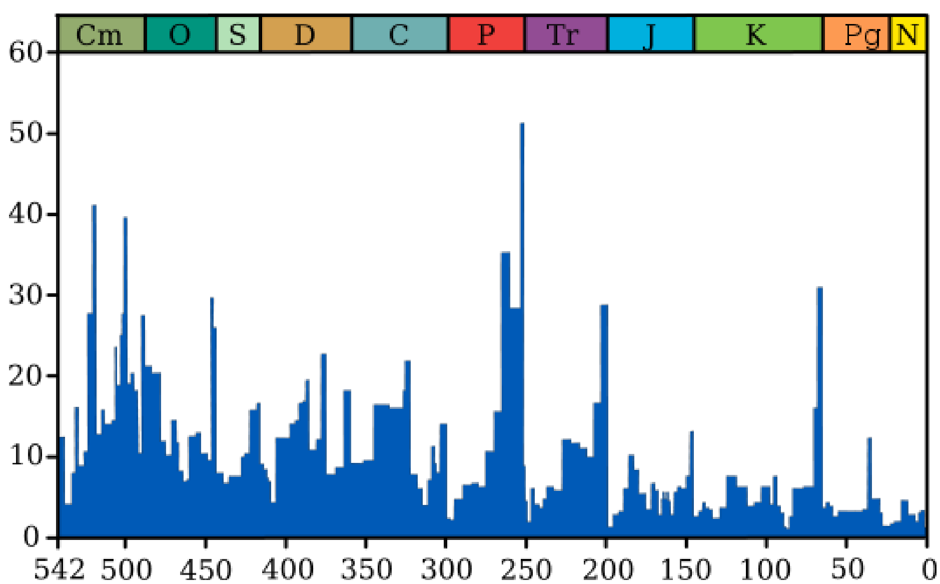
The sacrifice of breeding opportunities by most individuals has long been explained as a consequence of these species' unusual haplodiploid method of sex determination, which has the paradoxical consequence that two sterile worker daughters of the same queen share more genes with each other than they would with their offspring if they could breed. However Wilson and Hölldobler argue that this explanation is faulty: for example, it is based on kin selection, but there is no evidence of nepotism in colonies that have multiple queens. Instead, they write, eusociality evolves only in species that are under strong pressure from predators and competitors, but in environments where it is possible to build "fortresses"; after colonies have established this security, they gain other advantages though co-operative foraging. In support of this explanation they cite the appearance of eusociality in bathyergid mole rats, which are not haplodiploid.

The earliest fossils of insects have been found in Early Devonian rocks from about 400 million years ago, which preserve only a few varieties of flightless insect. The Mazon Creek lagerstätten from the Late Carboniferous, about 300 million years ago, include about 200 species, some gigantic by modern standards, and indicate that insects had occupied their main modern ecological niches as herbivores, detritivores and insectivores. Social termites and ants first appear in the Early Cretaceous, and advanced social bees have been found in Late Cretaceous rocks but did not become abundant until the Mid Cenozoic.

Humans

Modern humans evolved from a lineage of upright-walking apes that has been traced back over 6 million years ago to *Sahelanthropus*. The first known stone tools were made about 2.5 million years ago, apparently by *Australopithecus garhi*, and were found near animal bones that bear scratches made by these tools. The earliest hominines had chimp-sized brains, but there has been a fourfold increase in the last 3 million years; a statistical analysis suggests that hominine brain sizes depend almost completely on the date of the fossils, while the species to which they are assigned has only slight influence. There is a long-running debate about whether modern humans evolved all over the world simultaneously from existing advanced hominines or are descendants of a single small population in Africa, which then migrated all over the world less than 200,000 years ago and replaced previous hominine species. There is also debate about whether anatomically-modern humans had an intellectual, cultural and technological "Great Leap Forward" under 100,000 years ago and, if so, whether this was due to neurological changes that are not visible in fossils.

Mass extinctions



Apparent extinction intensity, i.e. the fraction of genera going extinct at any given time, as reconstructed from the fossil record. (Graph not meant to include recent epoch of Holocene extinction event)

Life on earth has suffered occasional mass extinctions at least since 542 million years ago. Although they are disasters at the time, mass extinctions have sometimes accelerated the evolution of life on earth. When dominance of particular ecological niches passes from one group of organisms to another, it is rarely because the new dominant group is "superior" to the old and usually because an extinction event eliminates the old dominant group and makes way for the new one.

The fossil record appears to show that the gaps between mass extinctions are becoming longer and the average and background rates of extinction are decreasing. Both of these phenomena could be explained in one or more ways:

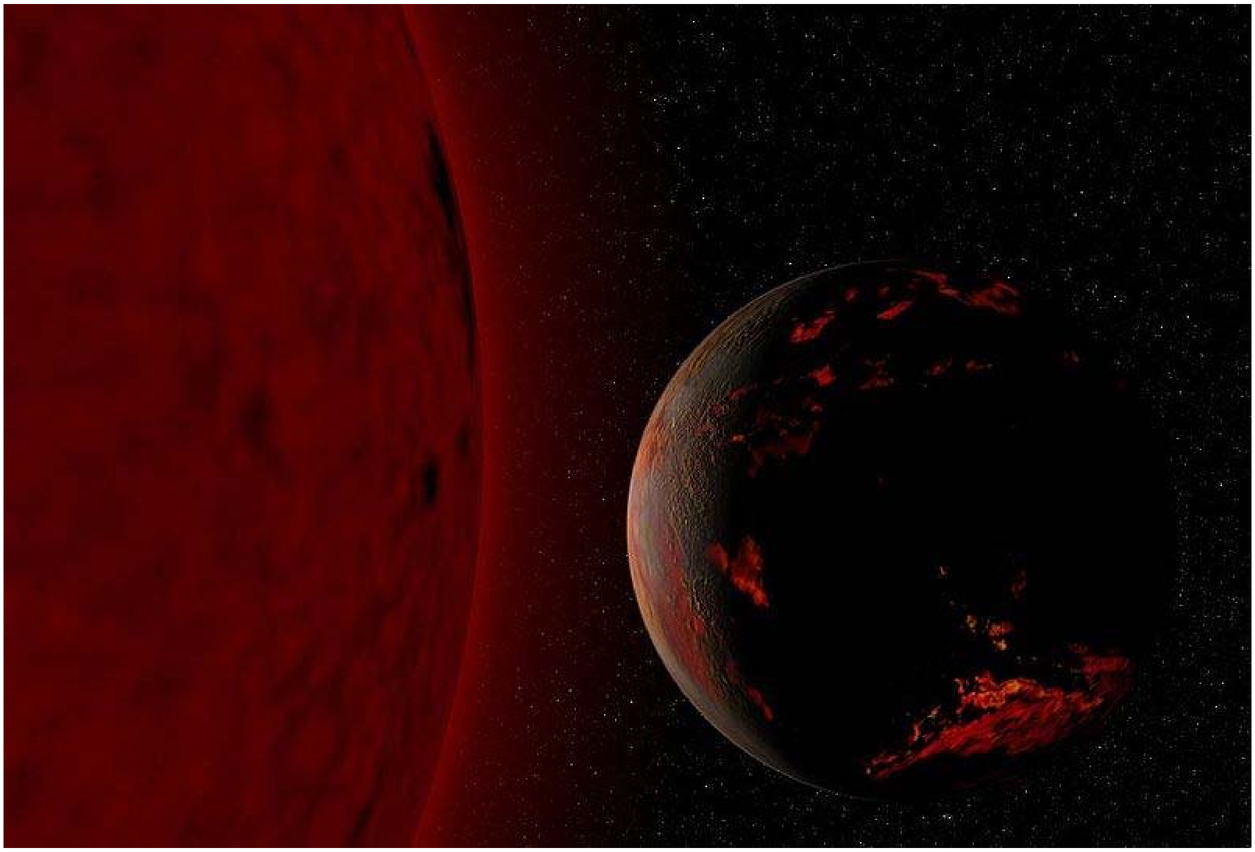
- The oceans may have become more hospitable to life over the last 500 million years and less vulnerable to mass extinctions: dissolved oxygen became more widespread and penetrated to greater depths; the development of life on land reduced the run-off of nutrients and hence the risk of eutrophication and anoxic events; and marine ecosystems became more diversified so that food chains were less likely to be disrupted.
- Reasonably complete fossils are very rare, most extinct organisms are represented only by partial fossils, and complete fossils are rarest in the oldest rocks. So paleontologists have mistakenly assigned parts of the same organism to different genera which were often defined solely to accommodate these finds – the story of *Anomalocaris* is an example of this. The risk of this mistake is higher for older fossils because these are often unlike parts of any living organism. Many of the "superfluous" genera are represented by fragments which are not found again and the "superfluous" genera appear to become extinct very quickly.

The present

Oxygenic photosynthesis accounts for virtually all of the production of organic matter from non-organic ingredients. Production is split about evenly between land and marine plants, and phytoplankton are the dominant marine producers.

The processes that drive evolution are still operating. Well-known examples include the changes in coloration of the peppered moth over the last 200 years and the more recent appearance of pathogens that are resistant to antibiotics. There is even evidence that humans are still evolving, and possibly at an accelerating rate over the last 40,000 years.

Future of the Earth



Conjectured illustration of the scorched Earth after the Sun has entered the red giant phase, seven billion years from now

The **future of the Earth** will be determined by a variety of factors, including increases in the luminosity of the Sun, loss of heat energy from the Earth's core, perturbations by the other bodies in the Solar System and the biochemistry at the Earth's surface. Milankovitch theory predicts the planet will continue to undergo glaciation cycles because of eccentricity, axial tilt, and precession of the Earth's orbit. As part of the ongoing supercontinent cycle, plate tectonics will probably result in a supercontinent in 250 million–350 million years. Some time in the next 1.5 billion–4.5 billion years, the axial tilt of the Earth may begin to undergo chaotic variations, with changes in the axial tilt of up to 90°.

One billion to two billion years in the future, the steady increase in solar radiation caused by the helium build-up at the core of the Sun will result in the loss of the oceans and the cessation of continental drift. Four billion years from now, the increase in the Earth's surface temperature will cause a runaway greenhouse effect. By that point, most if not all the life on the surface will be extinct. The most likely ultimate 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 to cross the planet's orbit.

Human influence

Humans now play a key role in the biosphere, with the large human population dominating many of Earth's ecosystems. This has resulted in a widespread, ongoing extinction of other species during the present geological epoch, now known as the Holocene extinction. The large scale loss of species caused by human influence since the 1950s has been called a biotic crisis, with an estimated 10% of the total species lost as of 2007. At current rates, about 30% of species are at risk of extinction in the next hundred years. The Holocene extinction event is the result of habitat destruction, the widespread distribution of invasive species, and hunting and climate change. In the present day, human activity has had a significant impact on the surface of the planet. More than a third of the land surface has been modified by human actions, and humans use about 20% of global primary production. The concentration of carbon dioxide in the atmosphere has increased by close to 30% since the start of the Industrial Revolution.

The consequences of a persistent biotic crisis have been predicted to last for at least five million years. It could result in a decline in biodiversity and homogenization of biotas, accompanied by a proliferation of species that are opportunistic, such as pests and weeds. Novel species may also emerge; in particular taxa that prosper in human-dominated ecosystems may rapidly diversify into many new species. Microbes are likely to benefit from the increase in nutrient-enriched environmental niches. However, no new species of existing large vertebrates are likely to arise and food chains will probably be shorter.

Orbit and rotation

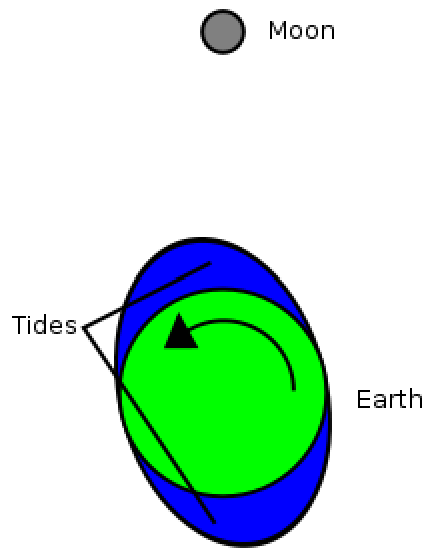
The gravitational perturbations of the other planets in the Solar System combine to modify the orbit of the Earth and the orientation of its spin axis. These changes can influence the planetary climate.

Glaciation

Historically, there have been cyclical periods of glaciation in which ice sheets covered the higher latitudes of the continents. The Milankovitch theory predicts that glaciation occurs because of astronomical factors in combination with climate feedback mechanisms and plate tectonics. The primary astronomical drivers are a higher than normal orbital eccentricity, a low axial tilt (or obliquity), and the alignment of summer solstice with the aphelion. Each of these effects occur cyclically. For example, the eccentricity changes over time cycles of about 100,000 and 400,000 years, with the value ranging from less than 0.01 up to 0.05. This is equivalent to a change of the semiminor axis of the planet's orbit from 99.95% of the semimajor axis to 99.88%, respectively.

At present the Earth is in an interglacial period, which would normally be expected to end in about 25,000 years. The current rate of increased carbon dioxide release into the atmosphere by humans may delay the onset of the next period of glaciation until at least 50,000–130,000 years from now. However, a global warming period of finite duration (based on the assumption that fossil fuel use will cease by the year 2200) will probably only impact the glaciation cycle for about 5,000 years. Thus, a brief period of global warming induced through a few centuries worth of greenhouse gas emission would only have a limited impact in the long term.

Obliquity



The rotational offset of the tidal bulge exerts a net torque on the Moon, boosting it while slowing the Earth's rotation.

The tidal acceleration of the Moon slows the rotation rate of the Earth and increases the Earth-Moon distance. Other effects that can dissipate the Earth's rotational energy are friction between the core and mantle, tides in the atmosphere, convection in the mantle, and climate changes that can increase or decrease the ice load at the poles. These combined effects are expected to increase the length of the day by more than 1.5 hours over the next 250 million years, and to increase the obliquity by about a half degree. The distance to the Moon will increase by about 1.5 Earth radii during the same period.

Based on computer models, the presence of the Moon appears to stabilize the obliquity of the Earth, which may help the planet to avoid dramatic climate changes. This stability is achieved because the Moon increases the precession rate of the Earth's spin axis, thereby avoiding resonances between the precession of the spin and precession frequencies of the ascending node of the planet's orbit. (That is, the precession motion of the ecliptic.) However, as the semimajor axis of the Moon's orbit continues to increase in the future, this stabilizing effect will diminish. At some point perturbation effects will probably cause chaotic variations in the obliquity of the Earth, and the axial tilt may change by angles as high as 90° from the plane of the orbit. This is expected to occur within about 1.5–4.5 billion years, although the exact time is unknown.

A high obliquity would probably result in dramatic changes in the climate and may destroy the planet's habitability. When the axial tilt of the Earth reaches 54°, the equator will receive less radiation from the Sun than the poles. The planet could remain at an obiliquity of 60° to 90° for periods as long as 10 million years.

Plate tectonics

Pangaea was the last supercontinent to form before the present

The theory of plate tectonics demonstrates that the continents of the Earth are moving across the surface at the rate of a few centimeters per year. This is expected to continue, causing the plates to relocate and collide. Continental drift is facilitated by two factors: the energy generation within the planet and the presence of a hydrosphere. With the loss of either of these, continental drift will come to a halt. The production of heat through radiogenic processes is sufficient to maintain mantle convection and plate subduction for at least the next 1.1 billion years.

At present, the continents of North and South America are moving westward from Africa and Europe. Researchers have produced several scenarios about how this will continue in the future. These geodynamic models can be distinguished by the subduction flux, whereby the oceanic crust moves under a continent. In the introversion model, the younger, interior, Atlantic ocean becomes preferentially subducted and the current migration of North and South America is reversed. In the extroversion model, the older, exterior, Pacific ocean remains preferentially subducted and North and South America migrate toward eastern Asia.

As the understanding of geodynamics improves, these models will be subject to revision. In 2008, for example, a computer simulation was used to predict that a reorganization of the mantle convection will occur, causing a supercontinent to form around Antarctica.

Regardless of the outcome of the continental migration, the continued subduction process causes water to be transported to the mantle. After a billion years from the present, a geophysical model gives an estimate that 27% of the current ocean mass will have been subducted. If this process were to continue unmodified into the future, the subduction and release would reach a point of stability after 65% of the current ocean mass has been subducted.

