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Beyond Darwin: from the elements to the Universe

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Resum. La paraula evolució era utilitzada de diferents maneres, tant abans com després dels temps de Darwin. Per exemple, pels Lamarckians es referia a la primera (defectuosa) teoria d'evolució biològica; per Charles Lyell, als processos incrementals que produïen els trets geològics de la terra; per Herbert Spencer, a l'origen i el desenvolupament d'institucions culturals i polítiques, i per l'avi de Darwin, al desenvolupament gradual d'una planta o un animal jove des de la llavor o l'ou. Més recentment, s'utilitza per a caracteritzar el desenvolupament de les societats d'insectes i animals, el desenvolupament de llengües humanes i institucions polítiques, el naixement, el creixement i la mort d'estrelles i galàxies, el desenvolupament de l'Univers neonatal, i molt més. Aquesta xerrada se centrarà en diversos aspectes de l'evolució que es troben fora del context biològic, com ara la creació i descoberta dels elements químics, l'evolució estel·lar, amb una referència particular al nostre Sol, i el desenvolupament de certs conceptes científics.

Paraules clau: Charles Darwin · evolució · història de la ciència · l'Univers · elements químics

Summary. The word 'evolution' has and has had many meanings, both before and after Darwin's time. For example, to Lamarckians it referred to the first (flawed) theory of biological evolution; to Charles Lyell, the incremental processes that produced the geologic features of the Earth; to Herbert Spencer, the origin and development of cultural and political institutions; and to Darwin's grandfather, the gradual development of a young plant or animal from its seed or egg. More recently, it has been used to characterize the development of insect societies, the development of human languages and political institutions, the birth, growth, and death of stars and galaxies, the development of the neonatal Universe, and much more. This article focuses on various aspects of evolution lying outside the biological context, such as the creation and discovery of the chemical elements, stellar evolution with particular reference to our Sun, and the development of certain scientific concepts.

Key words: Charles Darwin · evolution · history of science · the Universe · chemical elements

Introduction

So far as I am aware, Charles Darwin did not use the term evolution even once in the first edition of *On the Origin of Species*, except for a form of the word that concludes his great opus:

> "There is grandeur in this view of life, with its several powers, having been originally breathed into a few forms or into one; and that, whilst this planet has gone cycling on according to the fixed law of gravity, from so simple a beginning endless forms most beautiful and most wonderful have been, and are being, evolved."

Today, however, the concept of evolution applies not only to the alteration and diversification of living organisms, but also to the origin and development of stars, galaxies, the universe, or virtually any aspect of the natural world or human (and other) societies and cultures.

Darwin lived in interesting times

It is interesting to examine, albeit briefly here, the period in which Darwin wrote his great book.

In 1856, Gregor Mendel began his studies of inheritance. This work was forgotten for many years, approximately half a century. In the same year, Rudolf Clausius propounds the 2nd law of thermodynamics. A year later, in 1857, a young British man, Henry Perkin, patents the first aniline dye and calls it

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mauve, marking the beginning of the synthetic chemistry industry. It was also the year of India's First War of Independence, which is sometimes called The Sepoy Mutiny. In 1859, Charles Darwin publishes *On the Origin of Species*. That same year, Charles Dickens publishes *A Tale of Two Cities*, Gustav Robert Kirchhoff determines the chemical composition of the Sun spectroscropically. This was a great surprise because philosophers, August Comte in particular, had said some decades earlier, "How much we are learning about the heavens," and he was saddened by the certainty that we would never learn the chemical composition of the stars. Ten years later, we did. Also in 1859, Edwin Drake drills the first oil well (in Pennsylvania), and France declares war on Austria, which is also known in Italy as the second Italian War of Independence. In 1860, Louis Pasteur explains fermentation and Abraham Lincoln is elected US president. In 1861, James Clerk Maxwell unifies electricity and magnetism, which to the field of Physics is as exciting as the publication of *On the Origin of Species*. That same year, Ignaz Semmelweis publishes his study of childbed fever, which was more or less ignored, and America begins its Civil War. In 1900, Mendel's work on inheritance is rediscovered, and the mechanism underlying the origin of species is revealed. It is fitting for this list to begin and end with Mendel, as it is just as fitting that the magical letters DNA appear in Darwin's name.

