GLOBAL FUTURE RESEARCH

The ultimate fate of planet Earth

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One of the big questions humans always ask is, "what is the ultimate fate of our planet Earth?"

This is of keen interest as people want to know how humanity will survive into the future, even the deep future.

They want to know if, and when, humans will need to escape Earth and set up civilisation somewhere safer.

These questions on ultimate fate only linger briefly, however, as scientists have assured us that Earth will survive for a very long time—probably another several billion years—as our Sun is likely to have a long, stable life before evolving into a more threatening form.

Humans have more immediate threats and dangers – from pandemics, to errant asteroids, to climate change – and hence the long-term future is discounted to one of minimal concern but nevertheless considerable interest.

This Insight summarises current scientific knowledge and thinking about the long-term future of planet Earth and its ultimate fate. To begin, a brief history of Earth's origin and evolution to date provides context for the following discussion.

Birth

Somewhat surprisingly, the origin of planet Earth is still not awfully clear from a scientific standpoint and a number of alternative theories exist. The most prominent scientific theory suggests that our Solar System, which comprises our Sun and its family of eight orbiting planets including Earth (and many smaller objects – moons, rings, asteroids, comets, meteorites, etc), formed essentially at the same time and as part of the same overall process around 4.5-4.6 billion years ago. The Sun and planets were created almost simultaneously out of a 'solar nebula' – a cloud of gas and dust within the outer reaches of our Milky Way galaxy. Our Solar System is located near the edge of one of the spiral arms of the Milky Way called the Orion Spur, orbiting around the centre of the galaxy at a distance of 27,000 light years.

You will notice immediately that our Solar System is a lot younger than the universe, whose origin dates back some 13.8 billion years to the Big Bang. It is also much younger than its galaxy, the Milky Way, whose age is estimated at 13.6 billion years—forming soon after the Big Bang. The relatively young age of our Solar System is important, because the composition of our solar nebula allowed rocky planets, including the Earth, to form from the dust particles present. The composition of the solar nebula by mass is estimated at 74% hydrogen, 24% helium and 2% condensed materials or 'dust particles'. These dust particles are made up of carbon, nitrogen and oxygen, with about 25% by mass being 'metals' (such as iron, magnesium, calcium, aluminium, chromium, manganese, potassium and titanium) and silicates (rock). These materials originated from nuclear fusion processes in stars some 8-15 times the mass of our Sun which have a shorter life and explosive supernova endings. Through supernova explosions, these heavier elements are thrown out into the interstellar medium – the birthplace of future stars like ours.

So, Earth began as dust particles within a gas cloud. It does seem at first surprising that dust particles could form into rocky planets and indeed the sun form from a very tenuous gas cloud comprised of hydrogen and helium. This happens due to gravity, whose reach stretches throughout the universe. Gravity pulls matter together whilst gas pressure can resist gravity. One of the fundamental questions is what triggered the gravitational collapse of an interstellar cloud to form our solar nebula. It could have been a random density fluctuation, or a shock wave from a supernova explosion or some other mechanism, but what we do know is that new stars are forming all the time in the Milky Way and other galaxies – hence the trigger must be quite common.

As our solar nebula collapsed under gravity, most of the material, in fact ultimately 99.9% of it, was pulled into the centre where our protosun formed within about 100,000 years (at this stage nuclear fusion had not commenced in the centre of the protosun). The surrounding and contracting solar nebula also began to rotate faster as the solar nebula contracted, flattening into a protoplanetary disc, which accounted for the remaining 0.1% of the solar nebula mass. Thin protoplanetary discs have been directly observed in recent years around young stars forming in our galaxy.

Our protosun continued to contract under gravity, increasing in pressure and temperature at its core, until after about 50 million years, with a core temperature of some 10 million degrees,

nuclear fusion of hydrogen into helium commenced. This created a vast source of energy and enough pressure to stabilise the Sun from further gravitational contraction. This marked the Sun's entry as a main sequence star—which it remains today.

