Future of an expanding universe

"Big Freeze" redirects here. For other uses, see Big Freeze (disambiguation).

Observations suggest that the expansion of the universe will continue forever. If so, then a popular theory is that the universe will cool as it expands, eventually becoming too cold to sustain life. For this reason, this future scenario is popularly called the *Heat Death*.[1]

If dark energy—represented by the cosmological constant, a *constant* energy density filling space homogeneously,[2] or scalar fields, such as quintessence or moduli, *dynamic* quantities whose energy density can vary in time and space—accelerates the expansion of the universe, then the space between clusters of galaxies will grow at an increasing rate. Redshift will stretch ancient, incoming photons (even gamma rays) to undetectably long wavelengths and low energies.[3] Stars are expected to form normally for 10^{12} to 10^{14} (1–100 trillion) years, but eventually the supply of gas needed for star formation will be exhausted. As existing stars run out of fuel and cease to shine, the universe will slowly and inexorably grow darker, one star at a time.[4][5] According to theories that predict proton decay, the stellar remnants left behind will disappear, leaving behind only black holes, which themselves eventually disappear as they emit Hawking radiation.[6] Ultimately, if the universe reaches a state in which the temperature approaches a uniform value, no further work will be possible, resulting in a final heat death of the universe.[7]

1 Cosmology

Nature timeline
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Axis scale: billions of years.
Also see: *Human timeline* and *Life timeline*

Infinite expansion does not determine the spatial curvature of the universe. It can be open (with negative spatial curvature), flat, (positive spatial curvature), although if it is closed, sufficient dark energy must be present to counteract the gravitational forces. Open and flat universes will expand forever even in the absence of dark energy.[8]

Observations of the cosmic background radiation by the Wilkinson Microwave Anisotropy Probe and the Planck mission suggest that the universe is spatially flat and has a significant amount of dark energy.[9][10] In this case, the universe should continue to expand at an accelerating rate. The acceleration of the universe's expansion has also been confirmed by observations of distant supernovae.[8] If, as in the concordance model of physical cosmology (Lambda-cold dark matter or ΛCDM), the dark energy is in the form of a cosmological constant, the expansion will eventually become exponential, with the size of the universe doubling at a constant rate.

If the theory of inflation is true, the universe went through an episode dominated by a different form of dark energy in the first moments of the Big Bang; but inflation ended, indicating an equation of state much more complicated than those assumed so far for present-day dark energy. It is possible that the dark energy equation of state could change again resulting in an event that would have consequences which are extremely difficult to parametrize or predict.

2 Future history

In the 1970s, the future of an expanding universe was studied by the astrophysicist Jamal Islam[11] and the physicist Freeman Dyson.[12] Then, in their 1999 book The Five Ages of the Universe, the astrophysicists Fred Adams and Gregory Laughlin have divided the past and future history of an expanding universe into five eras. The first, the *Primordial Era*, is the time in the past just after the Big Bang when stars had not yet formed. The second, the *Stelliferous Era*, includes the present day and all of the stars and galaxies we see. It is the time during which stars form from collapsing clouds of gas. In the subsequent *Degenerate Era*, the stars will have burnt out, leaving all stellar-mass objects as stellar remnants—white dwarfs, neutron stars, and black holes. In the *Black Hole Era*, white dwarfs, neutron stars, and other smaller astronomical objects have been destroyed by proton decay, leaving only black holes. Finally, in the *Dark Era*, even black holes have disappeared, leaving only a dilute gas of photons and leptons.[13]

This future history and the timeline below assume the continued expansion of the universe. If the universe begins to recontract, subsequent events in the timeline may not occur because the Big Crunch, the recontraction of the universe into a hot, dense state similar to that after the Big Bang, will supervene.[13][14]

3 Timeline

For the past, including the Primordial Era, see Chronology of the universe.