Introversion

Christopher Scotese and his colleagues have mapped out the predicted motions several hundred million years into the future as part of the Paleomap Project. In their scenario, 50 million years from now the Mediterranean sea may vanish and the collision between Europe and Africa will create a long mountain range extending to the current location of the Persian Gulf. Australia will merge with Indonesia, and Baja California will slide northward along the coast. New subduction zones may appear off the eastern coast of North and South America, and mountain chains will form along those coastlines. To the south, the migration of Antarctica to the north will cause all of its ice sheets to melt. This, along with the melting of the Greenland ice sheets, will raise the average ocean level by 90 metres (300 ft). The inland flooding of the continents will result in climate changes.

As this scenario continues, by 100 million years from the present the continental spreading will have reached its maximum extent and the continents will then begin to coalesce. In 250 million years, North America will collide with Africa while South America will wrap around the southern tip of Africa. The result will be the formation of a new supercontinent (sometimes called Pangaea Ultima), with the Pacific Ocean stretching across half the planet. The continent of Antarctica will reverse direction and return to the South Pole, building up a new ice cap.

Extroversion

The first scientist to extrapolate the current motions of the continents was Canadian geologist Paul F. Hoffman of Harvard University. In 1992, Hoffman predicted that continents of North and South America would continue to advance across the Pacific Ocean, pivoting about Siberia until they begin to merge with Asia. He dubbed the resulting supercontinent, Amasia. Later, in the 1990s, Roy Livermore calculated a similar scenario. He predicted that Antarctica would start to migrate northward, and east Africa and Madagascar would move across the Indian Ocean to collide with Asia.

In an extroversion model, the closure of the Pacific Ocean would be complete by about 350 million years. This marks the completion of the current supercontinent cycle, wherein the continents split apart and then rejoin each other about every 400–500 million years. Once the supercontinent is built, plate tectonics may enter a period of inactivity as the rate of subduction drops by an order of magnitude. This period of stability could cause an increase in the mantle temperature at the rate of 30–100 K every 100 million years, which is the minimum lifetime of past supercontinents. As a consequence, volcanic activity may increase.

Supercontinent

The formation of a supercontinent can dramatically affect the environment. The collision of plates will result in mountain building, thereby shifting weather patterns. Sea levels may fall because of increased glaciation. The rate of surface weathering can rise, resulting in an increase in the rate that organic material is buried. Supercontinents can cause a drop in global temperatures and an increase in atmospheric oxygen. These changes can result in more rapid biological evolution as new niches emerge. This, in turn, can affect the climate, further lowering temperatures.

The formation of a supercontinent insulates the mantle. The flow of heat will be concentrated, resulting in volcanism and the flooding of large areas with basalt. Rifts will form and the supercontinent will split up once more.

Solar evolution

The energy generation of the Sun is based upon thermonuclear fusion of hydrogen into helium. This occurs in the core region of the star using the proton–proton chain reaction process. Because there is no convection in the solar core, the fusion process results in a steady build-up of helium. The temperature at the core of the Sun is too low for nuclear fusion of helium atoms through the triple-alpha process, so these atoms do not contribute to the net energy generation that is needed to maintain hydrostatic equilibrium of the Sun.

At present, nearly half the hydrogen at the core has been consumed, with the remainder consisting primarily of helium. To compensate for the steadily decreasing number of hydrogen atoms per unit mass, the core temperature of the Sun has gradually increased through a rise in pressure. This has caused the remaining hydrogen to undergo fusion at a more rapid rate, thereby generating the energy needed to maintain the equilibrium. The result has been a steady increase in the energy output of the Sun. This increase can be approximated by the formula:

$$L(t) = \left[1 + \frac{2}{5}\left(1 - \frac{t}{t_{Sun}}\right)\right]^{-1} L_{Sun}$$

where t is a time period less than or equal to the present time t_{Sun}, $L(t)$ is the luminosity at time t, and L_{Sun} is the current solar luminosity.

When the Sun first became a main sequence star, it radiated only 70% of the current luminosity. The luminosity has increased in a nearly linear fashion to the present, increasing by 1% every 110 million years. Likewise, in three billion years the Sun is expected to be 33% more luminous. The hydrogen fuel at the core will finally be exhausted in 4.8 billion years, when the Sun will be 67% more luminous than at present. Thereafter the Sun will continue to burn hydrogen in a shell surrounding its core, until the increase in luminosity reaches 121% of the present value. This marks the end of the Sun's main sequence lifetime, and thereafter it will evolve into a red giant.

Climate impact

As the global temperature of the Earth climbs because of the rising luminosity of the Sun, the rate of weathering of silicate minerals will increase. This in turn will decrease the level of carbon dioxide in the atmosphere. Within the next 600 million years from the present, the concentration of CO_2 will fall below the critical threshold needed to sustain C_3 photosynthesis: about 50 parts per million. At this point, trees and forests in their current forms will no longer be able to survive. However, C_4 carbon fixation can continue at much lower concentrations, down to above 10 parts per million. Thus plants using C_4 photosynthesis may be able to survive for at least 0.8 billion years and possibly as long as 1.2 billion years from now, after which rising temperatures will make the biosphere unsustainable. Currently, C_4 plants represent about 5% of Earth's plant biomass and 1% of its known plant species. For example, about 50% of all grass species (Poaceae) use the C_4 photosynthetic pathway, as do many species in the herbaceous family Amaranthaceae.

When the levels of carbon dioxide fall to the limit where photosynthesis is barely sustainable, the proportion of carbon dioxide in the atmosphere is expected to oscillate up and down. This will allow land vegetation to reappear each time the level of carbon dioxide rises due to tectonic activity and animal life. However, the long term trend is for the plant life on land to die off altogether as most of the remaining carbon in the atmosphere becomes sequestered in the Earth. Some microbes are capable of photosynthesis at concentrations of CO_2 of a few parts per million, so these life forms would probably disappear only because of rising temperatures and the loss of the biosphere.

In their work *The Life and Death of Planet Earth*, authors Peter D. Ward and Donald Brownlee have argued that some form of animal life may continue even after most of the Earth's plant life has disappeared. Initially, they expect that some insects, lizards, birds and small mammals may persist, along with sea life. Without oxygen replenishment by plant life, however, they believe that the animals would probably die off from asphyxiation within a few million years. Even if sufficient oxygen were to remain in the atmosphere through the persistence of some form of photosynthesis, the steady rise in global temperature would result in a gradual loss of biodiversity. Much of the surface would become a barren desert and life would primarily be found in the oceans.

Once the solar luminosity is 10% higher than its current value, the average global surface temperature reaches 320 K (47 °C). The atmosphere will become a humid greenhouse leading to a runaway evaporation of the oceans. At this point, models of the Earth's future environment demonstrate that the stratosphere would contain increasing levels of water. These water molecules will be broken down through photodissociation by solar ultraviolet radiation, allowing hydrogen to escape the atmosphere. The net result would be a loss of the world's sea water in about 1.1 billion years from the present.

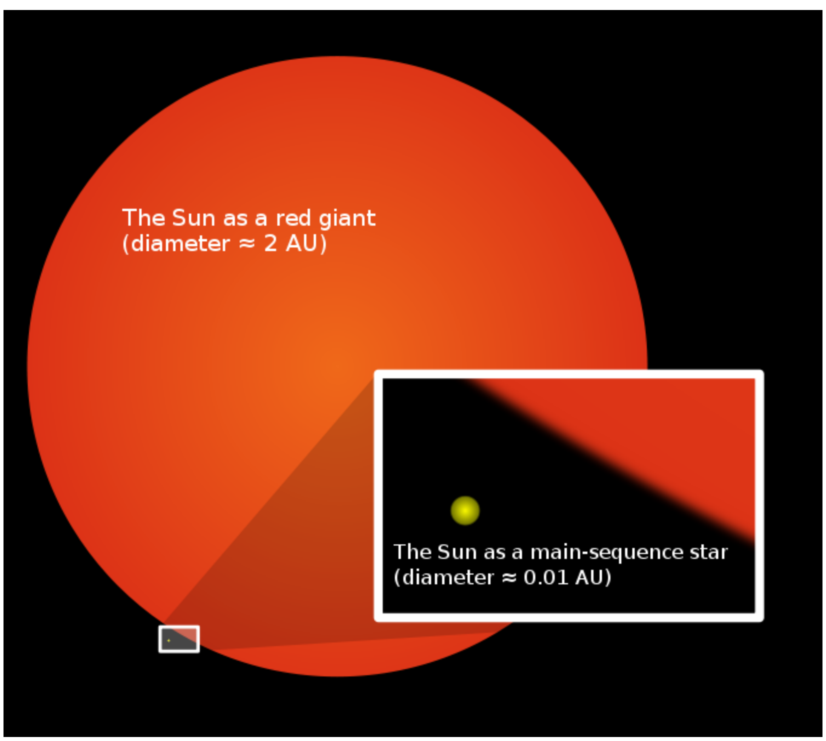
The atmosphere of Venus is in a "supergreenhouse" state

Still, there will continue to be some reservoirs at the surface as water is steadily released from the deep crust and mantle. Some water may be retained at the poles and there may be occasional rainstorms, but for the most part the planet would be a dry desert. What happens next depends on the level of tectonic activity. The release of carbon dioxide by volcanic eruption may eventually cause the atmosphere to enter a "supergreenhouse" state like that of the planet Venus. However, without surface water, plate tectonics would probably come to a halt and most of the carbonates would remain securely buried.

The loss of the oceans could be delayed until two billion years in the future if the total atmospheric pressure were to decline. A lower atmospheric pressure would reduce the greenhouse effect, thereby lowering the surface temperature. This could occur if natural processes were to remove the nitrogen from the atmosphere. Studies of organic sediments has shown that at least 100 kilopascals (1 bar) of nitrogen has been removed from the atmosphere over the past four billion years; enough to effectively double the current atmospheric pressure if it were to be released. This rate of removal would be sufficient to counter the effects of increasing solar luminosity for the next two billion years. However, beyond that point, the amount of water in the lower atmosphere will have risen to 40% and the runaway moist greenhouse will commence.

A runaway greenhouse effect will take place when the luminosity from the Sun reaches 40% more than its current value, four billion years from now. The atmosphere will heat up and the surface temperature will rise. However, most of the atmosphere will be retained until the Sun has entered the red giant stage.

Red giant stage



The size of the current Sun (now in the main sequence) compared to its estimated size during its red giant phase.

Once the Sun changes from burning hydrogen at the core to burning hydrogen around a shell, the core will start to contract and the outer envelope will expand. The total luminosity will steadily increase over the next billion years until it reaches 2,730 times the Sun's current luminosity at the age of 12.167 billion years. During this phase the Sun will undergo mass loss, with about 33% of its total mass shed with the solar wind. The loss of mass will mean that the orbits of the planets will expand. The orbital distance of the Earth will increase to at most 150% of its current value.

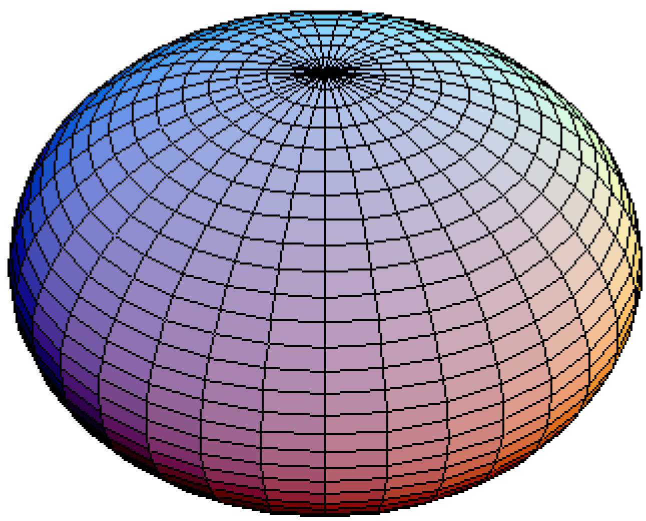
The most rapid part of the Sun's expansion into a red giant occurs during the final stages, when the Sun is about 12 billion years old. It is likely to expand to swallow both Mercury and Venus, reaching a maximum radius of 1.2 astronomical units (180 Gm). The Earth will interact tidally with the Sun's outer atmosphere, which would serve to decrease the orbital radius. Drag from the chromosphere of the Sun would also reduce the Earth's orbit. These effects will act to counterbalance the mass loss by the Sun, and the Earth will most likely be engulfed by the sun.

By the time the Sun begins to grow as a red giant, the orbit of the Moon will have expanded until it takes 47 days to complete. The drag from the solar atmosphere may cause the orbit of the Moon to decay. Once the orbit of the Moon closes to a distance of 18,470 km, it will cross the Earth's Roche limit. The tidal interaction with the Earth will break apart the Moon, turning it into a ring system. Most of the orbiting ring will then begin to decay, and the debris will impact the Earth. Hence, even if the Earth is not swallowed up by the Sun, the planet may be left moonless.

Chapter- 2

Composition and Structure of Earth

Figure of the Earth



An oblate spheroid

The expression **figure of the Earth** has various meanings in geodesy according to the way it is used and the precision with which the Earth's size and shape is to be defined. The actual topographic surface is most apparent with its variety of land forms and water areas. This is, in fact, the surface on which actual Earth measurements are made. It is not suitable, however, for exact mathematical computations, because the formulas which would be required to take the irregularities into account would necessitate a prohibitive amount of computations. The topographic surface is generally the concern of topographers and hydrographers.

The Pythagorean concept of a spherical Earth offers a simple surface which is mathematically easy to deal with. Many astronomical and navigational computations use it as a surface representing the Earth. While the sphere is a close approximation of the true figure of the Earth and satisfactory for many purposes, to the geodesists interested in the measurement of long distances—spanning continents and oceans—a more exact figure is necessary. Closer approximations range from modelling the shape of the entire Earth as an oblate spheroid or an oblate ellipsoid, to the use of spherical harmonics or local approximations in terms of local reference ellipsoids. The idea of a planar or flat surface for Earth, however, is still acceptable for surveys of small areas, as local topography is more important than the curvature. Plane-table surveys are made for relatively small areas, and no account is taken of the curvature of the Earth. A survey of a city would likely be computed as though the Earth were a plane surface the size of the city. For such small areas, exact positions can be determined relative to each other without considering the size and shape of the total Earth.

The curvature of Earth as seen in Valencia, Spain (Playa de la Malvarrosa)

In the mid- to late- 20th century, research across the geosciences contributed to drastic improvements in the accuracy of the Figure of the Earth. The primary utility (and the motivation for funding, mainly from the military) of this improved accuracy was to provide geographical and gravitational data for the inertial guidance systems of ballistic missiles. This funding also drove the expansion of geoscientific disciplines, fostering the creation and growth of various geoscience departments at many universities.

Ellipsoid of revolution

Since the Earth is flattened at the poles and bulging at the equator, the geometrical figure used in geodesy to most nearly approximate Earth's shape is an oblate spheroid. An oblate spheroid, or oblate ellipsoid, is an ellipsoid of revolution obtained by rotating an ellipse about its shorter axis. A spheroid describing the figure of the Earth or other celestial body is called a reference ellipsoid.

An ellipsoid of revolution is uniquely defined by two numbers-- two dimensions, or one dimension and a number representing the difference between the two dimensions. Geodesists, by convention, use the semimajor axis and flattening. The size is represented by the radius at the equator—the semimajor axis of the cross-sectional ellipse—and designated by the letter a. The shape of the ellipsoid is given by the flattening, f, which indicates how much the ellipsoid departs from spherical. (In practice, the two defining numbers are usually the equatorial radius and the reciprocal of the flattening, rather than the flattening itself; for the WGS84 spheroid used by today's GPS systems, the reciprocal of the flattening is set at 298.257223563 exactly.)

The difference between a sphere and a reference ellipsoid for Earth is small, only about one part in 300. Historically flattening was computed from grade measurements. Nowadays geodetic networks and satellite geodesy are used. In practice, many reference ellipsoids have been developed over the centuries from different surveys. The flattening value varies slightly from one reference ellipsoid to another, reflecting local conditions and whether the reference ellipsoid is intended to model the entire earth or only some portion of it.

A sphere has a single radius of curvature, which is simply the radius of the sphere. More complex surfaces have radii of curvature that vary over the surface. The radius of curvature describes the radius of the sphere that best approximates the surface at that point. Oblate ellipsoids have constant radius of curvature east to west along parallels, if a graticule is drawn on the surface, but varying curvature in any other direction. For an oblate ellipsoid, the polar radius of curvature r_p is larger than the equatorial

$$r_p = \frac{a^2}{b},$$

because the pole is flattened: the flatter the surface, the larger the sphere must be to approximate it. Conversely, the ellipsoid's north-south radius of curvature at the equator r_e is smaller than the polar

$$r_e = \frac{b^2}{a}.$$

Historical Earth ellipsoids

The reference ellipsoid models listed below have had utility in geodetic work and many are still in use. The older ellipsoids are named for the individual who derived them and the year of development is given. In 1887 the English mathematician Col Alexander Ross Clarke CB FRS RE was awarded the Gold Medal of the Royal Society for his work in determining the figure of the Earth. The international ellipsoid was developed by John Fillmore Hayford in 1910 and adopted by the International Union of Geodesy and Geophysics (IUGG) in 1924, which recommended it for international use.