The dust particles in the solar nebula orbited the protosun independently under gravity and eventually settled out into a disc which became the plane of planet formation. Gravity intervened again, fragmenting the dust disc into local clumps of dust particles which themselves coalesced into larger bodies over time through collisions and further particle accretion from the disc. Ultimately protoplanets began to dominate orbital zones, sweeping up smaller bodies and particles in their path.

By the time protoplanets were forming, the Sun was very hot, meaning planets forming out to about four times the orbit of Earth could only accrete non-volatile compounds such as iron, nickel, aluminium and silicates – these were the building blocks of the so-called terrestrial planets, Mercury, Venus, Earth and Mars. The giant planets formed further out where it was cooler, initially from volatile icy compounds that remained solid beyond the 'frost line', a point between Mars and Jupiter. The abundant icy compounds allowed rapid protoplanetary accretion to a size that could capture hydrogen and helium, the main elements in Jupiter and Saturn - the gas giants. The growth phase of planets concluded when the Sun's solar wind became so strong it blew the remaining solar nebula gas and dust into interstellar space, likely limiting Uranus and Neptune's growth potential.

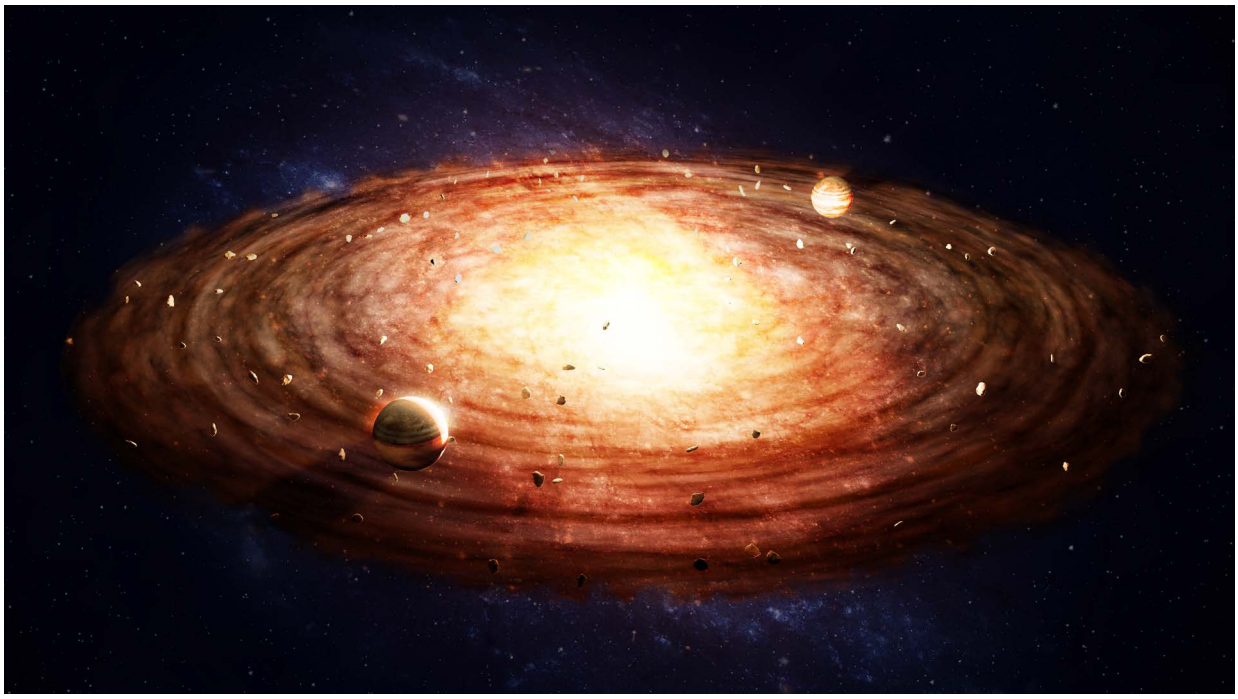


Illustration of the birth of a solar system- protoplanetary disc. Mopic, Shutterstock.

