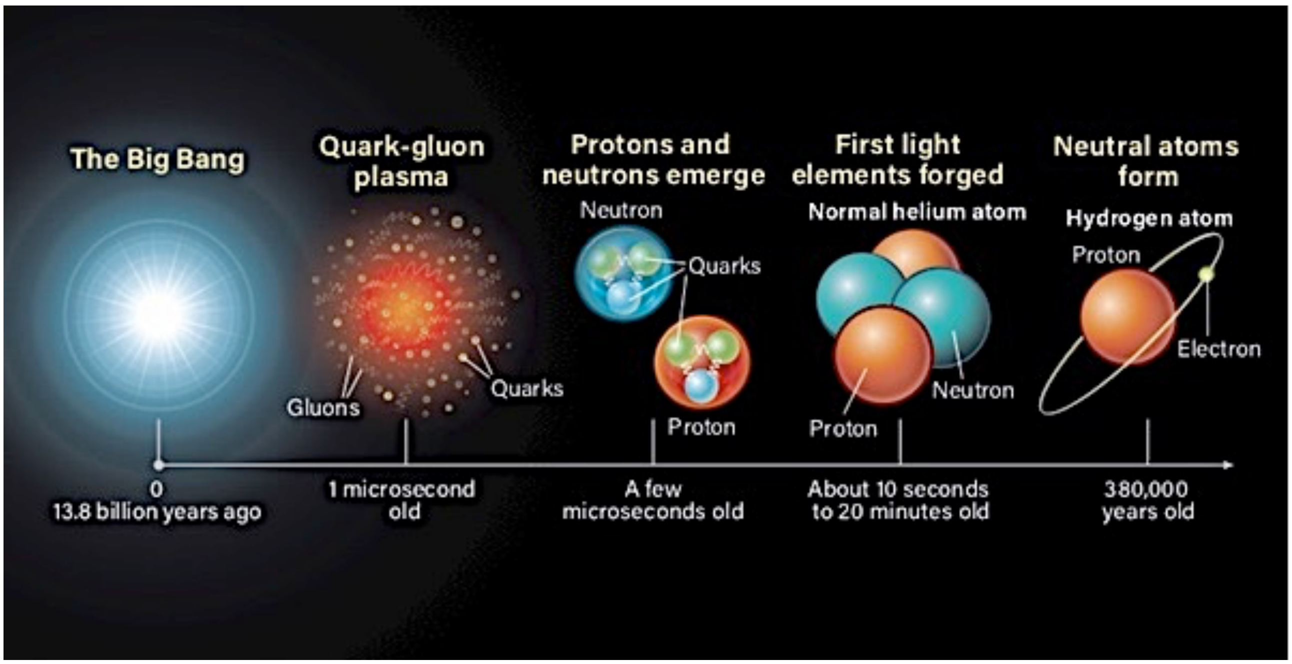
The Beginning of Everything



Astronomy

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6 The Beginning of Everything

About 13.8 billion years ago, for reasons we do not yet understand, the universe came into existence. At that instant there was no such thing as time, space, or matter. At time $t = 0^{+} << 10^{-43}$ seconds, the universe existed as a single point of incredible energy far beyond our comprehension. All of time, space, and matter rapidly expanded out of that single point. How rapidly? It is estimated that the universe expanded a trillion trillion-fold from about the size of a proton, 8.5×10^{-19} km in diameter, to over a light year across, $9.46 \times 10^{+12}$ km, in less than a trillionth of a trillionth of a second. We call the rapid emergence of the universe the “Big Bang” because time, space, matter, everything that we are aware of seemed to “explode” into existence. There is nothing “before” the Big Band. The Big Bang 13.8 billion years ago is the beginning of time.

The term Big Bang, while accurate, is very misleading because we think of it as an explosion like those that we are familiar with, a dynamite explosion, eruption of a volcano, a super nova explosion of a massive star, etc. We always view such explosions from outside the explosion. We watch it happen. That is not the case with the Big Bang. If we refer to the Big Bang as an explosion, then we are inside that explosion being hurled outward at enormous speed along with everything else around us. We are not aware of anything “outside” the explosion. For us there is no such thing as outside the explosion. Everything that we have knowledge of exists entirely in the rapidly expanding space within the explosion. So it is with the Big Bang.