At the 1967 meeting of the IUGG held in Lucerne, Switzerland, the ellipsoid called GRS-67 (Geodetic Reference System 1967) in the listing was recommended for adoption. The new ellipsoid was not recommended to replace the International Ellipsoid (1924), but was advocated for use where a greater degree of accuracy is required. It became a part of the GRS-67 which was approved and adopted at the 1971 meeting of the IUGG held in Moscow. It is used in Australia for the Australian Geodetic Datum and in South America for the South American Datum 1969.

The GRS-80 (Geodetic Reference System 1980) as approved and adopted by the IUGG at its Canberra, Australia meeting of 1979 is based on the equatorial radius (semi-major axis of Earth ellipsoid) a, total mass GM, dynamic form factor J_2 and angular velocity of rotation ω, making the inverse flattening $1 / f$ a derived quantity. The minute difference in $1 / f$ seen between GRS-80 and WGS-84 results from an unintentional truncation in the latter's defining constants: while the WGS-84 was designed to adhere closely to the GRS-80, incidentally the WGS-84 derived flattening turned out to be slightly different than the GRS-80 flattening because the normalized second degree zonal harmonic gravitational coefficient, that was derived from the GRS-80 value for J2, was truncated to 8 significant digits in the normalization process.

An ellipsoidal model describes only the ellipsoid's geometry and a normal gravity field formula to go with it. Commonly an ellipsoidal model is part of a more encompassing geodetic datum. For example, the older ED-50 (European Datum 1950) is based on the Hayford or International Ellipsoid. WGS-84 is peculiar in that the same name is used for both the complete geodetic reference system and its component ellipsoidal model. Nevertheless the two concepts—ellipsoidal model and geodetic reference system—remain distinct.

Note that the same ellipsoid may be known by different names. It is best to mention the defining constants for unambiguous identification.

Reference ellipsoid name	Equatorial radius (m)	Polar radius (m)	Inverse flattening	Where used
Maupertuis (1738)	6,397,300	6,363,806.283	191	France
Plessis (1817)	6,376,523.0	???	308.64	France
Everest (1830)	6,377,299.365	6,356,098.359	300.80172554	India
Everest 1830 Modified (1967)	6,377,304.063	6,356,103.0390	300.8017	West Malaysia & Singapore
Everest 1830 (1967 Definition)	6,377,298.556	6,356,097.550	300.8017	Brunei & East Malaysia
Airy (1830)	6,377,563.396	6,356,256.909	299.3249646	Britain
Bessel (1841)	6,377,397.155	6,356,078.963	299.1528128	Europe, Japan
Clarke (1866)	6,378,206.4	6,356,583.8	294.9786982	North America
Clarke (1878)	6,378,190	6,356,456	293.4659980	North America
Clarke (1880)	6,378,249.145	6,356,514.870	293.465	France, Africa

Helmert (1906)	6,378,200	6,356,818.17	298.3	
Hayford (1910)	6,378,388	6,356,911.946	297	USA
International (1924)	6,378,388	6,356,911.946	297	Europe
NAD 27 (1927)	6,378,206.4	6,356,583.800	294.978698208	North America
Krassovsky (1940)	6,378,245	6,356,863.019	298.3	Russia
WGS66 (1966)	6,378,145	6,356,759.769	298.25	USA/DoD
Australian National (1966)	6,378,160	6,356,774.719	298.25	Australia
New International (1967)	6,378,157.5	6,356,772.2	298.24961539	
GRS-67 (1967)	6,378,160	6,356,774.516	298.247167427	
South American (1969)	6,378,160	6,356,774.719	298.25	South America
WGS-72 (1972)	6,378,135	6,356,750.52	298.26	USA/DoD
GRS-80 (1979)	6,378,137	6,356,752.3141	298.257222101	Global ITRS
NAD 83	6,378,137	6,356,752.3	298.257024899	North America
WGS-84 (1984)	6,378,137	6,356,752.3142	298.257223563	Global GPS
IERS (1989)	6,378,136	6,356,751.302	298.257	
IERS (2003)	6,378,136.6	6,356,751.9	298.25642	

More complicated figures

The possibility that the Earth's equator is an ellipse rather than a circle and therefore that the ellipsoid is triaxial has been a matter of scientific controversy for many years. Modern technological developments have furnished new and rapid methods for data collection and since the launch of *Sputnik 1*, orbital data have been used to investigate the theory of ellipticity.

A second theory, more complicated than triaxiality, proposed that observed long periodic orbital variations of the first Earth satellites indicate an additional depression at the south pole accompanied by a bulge of the same degree at the north pole. It is also contended that the northern middle latitudes were slightly flattened and the southern middle latitudes bulged in a similar amount. This concept suggested a slightly pear-shaped Earth and was the subject of much public discussion. Modern geodesy tends to retain the ellipsoid of revolution and treat triaxiality and pear shape as a part of the geoid figure: they are represented by the spherical harmonic coefficients C_{22},S_{22} and C_{30}, respectively, corresponding to degree and order numbers 2.2 for the triaxiality and 3.0 for the pear shape.

Geoid

It was stated earlier that measurements are made on the apparent or topographic surface of the Earth and it has just been explained that computations are performed on an ellipsoid. One other surface is involved in geodetic measurement: the geoid. In geodetic surveying, the computation of the geodetic coordinates of points is commonly performed on a reference ellipsoid closely approximating the size and shape of the Earth in the area of the survey. The actual measurements made on the surface of the Earth with certain instruments are however referred to the geoid. The ellipsoid is a mathematically defined regular surface with specific dimensions. The geoid, on the other hand, coincides with that surface to which the oceans would conform over the entire Earth if free to adjust to the combined effect of the Earth's mass attraction (gravitation) and the centrifugal force of the Earth's rotation. As a result of the uneven distribution of the Earth's mass, the geoidal surface is irregular and, since the ellipsoid is a regular surface, the separations between the two, referred to as geoid undulations, geoid heights, or geoid separations, will be irregular as well.

The geoid is a surface along which the gravity potential is everywhere equal and to which the direction of gravity is always perpendicular. The latter is particularly important because optical instruments containing gravity-reference leveling devices are commonly used to make geodetic measurements. When properly adjusted, the vertical axis of the instrument coincides with the direction of gravity and is, therefore, perpendicular to the geoid. The angle between the plumb line which is perpendicular to the geoid (sometimes called "the vertical") and the perpendicular to the ellipsoid (sometimes called "the ellipsoidal normal") is defined as the deflection of the vertical. It has two components: an east-west and a north-south component.

Earth rotation and Earth's interior

Determining the exact figure of the Earth is not only a geodetic operation or a task of geometry, but is also related to geophysics. Without any idea of the Earth's interior, we can state a "constant density" of 5.515 g/cm^3 and, according to theoretical arguments, such a body rotating like the Earth would have a flattening of 1:230.

In fact the measured flattening is 1:298.25, which is more similar to a sphere and a strong argument that the Earth's core is *very compact*. Therefore the density must be a function of the depth, reaching from about 2.7 g/cm^3 at the surface (rock density of granite, limestone etc.) up to approximately 15 within the inner core. Modern seismology yields a value of 16 g/cm^3 at the center of the earth.

Global and regional gravity field

Also with implications for the physical exploration of the Earth's interior is the gravitational field, which can be measured very accurately at the surface and remotely by satellites. True vertical generally does not correspond to theoretical vertical (deflection ranges from 2" to 50") because topography and all *geological masses* disturb the gravitational field. Therefore the gross structure of the earth's crust and mantle can be determined by geodetic-geophysical models of the subsurface.

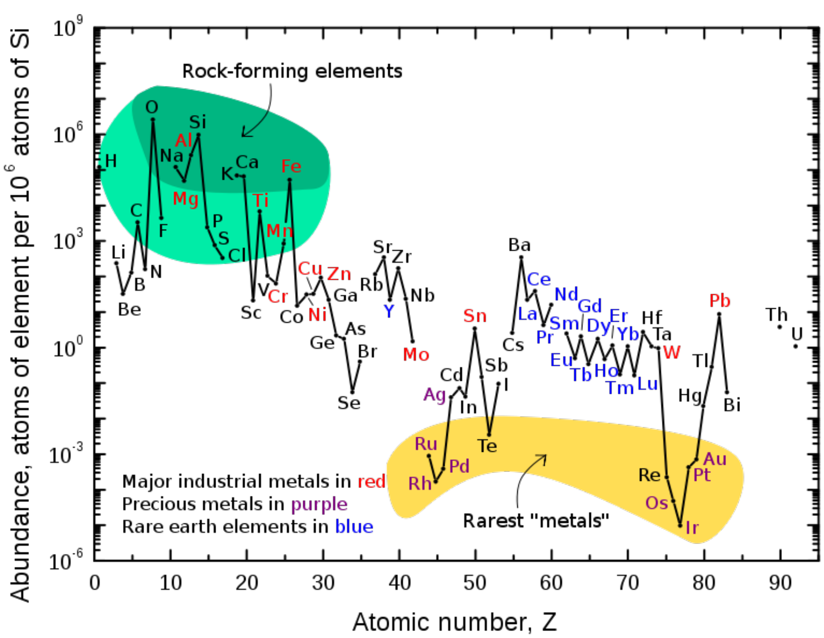
Volume

The volume of an oblate spheroid is $V = \frac{4}{3}\pi a^2 b;$
(where π is the mathematical constant *pi*, and *a* and *b* are the equatorial and polar radii respectively.)

Using the World Geodetic System's reference ellipsoid, where *a* = 6,378.137 km and *b* = 6,356.7523 km, Earth's volume is calculated as 1,083,210,000,000 km^3, or about 1.08321×10^{12} km^3, in scientific notation.

Abundance of elements in the Earth's crust

This graph illustrates the relative abundance of the chemical elements in Earth's upper continental crust.



Abundance (atom fraction) of the chemical elements in Earth's upper continental crust as a function of atomic number.

Many of the elements shown in the graphic are classified into (partially overlapping) categories:

1. rock-forming elements (major elements in green field and minor elements in light green field);
2. rare earth elements (lanthanides, La-Lu, and Y; labeled in blue);
3. major industrial metals (global production >~3×10^7 kg/year; labeled in red);
4. precious metals (labeled in purple);
5. the nine rarest "metals" — the six platinum group elements plus Au, Re, and Te (a metalloid) — in the yellow field.

Note that there are two breaks where the unstable elements technetium (atomic number: 43) and promethium (atomic number: 61) would be. These are both extremely rare, since on Earth they are only produced through the spontaneous fission of very heavy radioactive elements (for example, uranium, thorium, or the trace amounts of plutonium that exist in uranium ores), or by the interaction of certain other elements with cosmic rays. Both of the first two of these elements have been identified spectroscopically in the atmospheres of stars, where they are produced by ongoing nucleosynthetic processes. There are also breaks where the six noble gases would be since they are found in the Earth's crust due to decay chains from radioactive elements and are therefore extremely rare there. The six very rare, highly radioactive elements (polonium, astatine, francium, radium, actinium, and protactinium) are not included, since any of these elements that were present at the formation of the Earth have decayed away eons ago, and their quantity today is negligible.

Oxygen and silicon are notably quite common elements. They have frequently combined with each other to form common silicate minerals.

Rare-earth element abundances

"Rare" earth elements is a historical misnomer. The persistence of the term reflects unfamiliarity rather than true rarity. The more abundant rare earth elements are each similar in crustal concentration to commonplace industrial metals such as chromium, nickel, copper, zinc, molybdenum, tin, tungsten, or lead. The two least abundant rare earth elements (thulium and lutetium) are nearly 200 times more common than gold. However, in contrast to the ordinary base and precious metals, rare earth elements have very little tendency to become concentrated in exploitable ore deposits. Consequently, most of the world's supply of rare earth elements comes from only a handful of sources. Furthermore, the rare earth metals are all quite chemically similar to each other, and they are thus quite difficult to separate into quantities of the pure element.

Differences in abundances of individual rare earth elements in the upper continental crust of the Earth represent the superposition of two effects, one nuclear and one geochemical. First, the rare earth elements with even atomic numbers ($_{58}$Ce, $_{60}$Nd, ...) have greater cosmic and terrestrial abundances than the adjacent rare earth elements with odd atomic numbers ($_{57}$La, $_{59}$Pr, ...). Second, the lighter rare earth elements are more incompatible (because they have larger ionic radii) and therefore more strongly concentrated in the continental crust than the heavier rare earth elements. In most rare earth ore deposits, the first four rare earth elements - lanthanum, cerium, praseodymium, and neodymium - constitute 80% to 99% of the total amount of rare earth metal that can be found in the ore.

Ocean

Elemental composition of Earth's ocean water (by mass)

Element	Percent	Element	Percent
Oxygen	85.84	Sulfur	0.091
Hydrogen	10.82	Calcium	0.04
Chlorine	1.94	Potassium	0.04
Sodium	1.08	Bromine	0.0067
Magnesium	0.1292	Carbon	0.0028

Atmosphere

The order of elements by volume-fraction (which is approximately molecular mole-fraction) in the atmosphere is nitrogen (78.1%), oxygen (20.9%), argon (0.96%), followed by (in uncertain order) carbon and hydrogen because water vapor and carbon dioxide, which represent most of these two elements in the air, are variable components. Sulfur, phosphorus, and all other elements are present in significantly lower proportions.

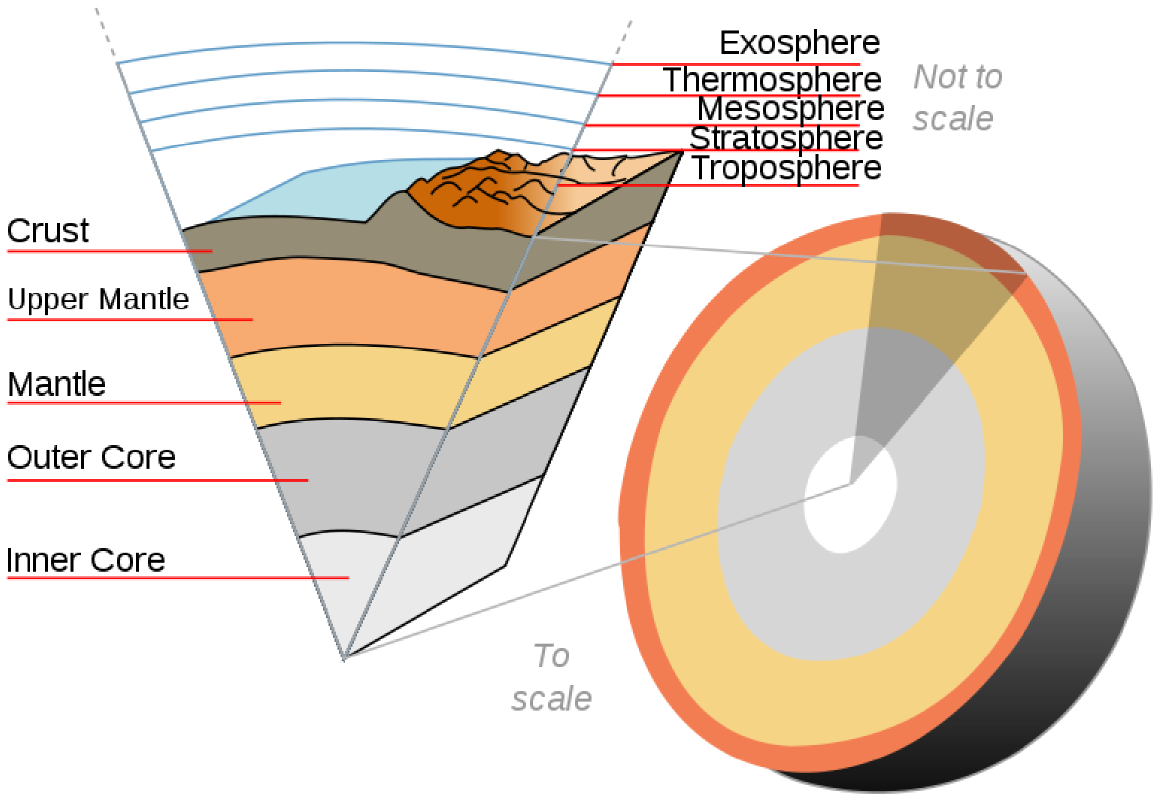
According to the above graphic, argon, a significant if not major component of the atmosphere, does not appear in the crust at all. This is because the atmosphere has a far smaller mass than the crust, so argon remaining in the crust contributes little to mass-fraction there, while at the same time buildup of argon in the atmosphere has become large enough to be significant.