Evolution to present time

Earth's formation process was largely complete within 10–20 million years. This relatively short time meant that the Earth formed hot and molten, through converting the kinetic energy of impacting material into heat, supplemented by internal radioactivity and gravitational compression. This molten state allowed liquid iron to sink to the core while lighter silicates formed the mantle and crust. The layered structure of the primitive Earth may have been evident as early as 10 million years after formation began. The planet's magnetic field probably formed around this time. The Earth's gravity may have captured some of the gases from the solar nebula (if not blown away by the solar wind) which made up the planet's early atmosphere.

The very early history of Earth can be determined by examining our oldest rocks which date back to about 4 billion years. Even older crystals within the rocks can be dated back to 4.4 billion years – these detrital zircon crystals show evidence of contact with liquid water indicating oceans had already formed at this time.

Volcanism started quickly in the forming Earth due to the large internal heat content and geothermal gradient. This early volcanic activity transported gases and water out from the Earth's interior. This formed Earth's second atmosphere comprising water vapour, carbon monoxide, carbon dioxide, hydrochloric acid, methane, ammonia, nitrogen and sulphur gases. Eventually rain started, forming freshwater oceans initially.

Life on Earth first appeared around 3.7 billion years ago according to fossils preserved in Greenland rocks.

These early life forms were anaerobic organisms appearing on an ancient seabed.

About 2 billion years ago cyanobacteria became the first organisms to produce oxygen, coinciding with more sunlight penetrating the Earth's atmosphere. For the next billion years all life on Earth was single-celled organisms, mainly bacteria and algae. Around 900 million years ago the first multi-celled organisms appeared – containing cells of different types and functions.

540 million years ago a sudden increase in the number of species occurred – known as the Cambrian explosion. This gave rise to the first skeletal and shelled organisms, molluscs and then vertebrates, and the colonisation of land from the ocean. By 400 million years ago the first four-legged animals appeared, followed by amphibians, insects and reptiles. Dinosaurs first appeared around 250 million years ago and became a dominant lifeform within 50 million years, when the first mammals and birds emerged. Plant species were also diversifying, with the first flowering plants occurring.

The fifth mass extinction of species occurred 66 million years ago due to one or more large asteroid impacts. This led to the extinction of all large animal species including dinosaurs. The end of the dinosaurs benefitted mammals, who quickly grew and diversified, spawning the primates—lemurs, gibbons, bonobos, orangutans, gorillas, and eventually humans. Many mammalian species grew to a huge size known as megafauna (like the Mammoths) who roamed the planet until around 10,000 years ago, when they too disappeared.

Origin of humans

The first of our human ancestors is thought to have evolved 6-7 million years ago, showing primitive forms of bipedalism— considered a defining feature of humans compared to other primates. A full biped, *Ardipithecus*, emerged 5.6 million years ago. Other human features that became more prominent over time include increasing brain size, lengthening gestation and infancy, decreased sexual dimorphism and the power and precision of hand grip. About 2.8 million years ago, the first of the genus *Homo* appeared as *Homo habilis*, known for their use of stone tools. Over the next million years, brain size doubled with the arrival of *Homo erectus* and *Homo ergaster*—the first to use fire and complex tools and leave Africa to inhabit Asia and Europe 1.3-1.8 million years ago.

Homo sapiens emerged in Africa around 300,000 years ago. Anatomically modern *homo sapiens* were present in eastern Africa around 200,000 years ago although the oldest fossil dates back to 315,000 years in Morocco. Genetic data suggests that the species went through a bottleneck in which the population became very small before rapidly spreading out globally – to China 80,000-120,000 years ago, to Australia 60,000-65,000 years ago, to Europe 43,000-45,000 years ago and the Americas 13,000-14,000 years ago. Genetic studies show that differences between populations geographically far apart are miniscule compared to differences within these populations.

Most likely future of Earth

The future of planet Earth is of course uncertain, but science gives a credible future scenario. Of most immediate interest to humans is whether our Sun is stable for long enough to not radically affect the Earth into the foreseeable future. This is indeed the case according to current science. The Sun has been stable for 4.6 billion years and, due to its medium size ($2x10^{30}$ kg or 333,000 times the size of Earth), has a long life yet in this stable phase. The larger the star, the shorter is its stable life before radically changing form. Earth's most probable fate is absorption by the Sun in about 7.5 billion years when the Sun has expanded into its red giant phase, swallowing up Mercury, then Venus and possibly Earth. While this fate is considered most likely, Earth could still survive.