No scientist is infallible, not even Darwin

The year 2009 is the bicentennial of Charles Darwin's birth and the sesquicentennial of the publication of the *On the Origin of Species*. These are certainly events worth celebrating, but we might also recall several examples of errors committed over the years by some of our most outstanding scientists, in physics as well as in biology.

Johannes Kepler (1571–1630). We are all familiar with Kepler's law of planetary motions, yet he read horoscopes for a living and propounded a mystical explanation for the values of the radii of the planetary orbits.

Galileo Galilei (1564–1642). Surely a great genius, yet he rejected Kepler's elliptical orbits. He also had a problem with, and never could understand, the operation of a suction pump. He tried to explain why it could never pump water more than 30 feet, proposing a solution which was complete nonsense. The problem was eventually solved by Torricelli, with his realization "that we live under an ocean of air."

Isaac Newton (1643–1727). A very great scientist, perhaps the greatest scientist ever, was so flushed with the success of his gravitational force that he tried his luck twice more, in the first introducing another force, which does not exist, to explain Boyle's law, defining the relationship between the pressure and volume of a gas, and in the second yet another hypothetical force, which also does not exist, between the particles of light and the particles of matter that would explain the bending of light as it enters a new medium, to deduce Snell's law.

Albert Einstein (1879–1955). As great a scientist perhaps as Newton, Einstein, who had done so much to create quantum mechanics, was never willing to accept it. Instead, he ignored all of atomic and nuclear physics as he followed the chimera of a Unified Field Theory.

Jean-Baptiste Lamarck (1744–1829). Lamarck constructed one of the first theoretical frameworks of organic evolution, yet he believed that organisms arose in their simplest forms via spontaneous generation and that the natural movements of fluids in living organisms drove them toward ever greater levels of complexity.

Charles Darwin (1809–1882). Lastly we come to Darwin, who seemed unable to abandon the old theory of evolution, Jean-Baptiste Lamarck's notion of the heritability of acquired characteristics. And, in *On the Origin of the Species* for example, he writes, "There can be no doubt that use in our domestic animals has strengthened and enlarged certain parts and disuse diminished them; and that such modifications are inherited." Today, we certainly know they are not, but being merely mortal in no way lessens Darwin's greatness.

The abuse of scientific terms

Let's turn now to the use and misuse of words. Scientific terms, in particular, are often used in crazy ways. Here are some examples I have collected.

Jiang Zemin, the leader of China some years ago said, "The *theory of relativity* worked out by Mr. Einstein... can also be applied to the political field." Lawrence Lessig, a well-known financial expert, has expressed, "This is the *Heisenberg uncertainty principle* for financial markets." Marie-Louise von Franz, a well-known psychoanalyst, a student of Jung, wrote that "Bohr's idea of *complementarity* is especially interesting to Jungian psychologists." Barbara Sher, a lifestyle coach said, "Doing is a *quantum leap* from imagining." Reverend Rick Warren, the preacher who gave a service at the time of the nomination of President Barack Obama said, "*Exponential* growth begins with *exponential* thinking." Maharishi Mahesh Yogi, the former leader of the Transcendental Meditation Movement, has discussed at length "*Quantum cosmology* and the *unified field* of pure consciousness." And on a television show, Babylon-5, "With this *wave-particle* theology, all gods and goddesses could be said to exist." Finally, the Oxford English Dictionary, as found on the web, states that, "*Evolution* is a cosmic force that reveals the potential that lies in the universe."