Human body

By mass, human cells consist of 65-90% water (H_2O), and a significant portion is composed of carbon-containing organic molecules. Oxygen therefore contributes a majority of a human body's mass, followed by carbon. 99% of the mass of the human body is made up of the six elements: oxygen, carbon, hydrogen, nitrogen, calcium, and phosphorus. The very common elements aluminum and silicon are conspicuously rare in the human body.

Element	Percent by mass
Oxygen	65
Carbon	18
Hydrogen	10
Nitrogen	3
Calcium	1.5
Phosphorus	1.2
Potassium	0.2
Sulfur	0.2
Chlorine	0.2
Sodium	0.1
Magnesium	0.05
Iron, Cobalt, Copper, Zinc, Iodine	<0.05 each
Selenium, Fluorine	<0.01 each

Structure of the Earth



Earth cutaway from core to exosphere. Left picture is not to scale

The interior **structure of the Earth**, similar to the outer, is layered. These layers can be defined by either their chemical or their rheological properties. The Earth has an outer silicate solid crust, a highly viscous mantle, a liquid outer core that is much less viscous than the mantle, and a solid inner core. Scientific understanding of Earth's internal structure is based on observations of topography and bathymetry, observations of rock in outcrop, samples brought to the surface from greater depths by volcanic activity, analysis of the seismic waves that pass through the Earth, measurements of the gravity field of the Earth, and experiments with crystalline solids at pressures and temperatures characteristic of the Earth's deep interior.

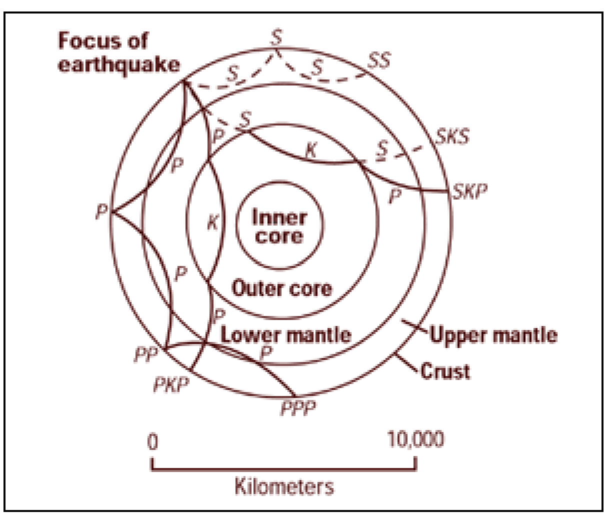
Assumptions

The force exerted by Earth's gravity can be used to calculate its mass, and by estimating the volume of the planet, its average density can be calculated. Astronomers can also calculate Earth's mass from its orbit and effects on nearby planetary bodies. Observations of rocks, bodies of water and atmosphere allow estimation of the mass, volume and density of rocks to a certain depth, so the remaining mass must be in the deeper layers.

Structure

The structure of Earth can be defined in two ways: by mechanical properties such as rheology, or chemically. Mechanically, it can be divided into lithosphere, asthenosphere, mesosphere, outer core, and the inner core. The interior of the earth is divided into 5 important layers. Chemically, Earth can be divided into the crust, upper mantle, lower mantle, outer core, and inner core. The geologic component layers of Earth are at the following depths below the surface:

Depth		
Kilometers	**Miles**	**Layer**
0–60	0–37	Lithosphere (locally varies between 5 and 200 km)
0–35	0–22	… Crust (locally varies between 5 and 70 km)
35–60	22–37	… Uppermost part of mantle
35–2,890	22–1,790	Mantle
100–200	62–125	… Asthenosphere
35–660	22–410	… Upper mantle
660–2,890	410–1,790	… Lower mantle
2,890–5,150	1,790–3,160	Outer core
5,150–6,360	3,160–3,954	Inner core



Mapping the interior of the Earth with earthquake waves

The layering of Earth has been inferred indirectly using the time of travel of refracted and reflected seismic waves created by earthquakes. The core does not allow shear waves to pass through it, while the speed of travel (seismic velocity) is different in other layers. The changes in seismic velocity between different layers causes refraction owing to Snell's law. Reflections are caused by a large increase in seismic velocity and are similar to light reflecting from a mirror.

Core

The average density of Earth is 5,515 kg/m^3. Since the average density of surface material is only around 3,000 kg/m^3, we must conclude that denser materials exist within Earth's core. Further evidence for the high density core comes from the study of seismology.

Seismic measurements show that the core is divided into two parts, a solid inner core with a radius of ~1,220 km and a liquid outer core extending beyond it to a radius of ~3,400 km. The solid inner core was discovered in 1936 by Inge Lehmann and is generally believed to be composed primarily of iron and some nickel.

In early stages of Earth's formation about 4.5 billion (4.5×10^9) years ago, melting would have caused denser substances to sink toward the center in a process called planetary differentiation, while less-dense materials would have migrated to the crust. The core is thus believed to largely be composed of iron (80%), along with nickel and one or more light elements, whereas other dense elements, such as lead and uranium, either are too rare to be significant or tend to bind to lighter elements and thus remain in the crust. Some have argued that the inner core may be in the form of a single iron crystal.

The liquid outer core surrounds the inner core and is believed to be composed of iron mixed with nickel and trace amounts of lighter elements.

Recent speculation suggests that the innermost part of the core is enriched in gold, platinum and other iron-loving (siderophile) elements.

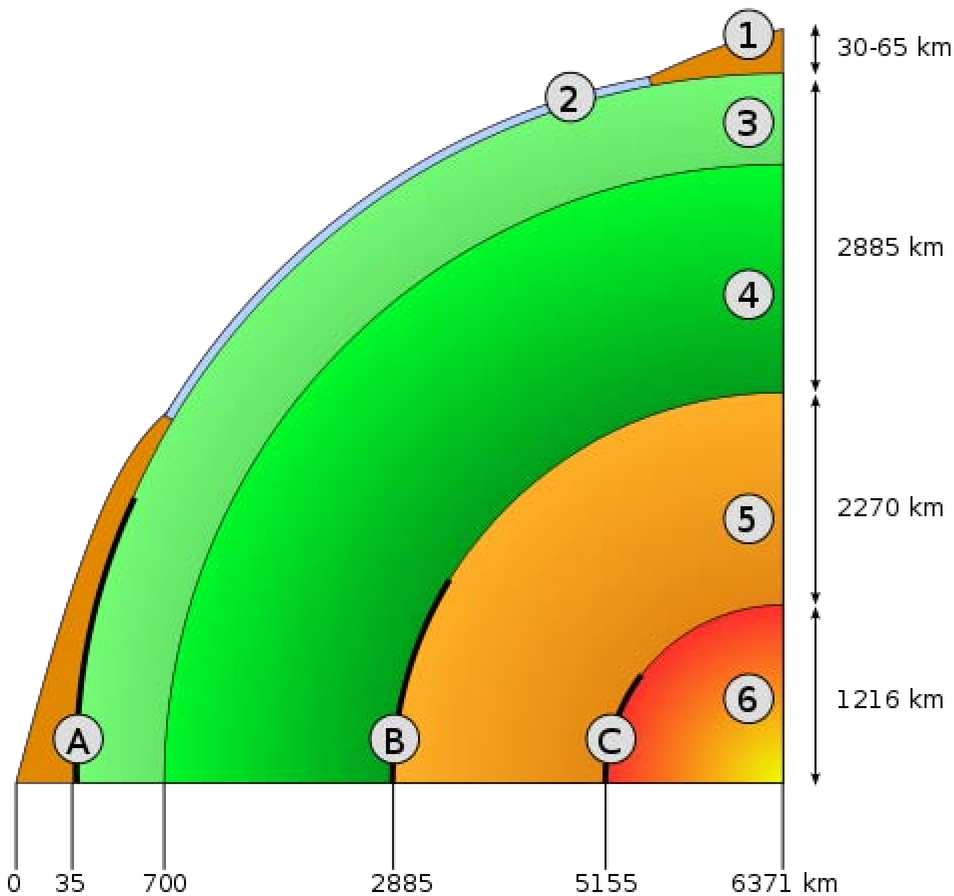
The matter that comprises Earth is connected in fundamental ways to matter of certain chondrite meteorites, and to matter of outer portion of the Sun. There is good reason to believe that Earth is, in the main, like a chondrite meteorite. Beginning as early as 1940, scientists, including Francis Birch, built geophysics upon the premise that Earth is like ordinary chondrites, the most common type of meteorite observed impacting Earth, while totally ignoring another, albeit less abundant type, called enstatite chondrites. The principal difference between the two meteorite types is that enstatite chondrites formed under circumstances of extremely limited available oxygen, leading to certain normally oxyphile elements existing either partially or wholly in the alloy portion that corresponds to the core of Earth.

Dynamo theory suggests that convection in the outer core, combined with the Coriolis effect, gives rise to Earth's magnetic field. The solid inner core is too hot to hold a permanent magnetic field but probably acts to stabilize the magnetic field generated by the liquid outer core.

Recent evidence has suggested that the inner core of Earth may rotate slightly faster than the rest of the planet. In August 2005 a team of geophysicists announced in the journal *Science* that, according to their estimates, Earth's inner core rotates approximately 0.3 to 0.5 degrees per year relative to the rotation of the surface.

The current scientific explanation for the Earth's temperature gradient is a combination of heat left over from the planet's initial formation, decay of radioactive elements, and freezing of the inner core.

Mantle



Schematic view of the interior of Earth. 1. continental crust - 2. oceanic crust - 3. upper mantle - 4. lower mantle - 5. outer core - 6. inner core - A: Mohorovičić discontinuity - B: Gutenberg Discontinuity - C: Lehmann discontinuity

Earth's mantle extends to a depth of 2,890 km, making it the thickest layer of the Earth. The pressure, at the bottom of the mantle, is ~140 GPa (1.4 Matm). The mantle is composed of silicate rocks that are rich in iron and magnesium relative to the overlying crust. Although solid, the high temperatures within the mantle cause the silicate material to be sufficiently ductile that it can flow on very long timescales. Convection of the mantle is expressed at the surface through the motions of tectonic plates. The melting point and viscosity of a substance depends on the pressure it is under. As there is intense and increasing pressure as one travels deeper into the mantle, the lower part of the mantle flows less easily than does the upper mantle (chemical changes within the mantle may also be important). The viscosity of the mantle ranges between 10^{21} and 10^{24} Pa·s, depending on depth. In comparison, the viscosity of water is approximately 10^{-3} Pa·s and that of pitch is 10^{7} Pa·s.

Crust

The crust ranges from 5–70 km in depth and is the outermost layer. The thin parts are the oceanic crust, which underlie the ocean basins(5–10 km) and are composed of dense (mafic) iron magnesium silicate rocks, like basalt. The thicker crust is continental crust, which is less dense and composed of (felsic) sodium potassium aluminium silicate rocks, like granite. The rocks of the crust fall into two major categories - sial and sima (Suess,1831–1914). As the main mineral constituents of the continental mass are silica and alumina, it is thus called sial (si-silica, 65–75% and al-alumina). The oceanic crust mainly consists of silica and magnesium; it is therefore called sima (si-silica and ma-magnesium). It is estimated that sima starts about 11 km below the Conrad discontinuity, a second order discontinuity. The uppermost mantle together with the crust constitutes the lithosphere. The crust-mantle boundary occurs as two physically different events. First, there is a discontinuity in the seismic velocity, which is known as the Mohorovičić discontinuity or Moho. The cause of the Moho is thought to be a change in rock composition from rocks containing plagioclase feldspar (above) to rocks that contain no feldspars (below). Second, in oceanic crust, there is a chemical discontinuity between ultramafic cumulates and tectonized harzburgites, which has been observed from deep parts of the oceanic crust that have been obducted onto the continental crust and preserved as ophiolite sequences.

Many rocks now making up Earth's crust formed less than 100 million (1×10^{8}) years ago; however the oldest known mineral grains are 4.4 billion (4.4×10^{9}) years old, indicating that Earth has had a solid crust for at least that long.

Historical development of alternative conceptions

In 1692 Edmund Halley (in a paper printed in *Philosophical Transactions of Royal Society of London*) put forth the idea of Earth consisting of a hollow shell about 500 miles thick, with two inner concentric shells around an innermost core, corresponding to the diameters of the planets Venus, Mars, and Mercury respectively. Halley's construct was a method of accounting for the (flawed) values of the relative density of Earth and the Moon that had been given by Sir Isaac Newton, in *Principia* (1687). "Sir Isaac Newton has demonstrated the Moon to be more solid than our Earth, as 9 to 5," Halley remarked; "why may we not then suppose four ninths of our globe to be cavity?"

Heat

Earth's internal heat comes from a combination of residual heat from planetary accretion (about 20%) and heat produced through radioactive decay (80%). The major heat-producing isotopes in the Earth are potassium-40, uranium-238, uranium-235, and thorium-232. At the center of the planet, the temperature may be up to 7,000 K and the pressure could reach 360 GPa. Because much of the heat is provided by radioactive decay, scientists believe that early in Earth history, before isotopes with short half-lives had been depleted, Earth's heat production would have been much higher. This extra heat production, twice present-day at approximately 3 billion years ago, would have increased temperature gradients within the Earth, increasing the rates of mantle convection and plate tectonics, and allowing the production of igneous rocks such as komatiites that are not formed today.

Present-day major heat-producing isotopes

Isotope	**Heat release** W/kg isotope	**Half-life** years	**Mean mantle concentration** kg isotope/kg mantle	**Heat release** W/kg mantle
^{238}U	9.46×10^{-5}	4.47×10^{9}	30.8×10^{-9}	2.91×10^{-12}
^{235}U	5.69×10^{-4}	7.04×10^{8}	0.22×10^{-9}	1.25×10^{-13}
^{232}Th	2.64×10^{-5}	1.40×10^{10}	124×10^{-9}	3.27×10^{-12}
^{40}K	2.92×10^{-5}	1.25×10^{9}	36.9×10^{-9}	1.08×10^{-12}

Total heat loss from the Earth is 4.2×10^{13} watts. A portion of the core's thermal energy is transported toward the crust by mantle plumes; a form of convection consisting of upwellings of higher-temperature rock. These plumes can produce hotspots and flood basalts. More of the heat in the Earth is lost through plate tectonics, by mantle upwelling associated with mid-ocean ridges. The final major mode of heat loss is through conduction through the lithosphere, the majority of which occurs in the oceans because the crust there is much thinner than that of the continents.

Atmosphere of Earth

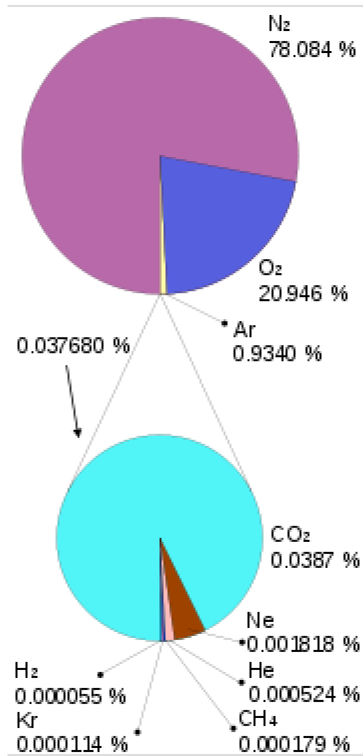
Blue light is scattered more than other wavelengths by the gases in the atmosphere, giving the Earth a blue halo when seen from space.