Our Sun, a medium size main sequence star, is projected to remain stable for another few billion years. This is because the Sun's nuclear energy, generated by converting hydrogen into helium, will continue for a long time yet.

The Sun is currently 75% hydrogen and 24% helium but nearly half the hydrogen in the core

of our Sun, where nuclear fusion is taking place, has been converted into helium. As the hydrogen component in the Sun's core decreases, the core contracts under gravity until the temperature and pressure rise to maintain hydrostatic equilibrium. This results in a higher core temperature which causes the remaining hydrogen in the core to undergo fusion at a faster rate. This in turn leads to a steady increase in the energy output, or luminosity of the Sun.

The Sun's luminosity has increased 30% since joining the main sequence, increasing in a nearly linear fashion by about 10% every billion years. In the next billion years, with the Sun 10% hotter again, the Earth's oceans will begin to evaporate, loading the atmosphere with water vapour. Water vapour is a potent greenhouse gas and will trap more of the Sun's heat, causing a runaway greenhouse effect that sends the temperatures soaring. At the same time, water held towards the top of Earth's atmosphere will be split into hydrogen and oxygen by high energy solar particles. The hydrogen and oxygen will escape the Earth's atmosphere, with the net result that the Earth loses water. This process will be gradual but, in about 3 billion years, all life on Earth, with the exception of the most resistant microorganisms, will be lost.

Scientific models that predict when water and life will be lost from the Earth often differ in their timing. The earliest time Earth could become inhospitable to life is before 1 billion years, due to complex interactions between rocks, oceans, plate tectonics and a heating planet. Other models predict life will last longer, but the fate is the same – Earth will become dry, hot and lifeless, not dissimilar to Venus is today.

Illustration of a planet with a giant red sun. Vladimir Arndt, Shutterstock.

While life may have gone, Earth as a rocky mass will continue to orbit the Sun—and the Sun, in turn, will continue to orbit the centre of the Milky Way. In around 4 billion years, the Milky Way is projected to collide and merge with the 'nearby' Andromeda galaxy. With the Milky Way containing around 300 billion stars and the Andromeda galaxy 1 trillion stars, you might expect to see fireworks, but the chance of even two stars colliding in the merger is negligibly small because of the huge distances between stars. Although stars may not collide, the super massive black holes at the centre of each galaxy are likely to coalesce.

Simulations suggest some alternative outcomes for our Solar System – our Sun could be torn apart by the tidal forces of the black hole if it gets too close, or could be catapulted out of the merged galaxies, or could be swept much further out from the centre of the merged galaxy but still remain within it. If the Sun orbits further out or leaves the galaxy altogether, impacts on its planets, including Earth, may be minimal.

Should our solar system remain intact after the merger of the two galaxies, then it will be the ongoing evolution of our Sun that will have the next biggest effect on Earth. In about 5 billion years from now, the hydrogen fuel in the Sun's core will finally be exhausted, leaving only helium. At this time the temperature in the core is too low to ignite helium burning and fusion ceases. The core contracts under gravity and heats up until hydrogen fusion commences in a thin shell around the core. This new source of energy expands the outer layers of the Sun with the outermost layers cooling. The large, cooler Sun turns red – entering the so-called red giant phase.

In the outer layers of the red giant Sun, cooling allows nuclei to capture electrons to form neutral atoms, at the same time emitting photons that are absorbed by adjacent atoms. This causes the outer layers of the Sun to heat up, expand outwards further and cool again, where the process repeats itself. The red giant Sun becomes so large and distended that the gravitational hold on the outer layers is weakened and they may be easily lost to space through the helium flash or other internal events. At its peak, our red giant Sun will be a huge 250 times bigger than now, but it will also have lost a third of its mass.