3.1 Stelliferous Era

From 10^6 (1 million) years to 10^{14} (100 trillion) years after the Big Bang

See also: Graphical timeline of the Stelliferous Era

The observable universe is currently 1.38×10^{10} (13.8 billion) years old.[15] This time is in the Stelliferous Era. About 155 million years after the Big Bang, the first star formed. Since then, stars have formed by the collapse of small, dense core regions in large, cold molecular clouds of hydrogen gas. At first, this produces a protostar, which is hot and bright because of energy generated by gravitational contraction. After the protostar contracts for a while, its center will become hot enough to fuse hydrogen and its lifetime as a star will properly begin.[13]

Stars of very low mass will eventually exhaust all their fusible hydrogen and then become helium white dwarfs.[16] Stars of low to medium mass, such as our own sun, will expel some of their mass as a planetary nebula and eventually become white dwarfs; more massive stars will explode in a core-collapse supernova, leaving behind neutron stars or black holes.[17] In any case, although some of the star's matter may be returned to the interstellar medium, a degenerate remnant will be left behind whose mass is not returned to the interstellar medium. Therefore, the supply of gas available for star formation is steadily being exhausted.

3.1.1 Milky Way Galaxy and the Andromeda Galaxy merge into one

4–8 billion years from now (17.7 – 21.7 billion years after the Big Bang)

Main article: Andromeda–Milky Way collision

The Andromeda Galaxy is currently approximately 2.5 million light years away from our galaxy, the Milky Way Galaxy, and they are moving towards each other at approximately 300 kilometers (186 miles) per second. Approximately five billion years from now, or 19 billion years after the Big Bang, the Milky Way and the Andromeda Galaxy will collide with one another and merge into one large galaxy based on current evidence. Up until 2012, there was no way to know whether the possible collision was definitely going to happen or not.[18] In 2012, researchers came to the conclusion that the collision is definite after using the Hubble Space Telescope between 2002 and 2010 to track the motion of Andromeda.[19]

3.1.2 Coalescence of Local Group and galaxies outside the Local Group are no longer accessible

10^{11} (100 billion) to 10^{12} (1 trillion) years

The galaxies in the Local Group, the cluster of galaxies which includes the Milky Way and the Andromeda Galaxy, are gravitationally bound to each other. It is expected that between 10^{11} (100 billion) and 10^{12} (1 trillion) years from now, their orbits will decay and the entire Local Group will merge into one large galaxy.[4]

Assuming that dark energy continues to make the universe expand at an accelerating rate, in about 150 billion years all galaxies outside the local group will pass behind the cosmological horizon. It will then be impossible for events in the local group to affect other galaxies. Similarly it will be impossible for events after 150 billion years, as seen by observers in distant galaxies, to affect events in the local group.[3] However, an observer in the local group will continue to see distant galaxies, but events they observe will become exponentially more time dilated (and red shifted[3]) as the galaxy approaches the horizon until time in the distant galaxy seems to stop. The observer in the local group never actually sees the distant galaxy pass beyond the horizon and never observes events after 150 billion years in their local time. Therefore, after 150 billion years intergalactic transportation and communication becomes causally impossible.

3.1.3 Luminosities of galaxies begin to diminish

8x10^{11} (800 billion) years

8x10^{11} (800 billion) years from now, the luminosities of the different galaxies, approximately similar until then to the current ones thanks to the increasing luminosity of the remaining stars as they age, will start to decrease, as the less massive red dwarf stars begin to die as white dwarfs.[20]

3.1.4 Galaxies outside the Local Supercluster are no longer detectable

2×10^{12} (2 trillion) years

2×10^{12} (2 trillion) years from now, all galaxies outside the Local Supercluster will be red-shifted to such an extent that even gamma rays they emit will have wavelengths longer than the size of the observable universe of the time. Therefore, these galaxies will no longer be detectable in any way.[3]

3.2 Degenerate Era

From 10^{14} (100 trillion) to 10^{40} (10 duodecillion) years

By 10^{14} (100 trillion) years from now, star formation will end,[4] leaving all stellar objects in the form of degenerate remnants. If protons do not decay, this era will last longer.