Limb view, of the Earth's atmosphere. Colours roughly denote the layers of the atmosphere

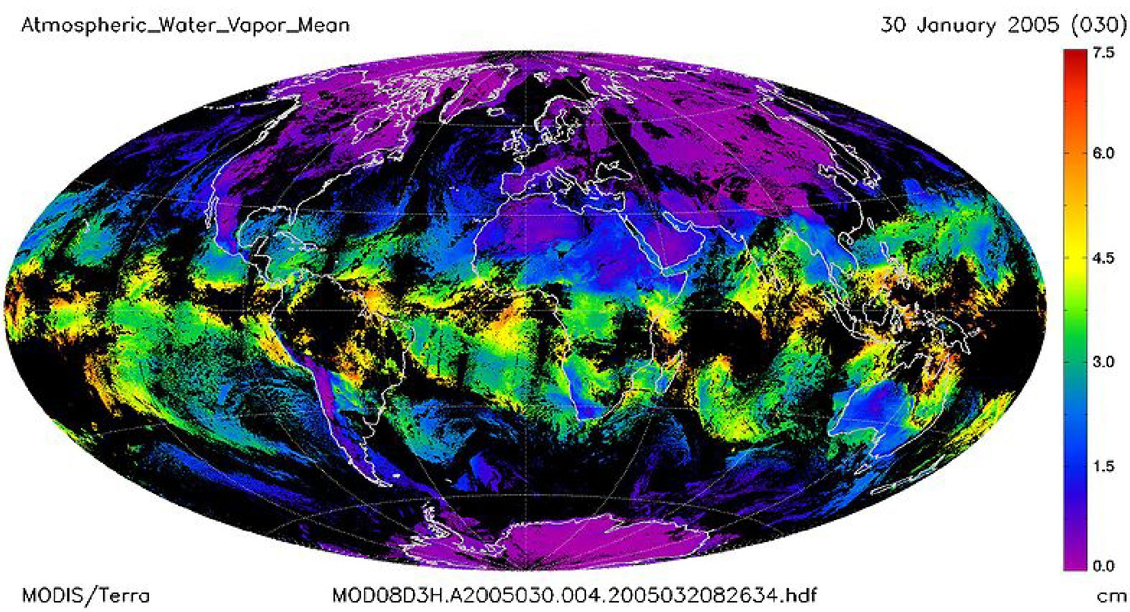
The **atmosphere of Earth** is a layer of gases surrounding the planet Earth that is retained by Earth's gravity. The atmosphere protects life on Earth by absorbing ultraviolet solar radiation, warming the surface through heat retention (greenhouse effect), and reducing temperature extremes between day and night. Dry air contains roughly (by volume) 78.09% nitrogen, 20.95% oxygen, 0.93% argon, 0.039% carbon dioxide, and small amounts of other gases. Air also contains a variable amount of water vapor, on average around 1%.

The atmosphere has a mass of about 5×10^{18} kg, three quarters of which is within about 11 km (6.8 mi; 36,000 ft) of the surface. The atmosphere becomes thinner and thinner with increasing altitude, with no definite boundary between the atmosphere and outer space. An altitude of 120 km (75 mi) is where atmospheric effects become noticeable during atmospheric reentry of spacecraft. The Kármán line, at 100 km (62 mi), also is often regarded as the boundary between atmosphere and outer space.

Composition



Composition of Earth's atmosphere. The lower pie represents the trace gases which together compose 0.039% of the atmosphere. Values normalized for illustration. The numbers are from a variety of years (mainly 1987, with CO_2 and methane from 2009) and do not represent any single source.



Mean atmospheric water vapor

Air is mainly composed of nitrogen, oxygen, and argon, which together constitute the major gases of the atmosphere. The remaining gases are often referred to as trace gases, among which are the greenhouse gases such as water vapor, carbon dioxide, methane, nitrous oxide, and ozone. Filtered air includes trace amounts of many other chemical compounds. Many natural substances may be present in tiny amounts in an unfiltered air sample, including dust, pollen and spores, sea spray, and volcanic ash. Various industrial pollutants also may be present, such as chlorine (elementary or in compounds), fluorine compounds, elemental mercury, and sulfur compounds such as sulfur dioxide [SO_2].

Composition of dry atmosphere, by volume

ppmv: parts per million by volume (note: volume fraction is equal to mole fraction for ideal gas only (thermodynamics))

Gas	Volume
Nitrogen (N_2)	780,840 ppmv (78.084%)
Oxygen (O_2)	209,460 ppmv (20.946%)
Argon (Ar)	9,340 ppmv (0.9340%)
Carbon dioxide (CO_2)	390 ppmv (0.039%)
Neon (Ne)	18.18 ppmv (0.001818%)
Helium (He)	5.24 ppmv (0.000524%)
Methane (CH_4)	1.79 ppmv (0.000179%)
Krypton (Kr)	1.14 ppmv (0.000114%)
Hydrogen (H_2)	0.55 ppmv (0.000055%)
Nitrous oxide (N_2O)	0.3 ppmv (0.00003%)
Carbon monoxide (CO)	0.1 ppmv (0.00001%)
Xenon (Xe)	0.09 ppmv (9×10^{-6}%) (0.000009%)
Ozone (O_3)	0.0 to 0.07 ppmv (0 to 7×10^{-6}%)
Nitrogen dioxide (NO_2)	0.02 ppmv (2×10^{-6}%) (0.000002%)

Iodine (I_2) 0.01 ppmv (1×10^{-6}%) (0.000001%)

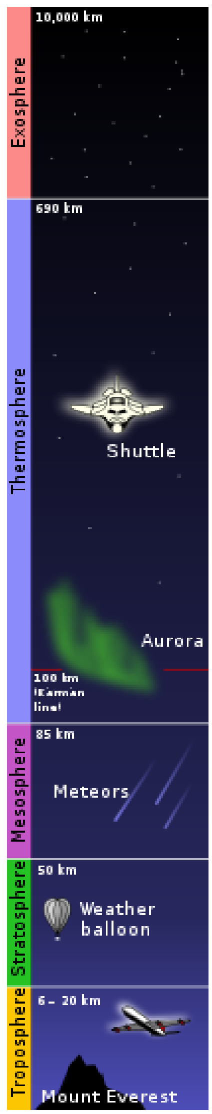
Ammonia (NH_3) trace

Not included in above dry atmosphere:

Water vapor (H_2O) ~0.40% over full atmosphere, typically 1%-4% at surface

Structure of the atmosphere

Principal layers



Layers of the atmosphere (not to scale)

Earth's atmosphere can be divided into five main layers. These layers are mainly determined by whether temperature increases or decreases with altitude. From highest to lowest, these layers are:

Exosphere

The outermost layer of Earth's atmosphere extends from the exobase upward. It is mainly composed of hydrogen and helium. The particles are so far apart that they can travel hundreds of kilometres without colliding with one another. Since the particles rarely collide, the atmosphere no longer behaves like a fluid. These free-moving particles follow ballistic trajectories and may migrate into and out of the magnetosphere or the solar wind.

Thermosphere

Temperature increases with height in the thermosphere from the mesopause up to the thermopause, then is constant with height. The temperature of this layer can rise to 1,500 °C (2,730 °F), though the gas molecules are so far apart that temperature in the usual sense is not well defined. The International Space Station orbits in this layer, between 320 and 380 km (200 and 240 mi). The top of the thermosphere is the bottom of the exosphere, called the exobase. Its height varies with solar activity and ranges from about 350–800 km (220–500 mi; 1,100,000–2,600,000 ft).

Mesosphere

The mesosphere extends from the stratopause to 80–85 km (50–53 mi; 260,000–280,000 ft). It is the layer where most meteors burn up upon entering the atmosphere. Temperature decreases with height in the mesosphere. The mesopause, the temperature minimum that marks the top of the mesosphere, is the coldest place on Earth and has an average temperature around −85 °C (−121 °F; 188.1 K). Due to the cold temperature of the mesophere, water vapor is frozen, forming ice clouds (or Noctilucent clouds). A type of lightning referred to as either sprites or ELVES, form many miles above thunderclouds in the troposphere.

Stratosphere

The stratosphere extends from the tropopause to about 51 km (32 mi; 170,000 ft). Temperature increases with height, which restricts turbulence and mixing. The stratopause, which is the boundary between the stratosphere and mesosphere, typically is at 50 to 55 km (31 to 34 mi; 160,000 to 180,000 ft). The pressure here is 1/1000th sea level.

Troposphere

The troposphere begins at the surface and extends to between 7 km (23,000 ft) at the poles and 17 km (56,000 ft) at the equator, with some variation due to weather. The troposphere is mostly heated by transfer of energy from the surface, so on average the lowest part of the troposphere is warmest and temperature decreases with altitude. This promotes vertical mixing (hence the origin of its name in the Greek word "τροπή", *trope*, meaning turn or overturn). The troposphere contains roughly 80% of the mass of the atmosphere. The tropopause is the boundary between the troposphere and stratosphere.

Other layers

Within the five principal layers determined by temperature are several layers determined by other properties.

- The ozone layer is contained within the stratosphere. In this layer ozone concentrations are about 2 to 8 parts per million, which is much higher than in the lower atmosphere but still very small compared to the main components of the atmosphere. It is mainly located in the lower portion of the stratosphere from about 15–35 km (9.3–22 mi; 49,000–110,000 ft), though the thickness varies seasonally and geographically. About 90% of the ozone in our atmosphere is contained in the stratosphere.

- The ionosphere, the part of the atmosphere that is ionized by solar radiation, stretches from 50 to 1,000 km (31 to 620 mi; 160,000 to 3,300,000 ft) and typically overlaps both the exosphere and the thermosphere. It forms the inner edge of the magnetosphere. It has practical importance because it influences, for example, radio propagation on the Earth. It is responsible for auroras.

- The homosphere and heterosphere are defined by whether the atmospheric gases are well mixed. In the homosphere the chemical composition of the atmosphere does not depend on molecular weight because the gases are mixed by turbulence. The homosphere includes the troposphere, stratosphere, and mesosphere. Above the *turbopause* at about 100 km (62 mi; 330,000 ft) (essentially corresponding to the mesopause), the composition varies with altitude. This is because the distance that particles can move without colliding with one another is large compared with the size of motions that cause mixing. This allows the gases to stratify by molecular weight, with the heavier ones such as oxygen and nitrogen present only near the bottom of the heterosphere. The upper part of the heterosphere is composed almost completely of hydrogen, the lightest element.

- The planetary boundary layer is the part of the troposphere that is nearest the Earth's surface and is directly affected by it, mainly through turbulent diffusion. During the day the planetary boundary layer usually is well-mixed, while at night it becomes stably stratified with weak or intermittent mixing. The depth of the planetary boundary layer ranges from as little as about 100 m on clear, calm nights to 3000 m or more during the afternoon in dry regions.

The average temperature of the atmosphere at the surface of Earth is 14 °C (57 °F; 287 K) or 15 °C (59 °F; 288 K), depending on the reference.

Physical properties

Pressure and thickness

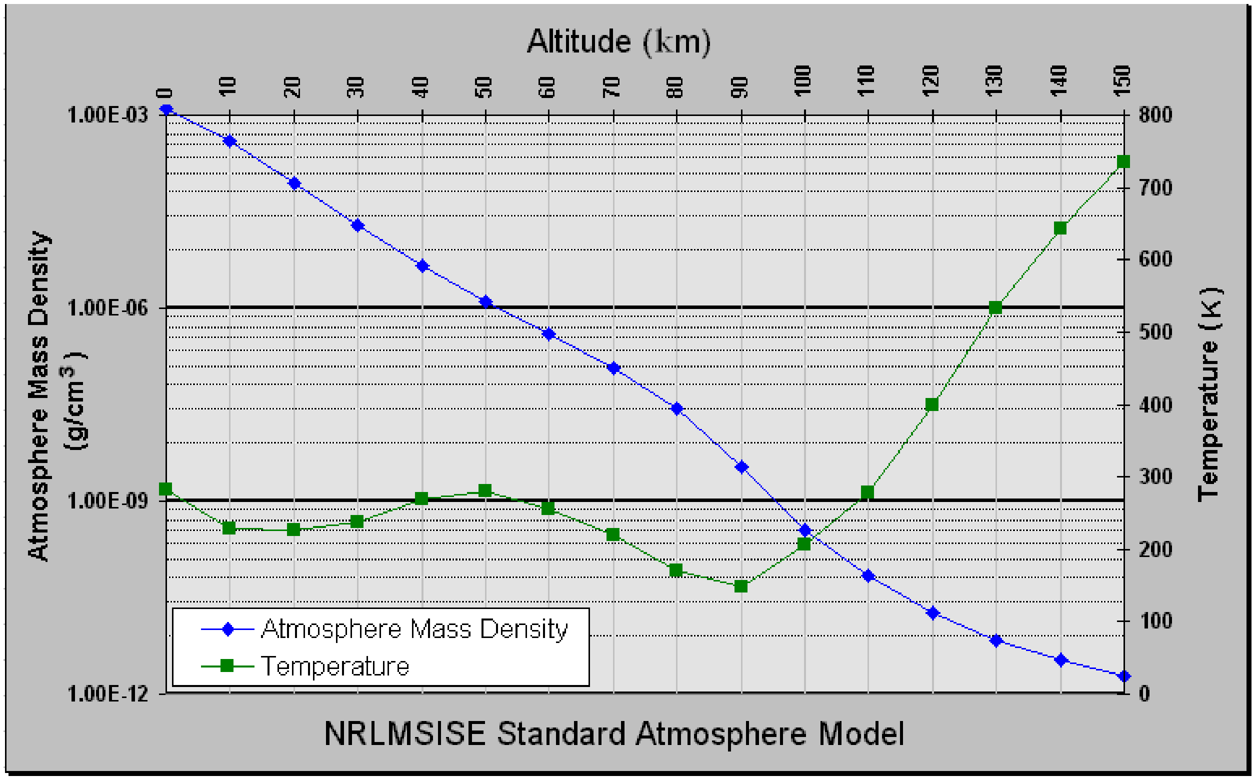
The average atmospheric pressure at sea level is about 1 atmosphere (atm) = 101.3 kPa (kilopascals) = 14.7 psi (pounds per square inch) = 760 torr = 29.9 inches of mercury (symbol Hg). Total atmospheric mass is 5.1480×10^{18} kg (1.135×10^{19} lb), about 2.5% less than would be inferred naively from the average sea level pressure and the Earth's area of 51007.2 megahectares, this defect having been displaced by the Earth's mountainous terrain. Atmospheric pressure is the total weight of the air above unit area at the point where the pressure is measured. Thus air pressure varies with location and time, because the amount of air above the Earth's surface varies.

If atmospheric density were to remain constant with height the atmosphere would terminate abruptly at 8.50 km (27,900 ft). Instead, density decreases with height, dropping by 50% at an altitude of about 5.6 km (18,000 ft). As a result the pressure decrease is approximately exponential with height, so that pressure decreases by a factor of two approximately every 5.6 km (18,000 ft) and by a factor of $e = 2.718\ldots$ approximately every 7.64 km (25,100 ft), the latter being the average scale height of Earth's atmosphere below 70 km (43 mi; 230,000 ft). However, because of changes in temperature, average molecular weight, and gravity throughout the atmospheric column, the dependence of atmospheric pressure on altitude is modeled by separate equations for each of the layers listed above. Even in the exosphere, the atmosphere is still present. This can be seen by the effects of atmospheric drag on satellites.

In summary, the equations of pressure by altitude in the above references can be used directly to estimate atmospheric thickness. However, the following published data are given for reference:

- 50% of the atmosphere by mass is below an altitude of 5.6 km (18,000 ft).
- 90% of the atmosphere by mass is below an altitude of 16 km (52,000 ft). The common altitude of commercial airliners is about 10 km (33,000 ft) and Mt. Everest's summit is 8,848 m (29,029 ft) above sea level.
- 99.99997% of the atmosphere by mass is below 100 km (62 mi; 330,000 ft), although in the rarefied region above this there are auroras and other atmospheric effects. The highest X-15 plane flight in 1963 reached an altitude of 108.0 km (354,300 ft).

Density and mass



Temperature and mass density against altitude from the NRLMSISE-00 standard atmosphere model (the eight dotted lines in each "decade" are at the eight cubes 8, 27, 64, ..., 729)

The density of air at sea level is about 1.2 kg/m^3 (1.2 g/L). Density is not measured directly but is calculated from measurements of temperature, pressure and humidity using the equation of state for air (a form of the ideal gas law). Atmospheric density decreases as the altitude increases. This variation can be approximately modeled using the barometric formula. More sophisticated models are used to predict orbital decay of satellites.

The average mass of the atmosphere is about 5 quadrillion (5×10^{15}) tonnes or 1/1,200,000 the mass of Earth. According to the National Center for Atmospheric Research, "The total mean mass of the atmosphere is 5.1480×10^{18} kg with an annual range due to water vapor of 1.2 or 1.5×10^{15} kg depending on whether surface pressure or water vapor data are used; somewhat smaller than the previous estimate. The mean mass of water vapor is estimated as 1.27×10^{16} kg and the dry air mass as $5.1352 \pm 0.0003 \times 10^{18}$ kg."