Back in the helium core of the Sun, the ongoing contraction eventually heats the core to 100 million degrees at which point helium burning starts, converting helium into carbon and oxygen. However, the core cannot contain the vast energy produced when helium burning commences and releases an uncontrolled burst of energy called the helium flash. The core expands, then contracts, heats up again but this time with more controlled helium burning. Eventually the helium in the Sun's core is converted entirely into carbon and oxygen, and the core contracts again and heats up – however not enough to initiate carbon burning.

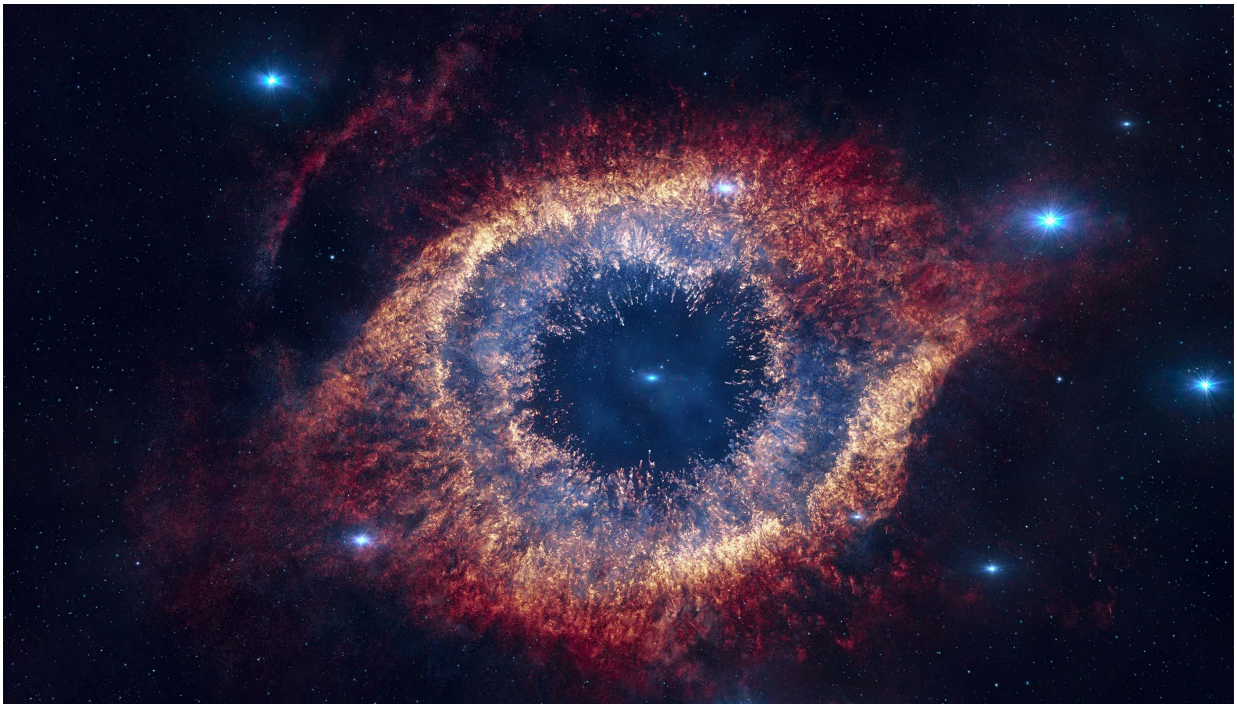
During its relatively brief (130 million year) helium-burning phase, the red giant Sun will expand past the orbit of Mercury, and then Venus. By the time it approaches the Earth, it will have lost a large amount of matter, reducing its gravitational pull on the planets and causing them to spiral outwards from the Sun. Eventually the red giant Sun will expand to where Mars orbits today, but Mars will have moved further away, escaping absorption by the Sun. Earth, on the other hand, has two options: either escape the expanding Sun or be consumed by it.

In 2008 scientists established that Earth will not escape the Sun's expansion, even though the Earth could expand to an orbit 50% more distant than where it is today. To survive, Earth would need to be 15% further from the Sun than its current orbit. The expanding Sun will engulf the Earth just before it reaches the end of the red giant phase, with the Sun still having another quarter of the current Earth-Sun distance to grow.