3.2.1 Star formation ceases

10^{14} (100 trillion) years

By 10^{14} (100 trillion) years from now, star formation will end. This period, known as the Degenerate Era, will last until the degenerate remnants finally decay.[21] The least massive stars take the longest to exhaust their hydrogen fuel (see stellar evolution). Thus, the longest living stars in the universe are low-mass red dwarfs, with a mass of about 0.08 solar masses ($M_\odot$), which have a lifetime of order 10^{13} (10 trillion) years.[22] Coincidentally, this is comparable to the length of time over which star formation takes place.[4] Once star formation ends and the least massive red dwarfs exhaust their fuel, nuclear fusion will cease. The low-mass red dwarfs will cool and become black dwarfs.[16] The only objects remaining with more than planetary mass will be brown dwarfs, with mass less than 0.08 $M_\odot$, and degenerate remnants; white dwarfs, produced by stars with initial masses between about 0.08 and 8 solar masses; and neutron stars and black holes, produced by stars with initial masses over 8 $M_\odot$. Most of the mass of this collection, approximately 90%, will be in the form of white dwarfs.[5] In the absence of any energy source, all of these formerly luminous bodies will cool and become faint.

The universe will become extremely dark after the last star burns out. Even so, there can still be occasional light in the universe. One of the ways the universe can be illuminated is if two carbon–oxygen white dwarfs with a combined mass of more than the Chandrasekhar limit of about 1.4 solar masses happen to merge. The resulting object will then undergo runaway thermonuclear fusion, producing a Type Ia supernova and dispelling the darkness of the Degenerate Era for a few weeks.[23][24] If the combined mass is not above the Chandrasekhar limit but is larger than the minimum mass to fuse carbon (about 0.9 $M_\odot$), a carbon star could be produced, with a lifetime of around 10^6 (1 million) years.[13] Also, if two helium white dwarfs with a combined mass of at least 0.3 $M_\odot$ collide, a helium star may be produced, with a lifetime of a few hundred million years.[13] Finally brown dwarfs can form new stars colliding with each other to form a red dwarf star, that can survive for 10^{13} (10 trillion) years,[22][23] or accreting gas at very slow rates from the remaining interstellar medium until they have enough mass to start hydrogen burning as red dwarfs too. This process, at least on white dwarfs, could induce Type Ia supernovae too.[25]

3.2.2 Planets fall or are flung from orbits by a close encounter with another star

10^{15} (1 quadrillion) years

Over time, the orbits of planets will decay due to gravitational radiation, or planets will be ejected from their local systems by gravitational perturbations caused by encounters with another stellar remnant.[26]

3.2.3 Stellar remnants escape galaxies or fall into black holes

10^{19} to 10^{20} (10 to 100 quintillion) years

Over time, objects in a galaxy exchange kinetic energy in a process called dynamical relaxation, making their velocity distribution approach the Maxwell–Boltzmann distribution.[27] Dynamical relaxation can proceed either by close encounters of two stars or by less violent but more frequent distant encounters.[28] In the case of a close encounter, two brown dwarfs or stellar remnants will pass close to each other. When this happens, the trajectories of the objects involved in the close encounter change slightly. After a large number of encounters, lighter objects tend to gain kinetic energy while the heavier objects lose it.[13]

Because of dynamical relaxation, some objects will gain enough energy to reach galactic escape velocity and depart the galaxy, leaving behind a smaller, denser galaxy. Since encounters are more frequent in the denser galaxy, the process then accelerates. The end result is that most objects (90% to 99%) are ejected from the galaxy, leaving a small fraction (maybe 1% to 10%) which fall into the central supermassive black hole.[4][13] It has been suggested that the matter of the fallen remnants will form an accretion disk around it that will create a quasar, as long as enough matter is present there.[29]

3.2.4 Nucleons start to decay

See also: Nucleon
Chance: 10^{34} (10 decillion) < 10^{39} years (1 duodecillion)

The subsequent evolution of the universe depends on the possibility and rate of proton decay. Experimental evidence shows that if the proton is unstable, it has a half-life of at least 10^{34} years.[30] Some of the Grand Unified theories (GUTs) predict long-term proton instability between 10^{31} and 10^{36} years, with the upper bound on standard (non-SUSY) proton decay at 1.4 x 10^{36} years and an overall upper limit maximum for any proton decay (including SUSY models) at 6 x 10^{39} years.[31][32] Recent research showing proton lifetime (if unstable) at or exceeding 10^{34}–10^{35} year range rules out simpler GUTs and most non-SUSY models.

Neutrons bound into nuclei are also expected to decay with a half-life comparable to that of protons. Planets (substellar objects) would decay in a simple cascade process from heavier elements to pure hydrogen while radiating energy.[33]

In the event that the proton does not decay at all, stellar objects would still disappear, but more slowly. See Future without proton decay below.