'Evolution' evolves

If you look up the word "evolution" you will find that it can mean the development of a mathematical curve; it can be a dance movement; or it can refer to such things as a military maneuver, the chemical release of a gas, or even an idea, a device, a language or a society. Here are several examples of the relevant usages of the word evolution back in Darwin's time:

- In 1832, Charles Lyell, a famous geologist, wrote, "The testacea of the ocean existed first, until some of them, by

gradual evolution, were improved into those inhabiting the land." I include this example because, in the Oxford English Dictionary, this is the first use of the word evolution in this context.
- Again, before Darwin, in 1851 J.T. Nichol stated, "As on Earth, there [are] also–ruling these high Heavens–vast processes of evolution."
- Edward Forbes wrote, in 1854, "Hence have arisen the... evolution of all organized types, during the course of time, from one rudimentary prototype; that of the succession of distinctly originating forms of animals and vegetables."
- Herbert Spencer, in 1857, "The advance from the simple to the complex through a process of successive differentiations is seen alike in the earliest changes of the universe... the geological evolution of the earth and of every single organism on its surface." This is another use of the word referring to the earliest changes in the universe.
- Darwin himself did not use the word evolution until 1873. The first published use of the word evolution by Darwin that I have found is, "As of the present day, almost all naturalists admit evolution in some form."
- Finally, a quote from 1880 from *Popular Science*, "I should regard a teacher of science who denied the theory of evolution as being as incompetent as one who doubted the Copernican theory." Today, unfortunately, in the United States there are teachers who not only deny evolution, but have never heard of the Copernican theory.

Most things evolve

Most things evolve, in one or another sense. From the natural world, we can mention plants, animals, microbes, land, oceans, our atmosphere, planets, stars, galaxies, atoms elements, or the universe. Cultural and man-made elements evolve as well, such as languages, literature, the arts, cities, nations, empires, science, technology, religion, agriculture, architecture, advertising, music, medicine, manufacturing, communication, computers, or genetic programs.

Everything evolves. But of course, there is something special about Darwinian evolution. In Darwinian evolution there is not just a change in variation, but there is also a cause, natural selection. And very few of the things listed above evolved by natural selection. Some do. Science, for example, evolves through natural selection, and computer programs can be made to evolve through neo-Darwinian evolution. I've seen a magnificent display on the web of the Mona Lisa being approximated in an evolutionary fashion by overlapping 55 rectangles on one another. After approximately 700,000 iterations you have a virtually perfect image of the Mona Lisa.

So there can be evolution outside of the biological context, although there is not always natural selection; and not always do the fittest survive. The evolution of such things as cities and societies are certainly subject to selective pressures, but this can hardly be said of the evolution of stars, galaxies, and the universe. For example, a large cloud of gas with the mass and composition of the Sun will certainly "evolve" into a star much like the Sun, while we could scarcely predict that primitive organisms on Earth would inevitably have evolved into rabbits. Evolutionary computer programs, on the other hand, are truly neo-Darwinian. They are designed to mimic biological evolution through random variation with imposed selective pressures. Such notions may someday lead to significant applications to biology, engineering, design, and mathematics.

Science evolves

As science evolves, it experiences selective pressures. Only the fittest scientific notions survive: those that best fit the data. Others, like Lamarck's flawed theory of evolution or Franz Mesmer's animal magnetism, are discarded. In biological evolution we are left with species that no longer exist today, extinct species. That has been quite a surprise and a disappointment to the more religious among us, because species created by God should never have disappeared, but disappear they do. And so it is that concepts in physics arise and disappear. Here is a short list of some of the extinct fauna of Physics:

The quintessence, or the fifth element of which the stars were made; geocentrism, the idea that everything rotates around the Earth; the abhorrent vacua or vacuum, which did not exist until Torricelli produced it; epicycles, equants, and eccentrics were tricks that allowed circular motion to explain the peculiar motion of the planets; phlogiston and caloric were two fundamental elements of nature, phlogiston was responsible for combustion, a theory abolished by Antoine Lavoisier, and caloric was the element of heat, a theory that was superseded when we realized that heat is a form of motion; Cartesian vortices were an alternative to Newton; action-at-a-distance, the interaction of two objects separated in space with no known mediator of the interaction, was much discussed long ago; vitalism was the idea that there is something special about living phenomena, that life cannot be described in terms of chemistry and physics, and most people, although unfortunately not all of them, have abandoned this concept; immutable atoms, the idea that atoms could not be taken apart, although of course they can; relativity was invented by Galileo but it was a different kind of relativity, which is wrong; Newton's gravity was replaced by Einstein's gravity, which works better; it was much discussed whether light was waves or particles, but we know today that light is neither waves nor particles, nor are we either waves or particles; determinism; the static universe; the æther; or more recently, in the 20th century, space and time reflection symmetries, the idea that the laws of physics are the same in a mirror, that they work the same forward and backward in time; neutrinos as undetectable particles (in 1930, Wolfgang Pauli hypothesized the existence of the neutrino, which was confirmed 25 years later, and 50 years later, a Nobel prize was given to the one surviving discoverer); neutrons and protons were once thought to be elementary particles; string theory, which is very popular among some physicists, was once thought to be a theory that made predictions, whereas today we realize that it makes no predictions.