Optical properties

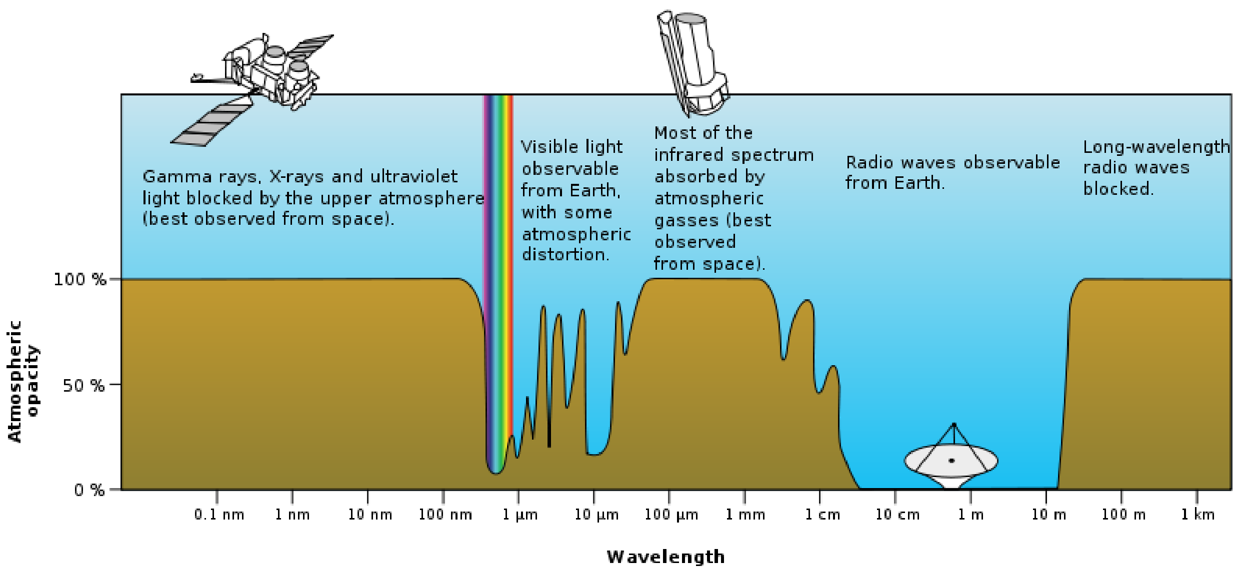
Solar radiation (or sunlight) is the energy the Earth receives from the Sun. The Earth also emits radiation back into space, but at longer wavelengths that we cannot see. Part of the incoming and emitted radiation is absorbed or reflected by the atmosphere.

Scattering

When light passes through our atmosphere, photons interact with it through *scattering*. If the light does not interact with the atmosphere, it is called *direct radiation* and is what you see if you were to look directly at the Sun. *Indirect radiation* is light that has been scattered in the atmosphere. For example, on an overcast day when you cannot see your shadow there is no direct radiation reaching you, it has all been scattered. As another example, due to a phenomenon called Rayleigh scattering, shorter (blue) wavelengths scatter more easily than longer (red) wavelengths. This is why the sky looks blue, you are seeing scattered blue light. This is also why sunsets are red. Because the Sun is close to the horizon, the Sun's rays pass through more atmosphere than normal to reach your eye. Much of the blue light has been scattered out, leaving the red light in a sunset.

Absorption

Different molecules absorb different wavelengths of radiation. For example, O_2 and O_3 absorb almost all wavelengths shorter than 300 nanometers. Water (H_2O) absorbs many wavelengths above 700 nm. When a molecule absorbs a photon, it increases the energy of the molecule. We can think of this as heating the atmosphere, but the atmosphere also cools by emitting radiation, as discussed below.



Rough plot of Earth's atmospheric transmittance (or opacity) to various wavelengths of electromagnetic radiation, including visible light.

The combined absorption spectra of the gases in the atmosphere leave "windows" of low opacity, allowing the transmission of only certain bands of light. The optical window runs from around 300 nm (ultraviolet-C) up into the range humans can see, the visible spectrum (commonly called light), at roughly 400–700 nm and continues to the infrared to around 1100 nm. There are also infrared and radio windows that transmit some infrared and radio waves at longer wavelengths. For example, the radio window runs from about one centimeter to about eleven-meter waves.

Emission

Emission is the opposite of absorption, it is when an object emits radiation. Objects tend to emit amounts and wavelengths of radiation depending on their "black body" emission curves, therefore hotter objects tend to emit more radiation, with shorter wavelengths. Colder objects emit less radiation, with longer wavelengths. For example, the Sun is approximately 6,000 K (5,730 °C; 10,340 °F), its radiation peaks near 500 nm, and is visible to the human eye. The Earth is approximately 290 K (17 °C; 62 °F), so its radiation peaks near 10,000 nm, and is much too long to be visible to humans.

Because of its temperature, the atmosphere emits infrared radiation. For example, on clear nights the Earth's surface cools down faster than on cloudy nights. This is because clouds (H_2O) are strong absorbers and emitters of infrared radiation. This is also why it becomes colder at night at higher elevations. The atmosphere acts as a "blanket" to limit the amount of radiation the Earth loses into space.

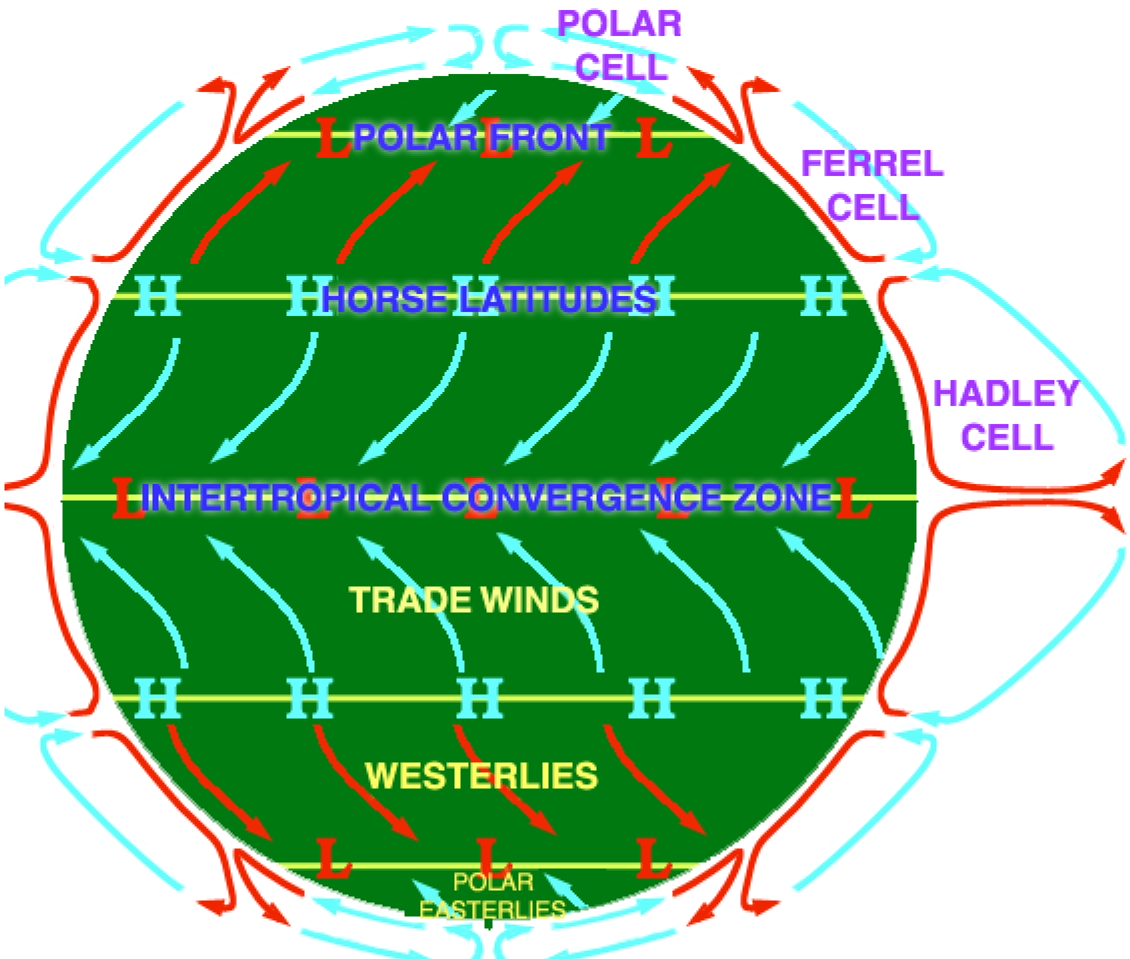
The *greenhouse effect* is directly related to this absorption and emission (or "blanket") effect. Some chemicals in the atmosphere absorb and emit infrared radiation, but do not interact with sunlight in the visible spectrum. Common examples of these chemicals are CO_2 and H_2O. If there are too much of these *greenhouse gases*, sunlight heats the Earth's surface, but the gases block the infrared radiation from exiting back to space. This imbalance causes the Earth to warm, and thus climate change.

Refractive index

The refractive index of air is close to, but just greater than 1. Systematic variations in refractive index can lead to the bending of light rays over long optical paths. One example is that, under some circumstances, observers onboard ships can see other vessels just over the horizon because light is refracted in the same direction as the curvature of the Earth's surface.

The refractive index of air depends on temperature, giving rise to refraction effects when the temperature gradient is large. An example of such effects is the mirage.

Circulation



An idealised view of three large circulation cells

Atmospheric circulation is the large-scale movement of air, and the means (with ocean circulation) by which heat is distributed around the Earth. The large-scale structure of the atmospheric circulation varies from year to year, but the basic structure remains fairly constant as it is determined by the Earth's rotation rate and the difference in solar radiation between the equator and poles.

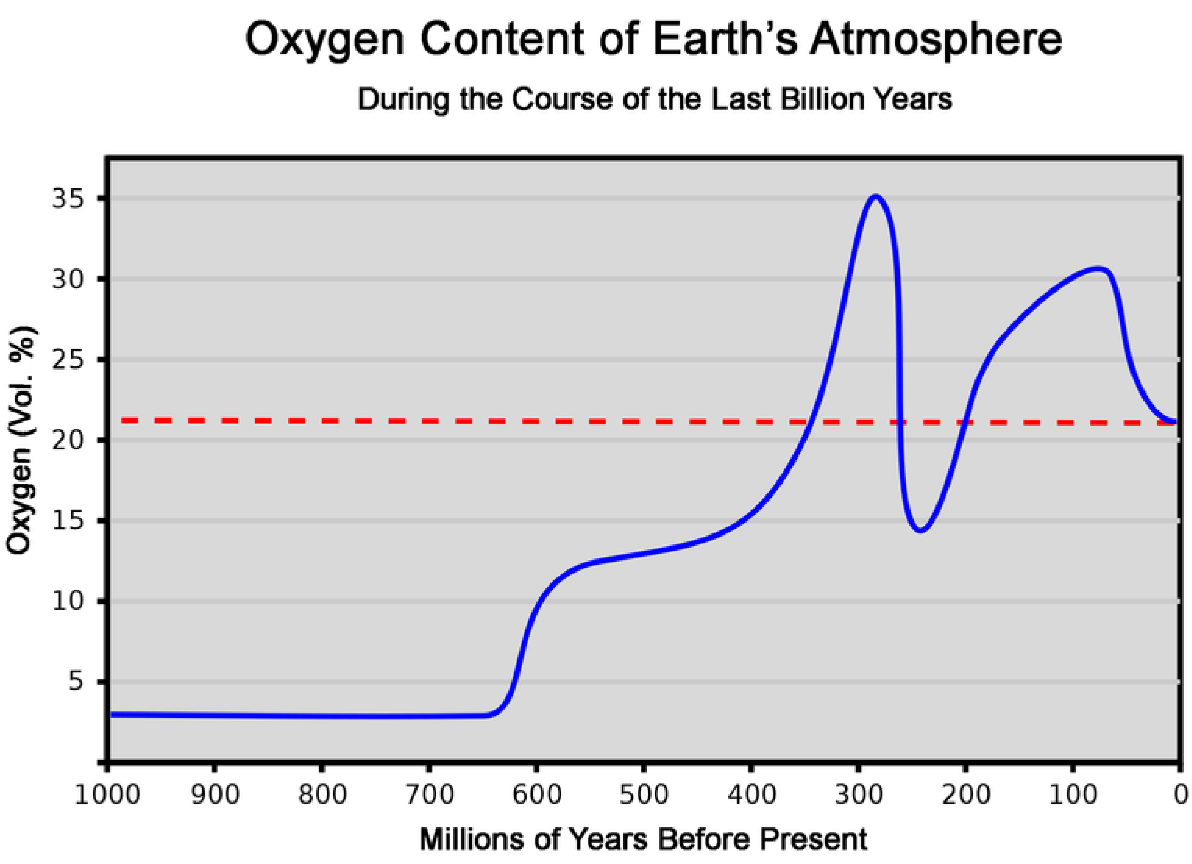
Evolution of Earth's atmosphere

Second atmosphere

Water related sediments have been found dating from as early as 3.8 billion years ago. About 3.4 billion years ago, nitrogen was the major part of the then stable "second atmosphere." An influence of life has to be taken into account rather soon in the history of the atmosphere, since hints of early life forms are to be found as early as 3.5 billion years ago. The fact that this is not perfectly in line with the - compared to today 30% lower - solar radiance of the early Sun has been described as the "Faint young Sun paradox".

The geological record however shows a continually relatively warm surface during the complete early temperature record of the Earth with the exception of one cold glacial phase about 2.4 billion years ago. In the late Archaean era an oxygen-containing atmosphere began to develop, apparently from photosynthesizing algae which have been found as stromatolite fossils from 2.7 billion years ago. The early basic carbon isotopy (isotope ratio proportions) is very much in line with what is found today, suggesting that the fundamental features of the carbon cycle were established as early as 4 billion years ago.

Third atmosphere



Oxygen content of the atmosphere over the last billion years

The accretion of continents about 3.5 billion years ago added plate tectonics, constantly rearranging the continents and also shaping long-term climate evolution by allowing the transfer of carbon dioxide to large land-based carbonate storages. Free oxygen did not exist until about 1.7 billion years ago and this can be seen with the development of the red beds and the end of the banded iron formations. This signifies a shift from a reducing atmosphere to an oxidising atmosphere. O_2 showed major ups and downs until reaching a steady state of more than 15%. The following time span was the Phanerozoic era, during which oxygen-breathing metazoan life forms began to appear.

Currently, anthropogenic greenhouse gases are increasing in the atmosphere. According to the Intergovernmental Panel on Climate Change, this increase is the main cause of global warming.

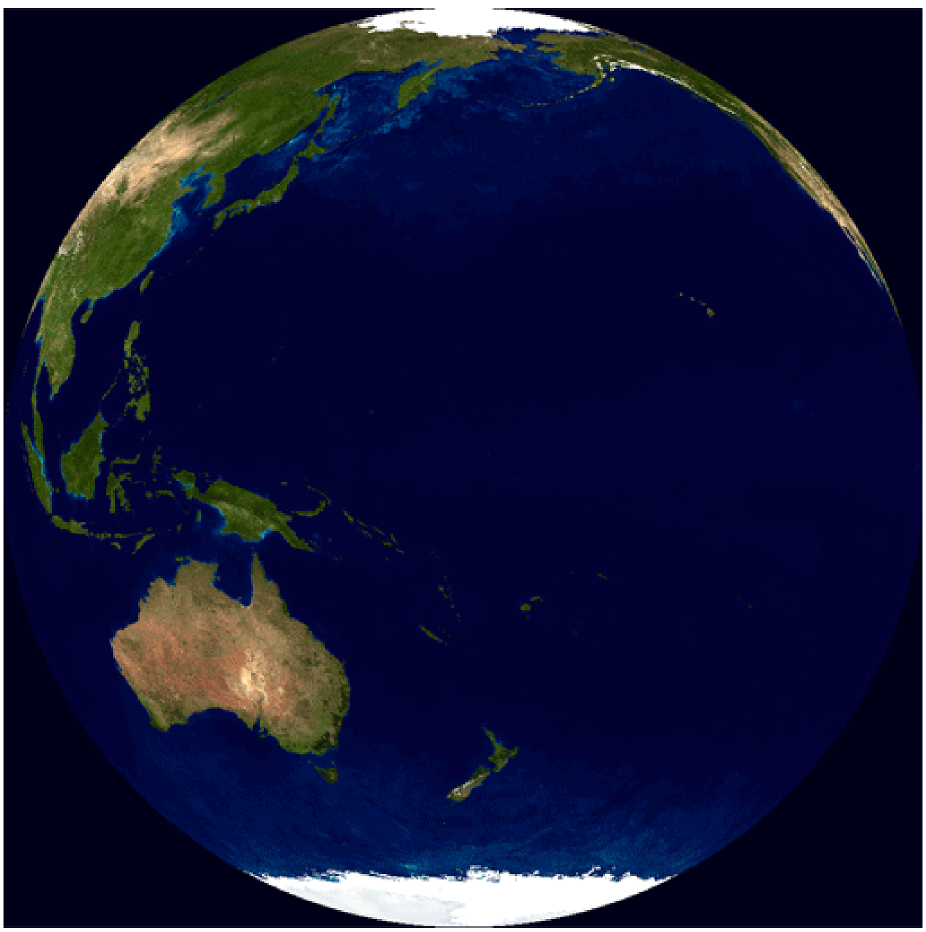
Air pollution

Air pollution is the introduction of chemicals, particulate matter, or biological materials that cause harm or discomfort to organisms into the atmosphere. Stratospheric ozone depletion is believed to be caused by air pollution (chiefly from chlorofluorocarbons).