As the red giant Sun expands to near Earth's orbit, tidal interactions and drag from the chromosphere will cause the Earth to spiral into the Sun. The intense heat will melt and then vaporise the Earth's surface, gradually removing the Earth's crust and mantle, until only the iron core remains. As heat increases further, the core will also melt down and vaporise. Earth could vanish in as little as 200 years through this process.

Inside the Sun, the carbon-oxygen core contracts but it never gets hot enough to ignite carbon burning. Contraction continues until electrons can no longer be compressed, at which stage they are said to be degenerate. The remnant core, with a hot surface temperature of 10,000 degrees, and size comparable to the Earth today, becomes a white dwarf star. Its outer envelope blows off into space, becoming a planetary nebula. The predicted final mass of the Sun is 54% of the present value, consisting primarily of carbon and oxygen. The white dwarf Sun slowly radiates its energy away, fading eventually into an invisible black dwarf. This is the fate of most stars in the universe, which will slowly become darker.

If the Earth is not absorbed by our red giant Sun, it could have some alternative fates.



The Helix Nebula is a large planetary nebula located in the constellation Aquarius. Its white dwarf star is clearly seen at its centre. Elements of this image furnished by NASA. Shutterstock.

One is the ejection of our Solar System from our galaxy by a process called violent relaxation – the gravitational ejection of one star from a group of stars that leaves the remaining stars more tightly bound. This could happen on a timescale of 10^{19} (10 quintillion) years, propelling our Solar System into empty space. If Earth is not destroyed by the expanding red giant Sun and the Earth is not ejected by violent relaxation, there is a possibility that our black dwarf Sun may collide with another black dwarf, producing a Type 1a supernova explosion and effectively destroying the remainder of the Solar System. This could occur within 10^{21} years.

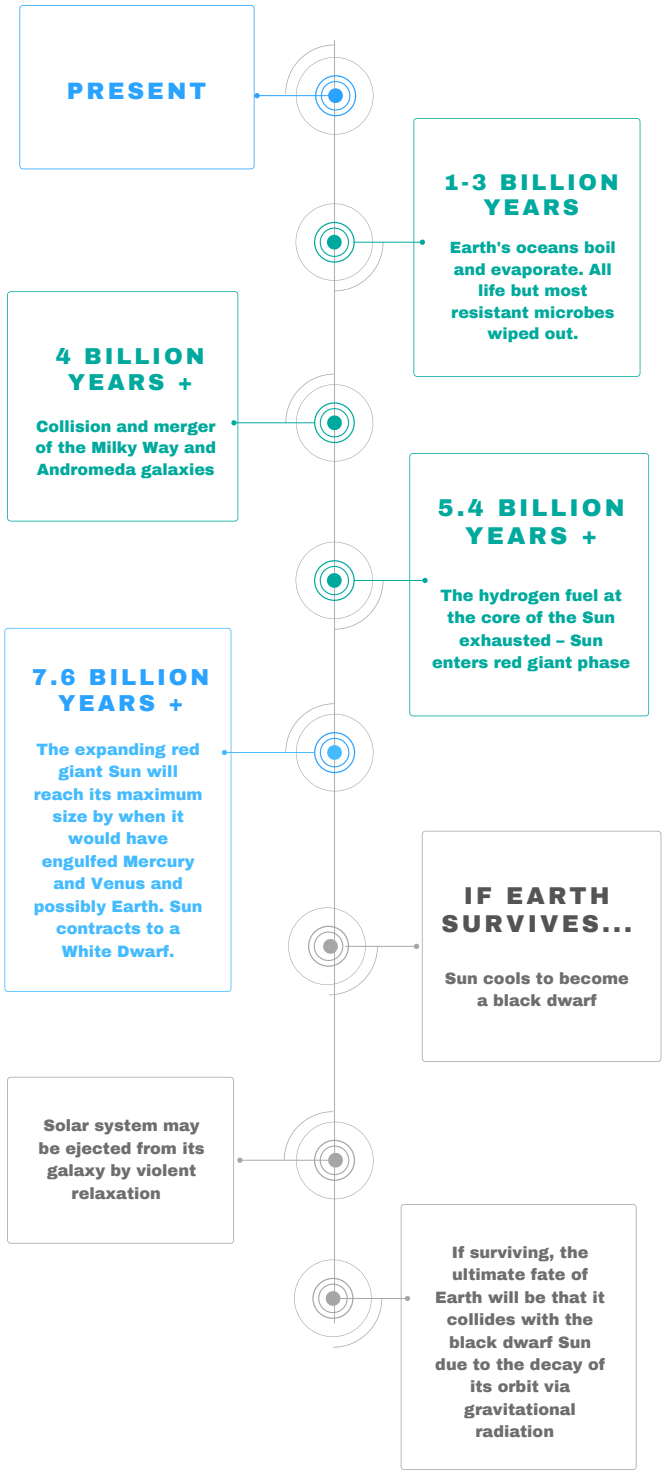
Alternatively, another body could collide directly with the Earth, bringing it to an end. However, whilst random collisions are possible, they are unlikely.