Table 1. Discovery of the chemical elements (by periods of 25 years)

25-year period	Number of elements discovered	Elements discovered/technological breakthroughs
1725–1749	3	Platinum, cobalt, zinc
1750–1774	6	Ni, Ti, Cr and O, N, Cl (Metallurgy developed over the next 25 years, gas chemistry began, people started studying the properties of air and other gases.)
1775–1799	10	Electrochemistry
1800–1824	18	This rapid period of discovery of chemical elements is due to the invention of the electric battery in 1798, with which one could electrolyze salts and produce elements such as sodium and potassium, and using these elements as reagents chemistry could evolve very quickly.
1825–1849	8	
1850–1874	4	Periodic table proposed
1875–1899	21	Radioactivity led to the discovery of many other chemical elements, and rare gases were discovered (including argon, krypton, and xenon).
1900–1925	5	Pa and the last stable elements
1926–1944	9	Synthetic elements and francium
1945–1974	9	All synthetic elements from here on
1975–1999	7	
2000–	4	From Z = 1 to Z = 118 except 117 (which has not yet been discovered or isolated or created).

Evolution of the chemical elements: Discovery

Thousands of years ago, some of the Greeks believed in fire and water as the basic elements, others believed in fire and earth, but most of them believed that there were four basic elements: fire, water, earth, and air.

In the Middle Ages, alchemists realized that other things were fundamental as well. These are the 12 elements that were identified or known, not necessarily as elements, prior to the birth of chemistry: carbon, sulfur, iron, copper, arsenic, tin, antimony, silver, gold, mercury, bismuth, and lead.

In1669, Hennig Brant, the last great alchemist, discovers phosphorus by processing human urine. Ironically enough, it took place in Hamburg, a city that was destroyed by phosphorus bombs many years later. Table 1 shows, by periods of 25 years, the sporadic way in which the rest of the chemical elements were discovered.

It is interesting to note how episodes of rapid growth in the number of known chemical elements can be attributed to developments in technology. For example, Alessandro Volta's invention of the electric battery enabled Humphry Davy to isolate sodium, potassium, and magnesium electrolytically.

Evolution of the chemical elements: How they came to be

We know today that in the first three minutes of the history of the universe, after the Big Bang, the universe cooled enough for neutrons and protons to form atomic nuclei. During this "Age of Nucleosynthesis," approximately 25% of them formed nuclei of He-4 (and a tiny amount of a few others: H-2, He-3, and Li-7). The short neutron lifetime, the lack of stable nuclei with A = 5 or 8, and the rapid expansion of the universe terminated primordial nucleosynthesis at this point.

The first stars (oddly enough, called by astronomers "population III stars") may have formed about 200 Ma later and consisted exclusively of H and He. They were bigger, brighter, and hotter than any stars now shining, as well as short-lived, surviving for only about a million years. Nuclear fusion within them produced all of the stable chemical species up to iron (with A = 26). Upon consuming their fuel, population III stars collapsed into black holes. The resulting supernovæ explosions expelled the heavier elements (all the way up to iron), thus making them available for subsequent star formation.

Later came population II stars, which are often found in globular clusters or in the central bulges of galaxies. About 98% of today's stars belong to this group. Because these stars contain small but significant quantities of elements up to iron, they are able, in their final violent stages, to create all of the remaining stable chemical elements through what are called the r-process (rapid, in supernovæ) and the s-process (slow, in red giants).