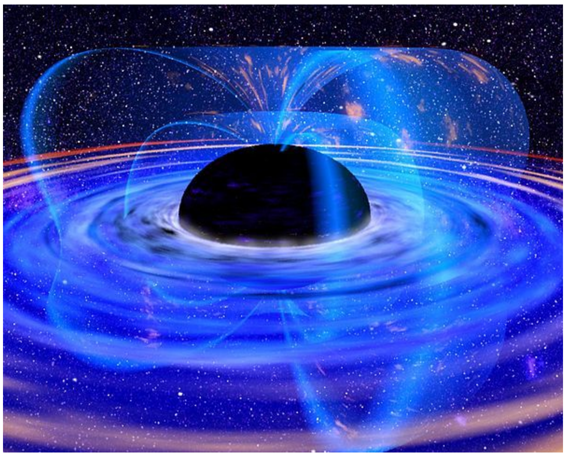
Shorter or longer proton half-lives will accelerate or decelerate the process. This means that after 10^{37} years (the maximum proton half-life used by Adams & Laughlin (1997)), one-half of all baryonic matter will have been converted into gamma ray photons and leptons through proton decay.

3.2.5 All nucleons decay

10^{40} (10 duodecillion) years

Given our assumed half-life of the proton, nucleons (protons and bound neutrons) will have undergone roughly 1,000 half-lives by the time the universe is 10^{40} years old.

To put this into perspective, there are an estimated 10^{80} protons currently in the universe.[34] This means that the number of nucleons will be slashed in half 1,000 times by the time the universe is 10^{40} years old. Hence, there will be roughly $½^{1,000}$ (approximately 10^{-301}) as many nucleons remaining as there are today; that is, *zero* nucleons remaining in the universe at the end of the Degenerate Age. Effectively, all baryonic matter will have been changed into photons and leptons. Some models predict the formation of stable positronium atoms with a greater diameter than the observable universe's current diameter in 10^{85} years, and that these will in turn decay to gamma radiation in 10^{141} years.[4][5]



The supermassive black holes are all that remains of galaxies once all protons decay, but even these giants are not immortal.

3.2.6 If protons decay on higher order nuclear processes

Chance: 10^{100} years to 10^{200} years

In the event that the proton does not decay according to the GUT theories above, the Degenerate Era will last longer, and will overlap or surpass the Black Hole Era. However, degenerate stellar objects can still experience proton decay, for example via processes involving virtual black holes, or higher-dimension supersymmetry with a half-life of under 10^{200} years.[4]

3.3 Black Hole Era

10^{40} (10 duodecillion) years to 10^{100} (1 googol) years

After 10^{40} years, black holes will dominate the universe. They will slowly evaporate via Hawking radiation.[4] A black hole with a mass of around 1 $M\odot$ will vanish in around $2{\times}10^{66}$ years. As the lifetime of a black hole is proportional to the cube of its mass, more massive black holes take longer to decay. A supermassive black hole

The photon is now the king of the universe as the last of the supermassive black holes evaporates.

with a mass of 10^{11} (100 billion) $M\odot$ will evaporate in around $2{\times}10^{99}$ years.[35]

Hawking radiation has a thermal spectrum. During most of a black hole's lifetime, the radiation has a low temperature and is mainly in the form of massless particles such as photons and hypothetical gravitons. As the black hole's mass decreases, its temperature increases, becoming comparable to the Sun's by the time the black hole mass has decreased to 10^{19} kilograms. The hole then provides a temporary source of light during the general darkness of the Black Hole Era. During the last stages of its evaporation, a black hole will emit not only massless particles, but also heavier particles, such as electrons, positrons, protons, and antiprotons.[13]

3.4 Dark Era and Photon Age

From 10^{100} years (10 duotrigintillion years)

After all the black holes have evaporated (and after all the ordinary matter made of protons has disintegrated, if protons are unstable), the universe will be nearly empty. Photons, neutrinos, electrons, and positrons will fly from place to place, hardly ever encountering each other. Gravitationally, the universe will be dominated by dark matter, electrons, and positrons (not protons).[36]

By this era, with only very diffuse matter remaining, activity in the universe will have tailed off dramatically (compared with previous eras), with very low energy levels and very large time scales. Electrons and positrons drifting through space will encounter one another and occasionally form positronium atoms. These structures are unstable, however, and their constituent particles must eventually annihilate.[37] Other low-level annihilation events will also take place, albeit very slowly. The universe now reaches an extremely low-energy state.