Chapter- 3

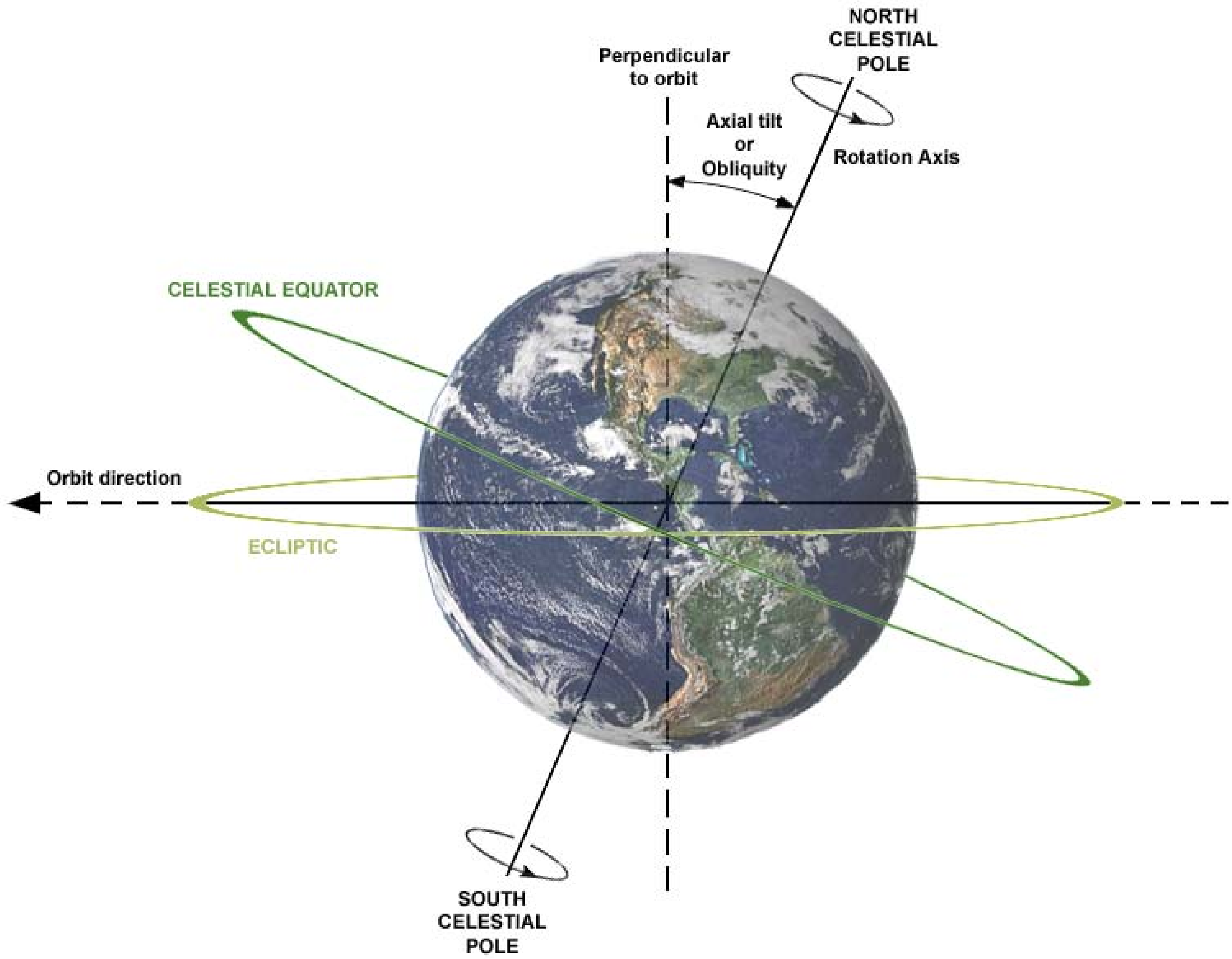
Earth’s Rotation and Orbit

Earth's rotation

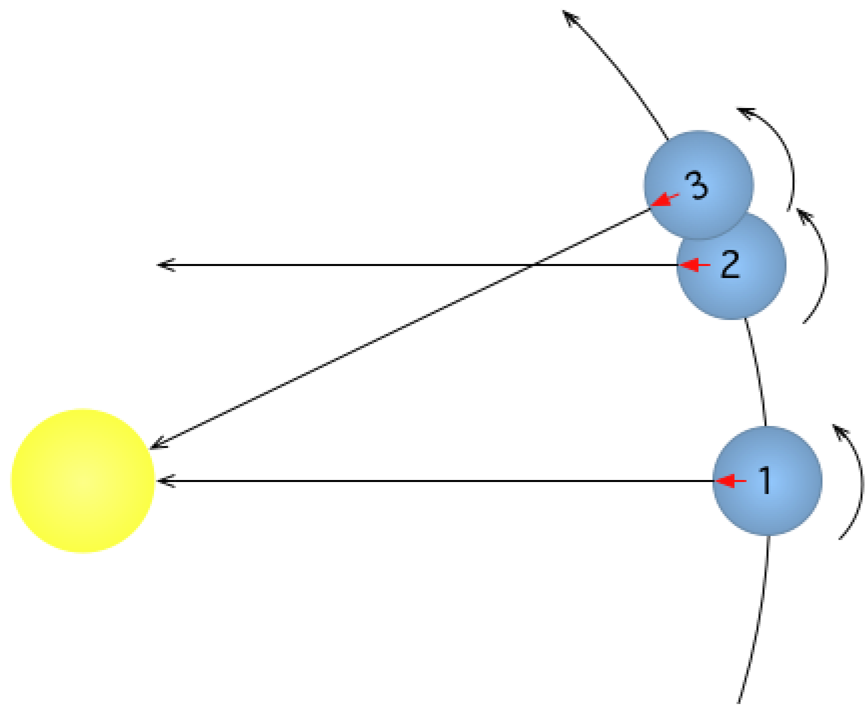


Earth's rotation is the rotation of the solid Earth around its own axis. The Earth rotates towards the east. As viewed from the North Star Polaris, the Earth turns counter-clockwise.

Rotation period



Earth's axial tilt (or *obliquity*) and its relation to the rotation axis and plane of orbit as viewed from the Sun during the March equinox.



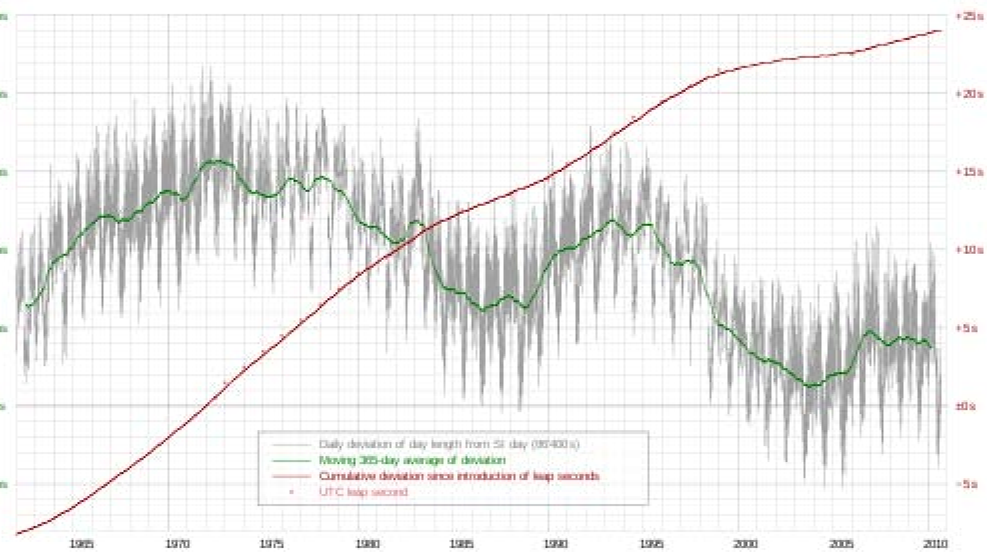
On a prograde planet like the Earth, the **stellar day** is shorter than the solar day. At time 1, the Sun and a certain distant star are both overhead. At time 2, the planet has rotated 360° and the distant star is overhead again but the Sun is not (1→2 = one stellar day). It is not until a little later, at time 3, that the Sun is overhead again (1→3 = one solar day).

Earth's rotation period relative to the Sun (true noon to true noon) is its **true solar day** or **apparent solar day**. It is the derivative of the equation of time and thus depends on the eccentricity of Earth's orbit and the tilt (obliquity) of Earth's axis. Both vary over thousands of years so the annual variation of the true solar day also varies. Generally, it is longer than the mean solar day twice a year and shorter twice a year. The true solar day tends to be longer near perihelion when the Sun apparently moves along the ecliptic through a greater angle than usual, taking about 10 seconds longer to do so. Conversely, it is about 10 seconds shorter near aphelion. It is about 20 seconds longer near a solstice when the projection of the Sun's apparent movement along the ecliptic onto the celestial equator causes the Sun to move through a greater angle than usual. Conversely, near an equinox the projection onto the equator is shorter by about 20 seconds. Currently, the perihelion and solstice effects combine to lengthen the true solar day near December 22 by 30 mean solar seconds, but the solstice effect is partially cancelled by the aphelion effect near June 19 when it is only 13 seconds longer. The effects of the equinoxes shorten it near March 26 and September 16 by 18 seconds and 21 seconds, respectively.

The average of the true solar day over an entire year is the **mean solar day**, which contains 86,400 mean solar seconds. Currently, each of these seconds is slightly longer than an SI second because Earth's mean solar day is now slightly longer than it was during the 19th century due to tidal friction. The mean solar second between 1750 and 1892 was chosen in 1895 by Simon Newcomb as the independent unit of time in his Tables of the Sun. These tables were used to calculate the world's ephemerides between 1900 and 1983, so this second became known as the ephemeris second. The SI second was made equal to the ephemeris second in 1967.

Earth's rotation period relative to the fixed stars, called its **stellar day** by the International Earth Rotation and Reference Systems Service (IERS), is 86,164.098 903 691 seconds of mean solar time (UT1) (23^h 56^m $4.098\ 903\ 691^s$, 0.997 269 663 237 16 mean solar days). Earth's rotation period relative to the precessing or moving mean vernal equinox, misnamed its **sidereal day**, is 86,164.090 530 832 88 seconds of mean solar time (UT1) (23^h 56^m $4.090\ 530\ 832\ 88^s$, 0.997 269 566 329 08 mean solar days). Thus the sidereal day is shorter than the stellar day by about 8.4 ms.

Both the stellar day and the sidereal day are shorter than the mean solar day by about 3 minutes 56 seconds. The mean solar day in SI seconds is available from the IERS for the periods 1623–2005 and 1962–2005.



Deviation of day length from SI based day, 1962–2010

Recently (1999–2010) the average annual length of the mean solar day in excess of 86,400 SI seconds has varied between 0.25 ms and 1 ms, which must be added to both the stellar and sidereal days given in mean solar time above to obtain their lengths in SI seconds.

The angular speed of Earth's rotation in inertial space is $(7.2921150 \pm 0.0000001) \times 10^{-5}$ radians per SI second (mean solar second). Multiplying by (180°/π radians)×(86,400 seconds/mean solar day) yields 360.9856°/mean solar day, indicating that Earth rotates more than 360° relative to the fixed stars in one solar day. Earth's movement along its nearly circular orbit while it is rotating once around its axis requires that Earth rotate slightly more than once relative to the fixed stars before the mean Sun can pass overhead again, even though it rotates only once (360°) relative to the mean Sun. Multiplying the value in rad/s by Earth's equatorial radius of 6,378,137 m (WGS84 ellipsoid) (factors of 2π radians needed by both cancel) yields an equatorial speed of 465.1 m/s, 1,674.4 km/h or 1,040.4 mi/h. Some sources state that Earth's equatorial speed is slightly less, or 1,669.8 km/h. This is obtained by dividing Earth's equatorial circumference by 24 hours. However, the use of only one circumference unwittingly implies only one rotation in inertial space, so the corresponding time unit must be a sidereal hour. This is confirmed by multiplying by the number of sidereal days in one mean solar day, 1.002 737 909 350 795, which yields the equatorial speed in mean solar hours given above of 1,674.4 km/h.

The permanent monitoring of the Earth's rotation requires the use of Very Long Baseline Interferometry coordinated with the Global Positioning System, Satellite laser ranging, and other satellite techniques. This provides the absolute reference for the determination of universal time, precession, and nutation.

Over millions of years, the rotation is significantly slowed by gravitational interactions with the Moon. However some large scale events, such as the 2004 Indian Ocean earthquake, have caused the rotation to speed up by around 3 microseconds. Post-glacial rebound, ongoing since the last Ice age, is changing the distribution of the earth's mass thus affecting the Moment of Inertia of the Earth and, by the Conservation of Angular Momentum, the Earth's rotation period.

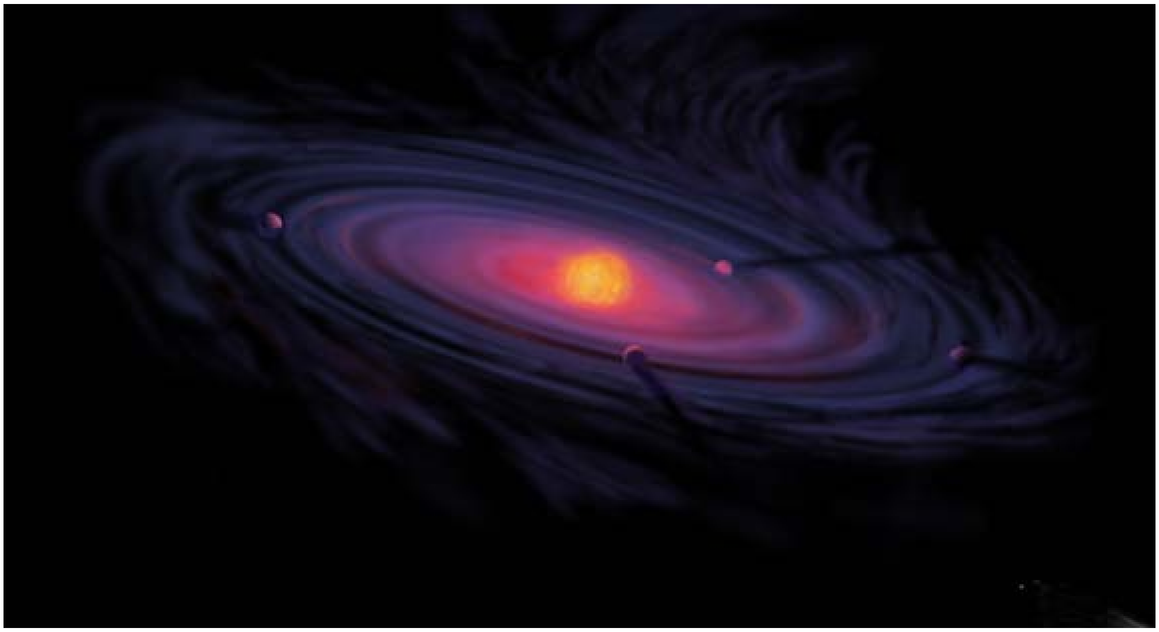
Precession

The axis of the Earth's rotation tends, like the axis of a gyroscope, to maintain its orientation with respect to inertial space. External forces acting on Earth from the Sun, Moon, and planets cause deviations from the fixed orientation. The large, periodic shift of the Earth's axis is called precession, while the smaller corrections are nutation and polar motion.

Physical effects

The velocity of the rotation of Earth has had various effects over time, including the Earth's shape (an oblate spheroid), climate, ocean depth and currents, and tectonic forces.

Origin



An artist's impression of protoplanetary disk

It is theorized that Earth formed as part of the birth of the Solar System: what eventually became the solar system initially existed as a large, rotating cloud of dust, rocks, and gas. It was composed of hydrogen and helium produced in the Big Bang, as well as heavier elements ejected by supernovas. As this interstellar dust is inhomogeneous, any asymmetry during gravitational accretion results in the angular momentum of the eventual planet. The current rotation period of the Earth is the result of this initial rotation and other factors, including tidal friction and the hypothetical impact of Theia.