The most recent population I stars are usually luminous, hot, relatively young, and found in the disks of spiral galaxies like our own. Our Sun is a typical population I star. The heavier elements that were released by the explosions of earlier stars constitute almost 2% of its mass.

On the age of the Earth

The question of the age of the Earth was a very interesting issue at the time *On the Origin of Species* was written. How old is the Earth? The religious answer, as expressed by Bishop Ussher in 1664, was 6000 years, based on Biblical chronology. In 1774, Buffon had a very rational argument about the cooling of molten earth, and he computed that the Earth could not be older than 75,000 years. Charles Lyell, the founder of modern geology, in1831, on the basis of the features of the creation of the Earth, came to the conclusion that it was 240 million years old. In 1852, William Thomson, not yet Lord Kelvin, concluded that the Sun could not be more than 20 million years old. Around the same time, in 1857, Hermann von Helmholtz had a rational argument on the source of the energy of the Sun being gravity, which he thought could last 21 million years. Darwin, on the other hand, wrote in 1859 that the Earth had to be older than 300 million years, based on fossil evidence. A few years later, in 1862, William Thomson, using a correct argument for Earth cooling, came to the conclusion that it was about 30 million years old. That same year, Thomson calculated the age of the Sun to be less than 100 million years old.

Thomson's arguments were very upsetting to Darwin. He wrote in 1867, some years after *On the Origin of Species* was published, "Thompson's views on the age of the world have been for some time one of my sorest problems." Darwin's sore problem would not be resolved during his lifetime. It awaited the key discovery, in 1896, of radioactivity by Henri Becquerel, and the realization much later that nuclear processes could explain the behavior of the Sun, that the source of the Sun's power and the Earth's internal heat lay deep within the atom. Its core remains molten because heat is continually produced by the decays of long-lived radioactive elements within the Earth... but what about the Sun?

In 1929, Robert Atkinson and Freidrich Houterman suggested that thermonuclear reactions might be the source of solar energy. A decade later, Hans Bethe proposed the specific nuclear processes that power the Sun and other stars. Very recently, detailed measurements of solar neutrinos have proven decisively that the standard model of power generation in the Sun is quantitatively correct. Earth's age is now known to be 4.54 billion years, far more than Darwin or Lyell could have imagined.

Table 2. Noteworthy evolutionary events (I) in log time

Log (t/year)	Noteworthy evolutionary event
~ 10	Planet Earth forms 4.54 Ga ago. Life begins on Earth; oxygenesis soon follows.
~ 9	Trilobites flourish. Dinosaurs evolve.
~ 8	Chicxulub impact. Some people think that this event led to the Cretaceous extinction. Large mammals and flowering plants evolve.
~ 7	Hominids diverge from apes. Hominids begin to walk.
~ 6	Mammoths evolve. *Homo sapiens* and Neanderthals diverge.
~ 5	Polar bears evolve; mammoths become extinct. Neanderthals become extinct.
~ 4	Malaria parasite evolves. Adult lactase gene evolves.
~ 3	Dengue fever virus evolves.
~ 2	Human AIDS virus evolves.
~ 1	Methicillin resistant staphylococcus evolves.

A very brief history of life on Earth

Now that we know the age of the Earth, we can talk about the history of life on Earth.

According to the logarithm of prior time (in which 10 = 10^{10} years ago), Table 2 shows some noteworthy evolutionary events. However, this rather anthropic display omits many early events, such as those in Table 3.

Table 3. Noteworthy evolutionary events (II)

Years	Event
3.8 billion years ago	First evidence of life on Earth.
2.9 billion years ago	Photosynthetic organisms evolve.
2.6 billion years ago	Significant oxygen in atmosphere.
1.3 billion years ago	Eukaryotic organisms arise.
0.6 billion years ago	First complex multicellular organisms.
0.5 billion years ago	Fish appear in the seas.
0.4 billion years ago	Animals roam the Earth.