3.5 Beyond

Beyond 10^{2500} years to the infinite future

What happens after this is speculative. It is possible that a Big Rip or a Big Freeze event may occur far off into the future.[38][39] The former singularity takes place at a finite scale factor while the latter occurs at an infinitely large radius. Also, the universe may enter a second inflationary epoch, or, assuming that the current vacuum state is a false vacuum, the vacuum may decay into a lower-energy state.[40]

Presumably, extreme low-energy states imply that localized quantum events become major macroscopic phenomena rather than negligible microscopic events because the smallest perturbations make the biggest difference in this era, so there is no telling what may happen to space or time. It is perceived that the laws of "macro-physics" will break down, and the laws of "quantum-physics" will prevail.[7]

The universe could possibly avoid eternal heat death through random quantum tunnelling and quantum fluctuations, given the non-zero probability of producing a new Big Bang of roughly $10^{-10^{10^{56}}}$.[41]

Over an infinite time there could be a spontaneous entropy decrease, by a Poincaré recurrence or through thermal fluctuations (see also fluctuation theorem).[42][43][44][45]

4 Future without proton decay

If the protons do not decay, stellar-mass objects will still become black holes, but more slowly. The following timeline assumes that proton decay does not take place.

4.1 Possible ionization of matter

>10^{23} years from now

In an expanding universe with decreasing density and nonzero cosmological constant, matter density would reach zero, resulting in all matter including stellar objects and planets ionizing and dissipating at thermal equilibrium.[46]

4.2 Sphaleron transitions and possible baryon violation

>10^{150} years from now

Although protons are stable in standard model physics, a quantum anomaly may exist on the electroweak level, which can cause groups of baryons (protons and neutrons) to annihilate into antileptons via the sphaleron transition.[47] Such baryon/lepton violations have a number of 3 and can only occur in multiples or groups of three baryons, which can restrict or prohibit such events. No experimental evidence of sphalerons has yet been observed at low energy levels, though they are believed to occur regularly at high energies and temperatures.

4.3 Matter decays into iron

10^{1500} years from now

In 10^{1500} years, cold fusion occurring via quantum tunnelling should make the light nuclei in ordinary matter fuse into iron-56 nuclei (see isotopes of iron.) Fission and alpha-particle emission should make heavy nuclei also decay to iron, leaving stellar-mass objects as cold spheres of iron, called iron stars.[12]

4.4 Collapse of iron star to black hole

$10^{(10^{26})}$ to $10^{(10^{76})}$ years from now

Quantum tunnelling should also turn large objects into black holes. Depending on the assumptions made, the time this takes to happen can be calculated as from $10^{(10^{26})}$ years to $10^{(10^{76})}$ years. Quantum tunnelling may also make iron stars collapse into neutron stars in around $10^{(10^{76})}$ years.[12]

5 Graphical timeline

Main article: Graphical timeline from Big Bang to Heat Death
See also: Graphical timeline of the universe and Graphical timeline of the Big Bang

6 Route diagram styled timeline

For use of this RDT-styled timeline, see Wikipedia: Route diagram template.

7 See also

- Big Rip
- Big Crunch
- Big Bounce

- Big Bang
- Chronology of the universe
- Cyclic model
- Dyson's eternal intelligence
- Entropy (arrow of time)
- Final anthropic principle
- Graphical timeline of the Stelliferous Era
- Graphical timeline of the Big Bang
- Graphical timeline from Big Bang to Heat Death. This timeline uses the double-logarithmic scale for comparison with the graphical timeline included in this article.
- Graphical timeline of the universe. This timeline uses the more intuitive linear time, for comparison with this article.
- Heat death of the universe
- Timeline of the Big Bang
- Timeline of the far future
- The Last Question, a short story by Isaac Asimov which considers the inevitable oncome of heat death in the universe and how it may be reversed.
- Ultimate fate of the universe

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9.1 Text

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