If our Solar System is ejected into space, then eventually Earth's orbit will decay, through gravitational radiation, slowly spiralling into the black dwarf Sun. This could take 10^{20} to 10^{25} years or longer.

In conclusion, we can see from the foregoing that planet Earth has a long life yet, and possibly a very long life. However, its ability to support animal and plant life will begin to decline in around a billion years when it heats up and dries out. That's just another 20% beyond its existence to date. Humans will likely need to seek a new home in the universe well before then – a subject of further investigation in GFR Insights.

Time since birth	Date compared to present	Event
0	-4.54 By	Birth / formation of the Earth
0-10 My	-4.53 By	Formation of the Earth's core, mantle and crust
0-10 My	-4.53 By	Initiation of Earth's magnetic field
0-10 My	-4.53 By	Capture of Earth's primordial atmosphere
0-10 My	-4.53 By	Active volcanism
140 My	-4.4 By	Detrital zircon crystals show evidence of having undergone contact with liquid water, suggesting that the Earth already had oceans at this time.
840 My	-3.7 By	Earliest fossil evidence of life on Earth
2.44 By	-2.1 By	Cyanobacteria become the first organisms to exhale oxygen into the Earth's atmosphere
3.64 By	-900 My	Simple multi-celled organisms start to appear
4 By	-540 My	Suddenly large numbers of species appear - the Cambrian explosion
4.14 By	-400 My	The first four-legged animals appear
4.29 By	-250 My	First emergence of dinosaurs
4.34 By	-200 My	First mammals appear
4.47 By	-66 My	The cretaceous-tertiary mass extinction event- dinosaurs wiped out
4.512 By	-2.8 My	First *homo genus* appears
4.534- 4.541 By	-300,000 y	*Homo sapiens* appears
	-10,000 y	The Younger Dryas extinction event
		Present

Planet Earth - from the present



Glossary

Anaerobic: Living or existing in the absence of oxygen.

Asteroid: Small rocky bodies that orbit the Sun, most commonly found between the orbits of Mars and Jupiter.

Big Bang: The origin of the universe 13.8 billion years ago from a single point in time and space, including a rapid expansion of matter of extreme density and temperature to eventually form the universe we observe today.

Bipedalism: Having two feet or using only two feet for locomotion.

Black dwarf star: A white dwarf that has cooled to the point that it emits no detectible heat or light. As this process takes longer than the age of the universe, no black dwarfs currently exist.

Black Hole: A region of space-time where gravity is so great that no particle or light can escape it.

Comet: Small icy bodies that orbit the Sun usually at great distances but when approaching the Sun form a large visible head and sometimes a tail.

Cyanobacteria: Also called blue-green algae – an ancient group of photosynthetic microbes that live in water.

Dust: Cosmic or interstellar dust consists of tiny solid particles occupying the space between stars. They are made of elements heavier than hydrogen and helium.