Evolution of the principles of relativity

Let us now discuss evolution in yet another context, because ideas also evolve. The principle of relativity is the statement of the notion that 'being at rest' is senseless and doesn't have any real meaning, and that the laws of physics are the same to all admissible observers.

The first person to state this, in the literature, may have been Dante in 1310, when, imagining himself sitting on Geriont's back as he descends to the eighth circle of Hell, says: "I perceived myself on all sides in the air and saw extinguished the sight of everything but the monster... Onward he goes, swimming slowly, slowly wheels his downward motion, unobserved by me but that the wind breathes upon my face and from below."

Giordano Bruno also spoke about this concept, in 1584: "There is no absolute up or down; no absolute position in space; but the position of a body is relative to that of other bodies. Everywhere there is incessant relative change in position throughout the universe, and the observer is always at the center of things."

Of course, it was much more explicit with Galileo. This is an English translation of his brilliant Italian prose, from 1632, in trying to explain the principle of relativity. Quoth Galileo: "Shut yourself up with some friend in the main cabin below decks on some large ship, and have with you there some flies, butterflies, and other small flying animals. Have a large bowl of water with some fish in it; hang up a bottle that empties drop by drop into a wide vessel beneath it. With the ship standing still, observe carefully how the little animals fly with equal speed to all sides of the cabin. The fish swim indifferently in all directions; the drops fall into the vessel beneath; and, in throwing something to your friend, you need to throw it no more strongly in one direction than another, the distances being equal; jumping with your feet together, you pass equal spaces in every direction... When you have observed all of these things carefully (though there is no doubt that when the ship is standing still everything must happen this way), have the ship proceed with any speed you like, so long as the motion is uniform and not fluctuating this way and that. You will discover not the least change in all the effects named, nor could you tell from any of them whether the ship was moving or standing still."

In 1687, Isaac Newton said, "Instead of absolute places and motions, we use relative ones... for it may be that there is nobody really at rest, to which the places and motions of others may be referred."

In 1861 Maxwell computes the speed of light solely from static electrical and magnetic measurements. Thus began the Age of the Luminiferous Æther, a period in which the concept of relativity appeared to be broken There was an Æther, and light moved at the speed Maxwell calculated relative to the Æther. Quoth Maxwell soon afterward: "Whatever difficulties we may have in forming a consistent idea of the composition of the æther, there can be no doubt that the interstellar spaces are not empty, but are occupied by a material substance or body, which is certainly the largest, and probably the most uniform body of which we have any knowledge."

Half a century later, in 1905, Einstein abolishes the Luminiferous Æther. His Special Theory of Relativity reveals that Maxwell's equations–and the speed of light–are frame independent. A decade later he develops the General Theory of Relativity, which vastly expands the domain of "admissible frames of reference," allowing us to calculate that the laws of physics are the same in all coordinate system, regardless of their motion.

And yet today, we have discovered that there is a preferred frame of reference in the Universe: that in which the Cosmic Microwave Background Radiation is isotropic.

Human life on log time

Thus far, we have been looking backward in time from the present epoch. In discussing the development of a human being, it is much more useful to display significant events in terms of the logarithm of time since conception.

If we put conception at $-\infty$ and death at 100 years, between conception and death, there are nine stages of human life, which are equally spaced, logarithmically. In other words, logarithmically you are a gastrula, for about as much time as you are a teenager (Table 4).

Note that the nine stages of human life are roughly equally spaced in log time. Had we organized things linearly in time, six of these stages would be compressed in the first one percent of the display. The same applies to the history of the Universe.

Table 4. Stages of human life in log time

Log (*t*/years)	Significant event
$-\infty$	Conception
–2.5	Free blastocyst
–2.0	Attached blastocyst
–1.5	Gastrula
–1.0	Embryo
–0.5	Fetus
0.0	Infant
+0.5	Child
+1.0	Teenager
+1.5	Adult
+2.0	Death

The Universe on log time

Now, starting with the Big Bang at $-\infty$, Table 5 shows significant events in the creation of the Universe.