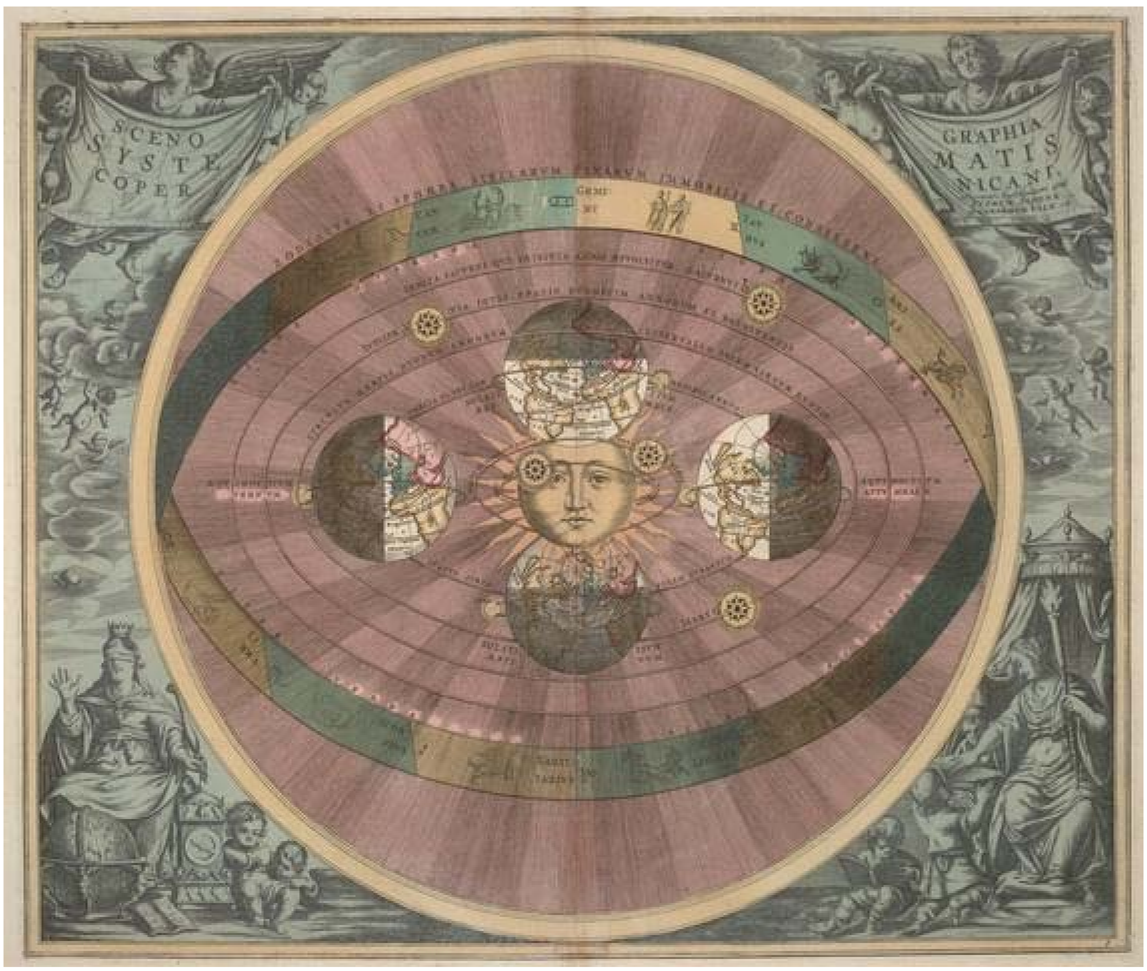
Evidence of Earth's rotation

In the Earth's rotating frame of reference, a freely moving body follows an apparent path that deviates from the one it would follow in a fixed frame of reference. Because of this Coriolis effect, falling bodies veer eastward from the vertical plumb line below their point of release, and projectiles veer right in the northern hemisphere (and left in the southern) from the direction in which they are shot. The Coriolis effect has many other manifestations, especially in meteorology, where it is responsible for the differing rotation direction of cyclones in the northern and southern hemispheres. Hooke, following a 1679 suggestion from Newton, tried unsuccessfully to verify the predicted half millimeter eastward deviation of a body dropped from a height of 8.2 meters, but definitive results were only obtained later, in the late 18th and early 19th century, by Giovanni Battista Guglielmini in Bologna, Johann Friedrich Benzenberg in Hamburg and Ferdinand Reich in Freiberg, using taller towers and carefully released weights.

Foucault pendulum

The most celebrated test of Earth's rotation is the Foucault pendulum first built by physicist Léon Foucault in 1851, which consisted of an iron sphere suspended 67 m from the top of the Panthéon in Paris. Because of the Earth's rotation under the swinging pendulum the pendulum's plane of oscillation appears to rotate at a rate depending on latitude. At the latitude of Paris the predicted and observed shift was about 11 degrees clockwise per hour. Foucault pendulums now swing in museums around the world.

Earth's orbit

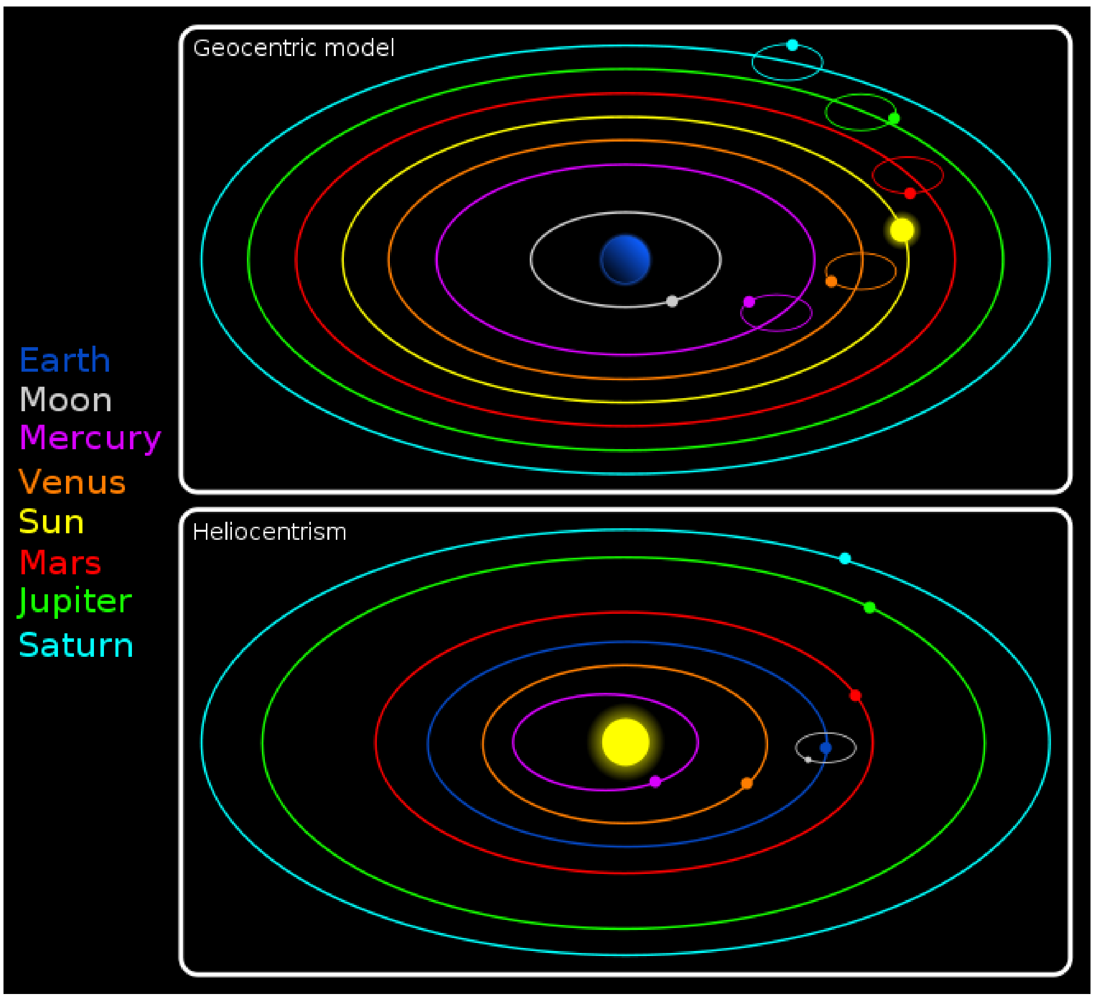


Heliocentric Solar System

In astronomy, the **Earth's orbit** is the motion of the Earth around the Sun, at an average distance of about 150 million kilometers, every 365.242199 mean solar days (1 sidereal year). This motion gives an apparent movement of the Sun with respect to the stars at a rate of about 1°/day (or a Sun or Moon diameter every 12 hours) eastward, as seen from Earth. On average it takes 24 hours—a solar day—for Earth to complete a full rotation about its axis relative to the Sun so that the Sun returns to the meridian. The orbital speed of the Earth around the Sun averages about 30 km/s (108,000 km/h), which is fast enough to cover the planet's diameter (about 12,700 km) in seven minutes, and the distance to the Moon of 384,000 km in four hours.

Viewed from a vantage point above the north poles of both the Sun and the Earth, the Earth appears to revolve in a counterclockwise direction about the Sun. From the same vantage point both the Earth and the Sun would appear to rotate in a counterclockwise direction about their respective axes.

History of study



Heliocentrism (lower panel) in comparison to the geocentric model (upper panel)

Heliocentrism is the theory that the sun is at the center of the Solar System. Historically, heliocentrism is opposed to geocentrism, which places the earth at the center. In the 16th century, Nicolaus Copernicus's *De revolutionibus* presented a full discussion of a heliocentric model of the universe in much the same way as Ptolemy's *Almagest* had presented his geocentric model in the 2nd century. This 'Copernican revolution' resolved the issue of planetary retrograde motion by arguing that such motion was only perceived and apparent, rather than real.

Influence on the earth

Because of the axial tilt of the Earth (often known as the obliquity of the ecliptic), the inclination of the Sun's trajectory in the sky (as seen by an observer on Earth's surface) varies over the course of the year. For an observer at a northern latitude, when the northern pole is tilted toward the Sun the day lasts longer and the Sun climbs higher in the sky. This results in warmer average temperatures from the increase in solar radiation reaching the surface. When the northern pole is tilted away from the Sun, the reverse is true and the climate is generally cooler. Above the arctic circle, an extreme case is reached where there is no daylight at all for part of the year. (This is called a polar night.) This variation in the climate (because of the direction of the Earth's axial tilt) results in the seasons.

Events in the orbit

By astronomical convention, the four seasons are determined by the solstices—the point in the orbit of maximum axial tilt toward or away from the Sun—and the equinoxes, when the direction of the tilt and the direction to the Sun are perpendicular. Winter solstice occurs on about December 21, summer solstice is near June 21, spring equinox is around March 20 and autumnal equinox is about September 23. The axial tilt in the southern hemisphere is exactly the opposite of the direction in the northern hemisphere. Thus the seasonal effects in the south are reversed.

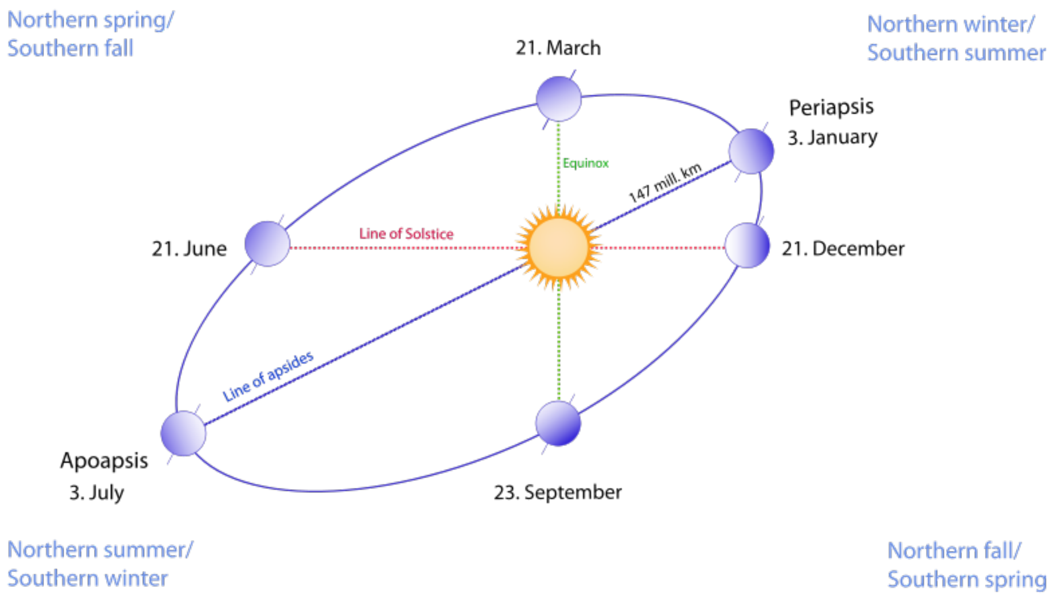
In modern times, Earth's perihelion occurs around January 3, and the aphelion around July 4. The changing Earth-Sun distance results in an increase of about 6.9% in solar energy reaching the Earth at perihelion relative to aphelion. Since the southern hemisphere is tilted toward the Sun at about the same time that the Earth reaches the closest approach to the Sun, the southern hemisphere receives slightly more energy from the Sun than does the northern over the course of a year. However, this effect is much less significant than the total energy change due to the axial tilt, and most of the excess energy is absorbed by the higher proportion of water in the southern hemisphere.

The Hill sphere (gravitational sphere of influence) of the Earth is about 1.5 Gm (or 1,500,000 kilometers) in radius. This is the maximum distance at which the Earth's gravitational influence is stronger than the more distant Sun and planets. Objects must orbit the Earth within this radius, or they can become unbound by the gravitational perturbation of the Sun.

Orbital Characteristics

epoch	J2000
aphelion	152,097,701 km, 1.0167103335 AU
perihelion	147,098,074 km, 0.9832898912 AU
semimajor	149,597,887.5 km, 1.0000001124 AU
eccentricity	0.016710219
inclination	Reference (0), 7.25° to Sun's equator
asc_node	348.73936°
arg_peri	114.20783°
period	365.256366 days, 1.0000175 yr
avg_speed	29.783 km/s, 107,218 km/h

The following diagram shows the relation between the line of solstice and the line of apsides of Earth's elliptical orbit. The orbital ellipse (with eccentricity exaggerated for effect) goes through each of the six Earth images, which are sequentially the perihelion (periapsis—nearest point to the sun) on anywhere from 2 January to 5 January, the point of March equinox on 20 or 21 March, the point of June solstice on 20 or 21 June, the aphelion (apoapsis—farthest point from the sun) on anywhere from 4 July to 7 July, the September equinox on 22 or 23 September, and the December solstice on 21 or 22 December.



Future

Mathematicians and astronomers (such as Laplace, Lagrange, Gauss, Poincaré, Kolmogorov, Vladimir Arnold, and Jürgen Moser) have searched for evidence for the stability of the planetary motions, and this quest led to many mathematical developments, and several successive 'proofs' of stability for the solar system. By most predictions, Earth's orbit will be relatively stable over long periods.

In 1988, Sussman and Wisdom found data using 'the Digital Orrery' which revealed that Pluto's orbit shows signs of chaos, due in part to its peculiar resonance with Neptune.

In 1989, Jacques Laskar's work showed that the Earth's orbit (as well as the orbits of all the inner planets) is chaotic and that an error as small as 15 metres in measuring the initial position of the Earth today would make it impossible to predict where the Earth would be in its orbit in just over 100 million years' time. Modeling the solar system is subject to the n-body problem.

The angle of the Earth's tilt is relatively stable over long periods. However, the tilt does undergo a slight, irregular motion (known as nutation) with a main period of 18.6 years. The orientation (rather than the angle) of the Earth's axis also changes over time, precessing around in a complete circle over each 25,800 year cycle; this precession is the reason for the difference between a sidereal year and a tropical year. Both of these motions are caused by the varying attraction of the Sun and Moon on the Earth's equatorial bulge. From the perspective of the Earth, the poles also migrate a few meters across the surface. This polar motion has multiple, cyclical components, which collectively are termed quasiperiodic motion. In addition to an annual component to this motion, there is a 14-month cycle called the Chandler wobble. The rotational velocity of the Earth also varies in a phenomenon known as length-of-day variation.