Frost line: The distance from the protosun into the solar nebula where it is cold enough for volatile compounds such as water, ammonia, methane, carbon dioxide and carbon monoxide to condense into solid ice grains.

Galaxy: A system of millions or billions of stars and their solar systems, together with gas and dust, held together by gravitation.

Genus: A biological classification that ranks between family and species.

Gravitational radiation: Disturbances in the curvature of space-time, generated by accelerated masses, that propagate as waves outward from their source at the speed of light.

Greenhouse effect: The trapping of the Sun's radiation in the Earth's lower atmosphere due to the greater transparency of the atmosphere to visible radiation from the Sun that to infrared radiation emitted from the Earth's surface.

Helium flash: A very brief thermal runaway nuclear fusion of large quantities of helium into carbon in the core of low-medium mass stars during their red giant phase.

Interstellar medium: The space between stars. It is composed primarily of gas and dust at very low densities.

Light year: The distance light can travel in one year (9.46×10^{12} km).

Luminosity: A measure of the brightness or power of a star, measured as the amount of energy emitted from its surface.

Main sequence star: A star that is fusing hydrogen in its core which maintains a stable balance between outward pressure from nuclear fusion and inward gravitational forces.

Metals: In astronomy, 'metals' refer to all elements heavier than hydrogen and helium.

Meteoroid: A small, rocky or metallic object travelling through interplanetary space.

Milky Way Galaxy: A large, barred spiral galaxy containing several hundred billion stars including our own Solar System and a super massive black hole at its centre.

Moon: A celestial body that orbits a planet as a natural satellite.

Our Solar System: The collection of eight planets and their moons and rings in orbit around the Sun together with the smaller asteroids, meteoroids and comets.

Photon: A particle representing a quantum of light or other electromagnetic radiation.

Photosynthesis: The process by which green plants and some other organisms use sunlight to synthesise nutrients from carbon dioxide and water, generating oxygen as a by-product.

Planet: A celestial body that orbits a star that is massive enough to be rounded by its own gravity but not massive enough to support thermonuclear fusion in its interior.

Planetary nebula: A shell of gas that is ejected from a star in transition from a red giant to a white dwarf.

Protoplanet: A planetary embryo that is in the early stages of forming a planet.

Protoplanetary disc: A rotating circumstellar disc of gas and dust surrounding a newly formed star that will form into a solar system.

Protosun: The sun in its early stage of formation before becoming dense and hot enough to ignite nuclear fusion in its interior.

Red Giant star: A low-medium mass star that has exhausted hydrogen fuel in its core and subsequently grown many times so that its outer atmosphere is cooler, giving it a reddish-orange hue.

Sexual dimorphism: The condition whereby the two sexes of the same species exhibit different characteristics beyond the differences in their sexual organs.

Solar nebula: The interstellar cloud of gas and dust from which our Solar System originated.

Spiral arm: Long thin arms comprising stars, gas and dust that spiral out from certain galaxies like the Milky Way.

Supernova: A luminous stellar explosion brought about either by the sudden gravitational collapse of the core of a massive star in its final evolutionary stages or the triggering of a white dwarf into runaway nuclear fusion.

Supernova shock wave: An exploding supernova creates a shock wave through the star and on into the surrounding interstellar medium creating a shock wave in the interstellar gas in the forward direction and also in the reverse direction, back into the supernova ejecta.

Violent relaxation: The gravitational ejection of one star from a group of stars that leaves the remaining stars more tightly bound.

White dwarf star: The remnant of stars up to 10 solar masses after nuclear fusion has ceased, comprising very dense electron degenerate matter within the volume of a planet and initially very hot.

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Professor Nick Schofield is the Founder and Director of Global Future Research, established in February 2021. Nick has a broad range of national and international experience across a wide range of sectors and held numerous leadership positions. Nick has a BSc (Hons) in Physics from Imperial College, London University and a Doctor of Philosophy in Astrophysics from York University, UK. He is a Visiting Professorial Fellow at the University of NSW (Sydney), an Adjunct Professor at Murdoch University (Perth) and Fellow of the Royal Society (NSW).

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