The birth and death of our Sun

Finally, we have the stages in which our Sun evolved. It is evolution, but, in this case it is evolution without natural selection, because any ball of gas, with a similar mass and composition to the ball of gas that became our Sun, would become a sun very much like ours.

Birth. The Sun, which is a typical population I star, begins as a huge ball of cool gas consisting mostly of H and He. Gravity causes it to contract (and therefore to heat up) very rapidly. After just a few years, it becomes a large, bright and red protostar, with $R \equiv R/R_\odot \simeq 50$ and $L \equiv L/L_\odot \simeq 300$.

Table 5. Significant events in the creation of the Universe, in log time

log (*t*/sec)	Significant event
$-\infty$	Big Bang
–37	Age of Cosmic Inflation (?). The universe, at its very first stages, was expanding exponentially.
–32	Age of Baryogenesis (?). There is more matter in the universe than there is antimatter, and allegedly that took place then.
. . .	
–12	Electroweak symmetry breaking, very early in the history of the universe.
. . .	
–6	Quark-hadron transition.
–5	Antinucleon annihilation.
. . .	
1	Positrons annihilate.
2	Synthesis of small nuclei.
. . .	
12	Age of Matter Dominance begins.
13	Nuclei and electrons form atoms, the first atoms, referred to as the Age of Recombination.
15	First stars and galaxies form.
16	Age of Dark Energy Dominance begins.
17	Solar system forms.
17.5	NOW!
18	The Sun explodes as a red giant engulfing Mercury, Venus and probably the Earth as well.
...	An indifferent Universe continues.

Gravitational contraction continues, during which the Sun's core becomes hot enough for nuclear reactions to burn H into He. After about 20 Ma, the contraction ceases and the Sun enters its present phase with $R \simeq 0.87$ and $L \simeq 0.77$

Main sequence. The burning of H into He within the solar core continues placidly for about ten billion years, as the Sun very slowly expands and grows brighter. We are now halfway to the end of this period, at which time $R \simeq 200$ and $L \simeq 5000$. At this point, Earth has long been uninhabitable.

Red giant. Hydrogen burning spreads to a shell about the solar core. The Sun rapidly expands and cools, becoming a red giant with $R \simeq 200$ and $L \simeq 5000$. The inner planets, including the Earth, will have been engulfed by the Sun.

Helium flash. After about a billion years as a red giant, conditions in the core will have enabled helium to fuse into carbon and oxygen. The Sun shrinks and dims, briefly rejoining the main sequence as a helium-burning star.

Planetary nebula. When the helium in the core is exhausted, the Sun collapses violently, expelling about half its mass as a nebulous cloud. The Sun survives as a gradually cooling white dwarf.

The birth and death of our Universe

I conclude this article with mention of several outstanding cosmological queries regarding the birth and death of our universe.

- Why was there a Big Bang? What, if anything, came before?
- What mechanism generated the exponential inflation of the early Universe?
- What are dark matter and dark energy, which dominate today's Universe?
- How did the first stars and galaxies form?
- Why are the fundamental constants of nature what they are?
- Must we depend on the Cosmic Anthropic Principle to 'answer' such questions??
- Is our Universe unique, or must we appeal to a Multiverse?
- What will be the ultimate fate of our Universe?

These questions are just reminder that there are many questions in cosmology and in particle physics that still remain unanswered.

About the author

Sheldon L. Glashow studied Physics at Cornell University and received his Ph.D. at Harvard University. He carried out his postdoctoral research at the University of Copenhagen, the European Organization for Nuclear Research (CERN), and the California Institute of Technology (Caltech). He has taught at Stanford, Berkeley, and for many years, at Harvard University. Currently, he is a Higgins Professor of Physics Emeritus at Harvard University and the Metcalf Professor of Science at Boston University. He is a member of numerous societies and scientific academies, such as the American Philosophical Society, the National Academy of Sciences (NAS), the American Society of Arts & Sciences, and the Science Academies of Russia, Korea and Costa Rica, among others. He has numerous academic distinctions, including the Erice Science for Peace Prize, the Oppenheimer Medal, and the Nobel Prize in Physics awarded in 1979, for his theory on the four fundamental forces in the Universe.