We have no problem relating to the beginning of time. The beginning of time is a common every day experience, the beginning of the day, the beginning of a hard earned vacation, etc. Similarly, the formation of matter is something that we can easily deal with. We are always building things out of other things, making cloths out of fabric, building cities out of mortar and bricks, developing new medicines, etc. But the creation of space out of nothing is something that conceptually we have trouble grappling with. We try. Figure 1 is a drawing illustrating the expansion of the universe over time. In nature there is nothing beyond the universe. But in Figure 1 the rest of the page is beyond the universe. In the drawing the universe began at a point on the left side of the page, the point labeled quantum fluctuations. In fact, the universe expanded out of nothing. There is no such thing as a place where creation of the universe began. Creation began “everywhere” in the incredibly tiny, extremely hot dense space of the rapidly expanding fledgling universe. Another analogy that sometimes helps is visualizing the universe expanding like an inflating balloon in which the entire universe exists only on the balloon’s surface. Here too the analogy falls short. In terms of the universe there is no such thing as inside the balloon or above the balloon. Everything in the universe exists only on the ever-expanding surface of the balloon. Because the universe is expanding, growing ever larger, galaxies are slowly drifting apart. It is not that the galaxies themselves are traveling way from one another, it is instead that the universe is continuing to expand (stretching out) separating the galaxies further and further apart. This is illustrated in Figure 2. In this figure three simulated galaxies are drawn on the surface of a balloon as red blotches. The blotches are permanently marked on the balloon. We can not physically move an individual blotch toward or away from the other two blotches. They are permanently adhered to the balloon surface. At some point in time two of the simulated galaxies are 1 cm and 2 cm away from the third galaxy.

Sometime later, as the balloon continues to expand, we find that the two galaxies are now 2 and 4 cm from the third galaxy. The inflating balloon stretched out the distances between the red blotches.

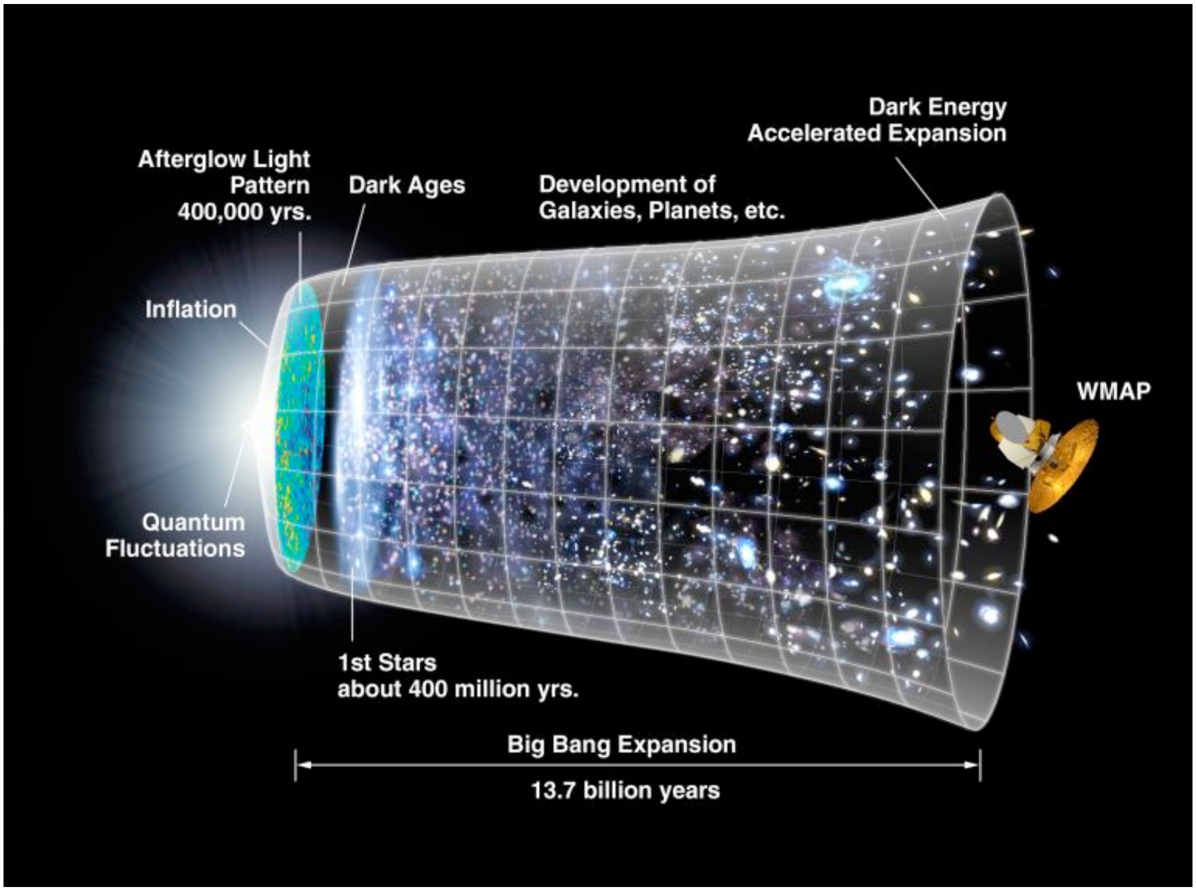


Figure 1 Expansion of the Universe (source: NASA)

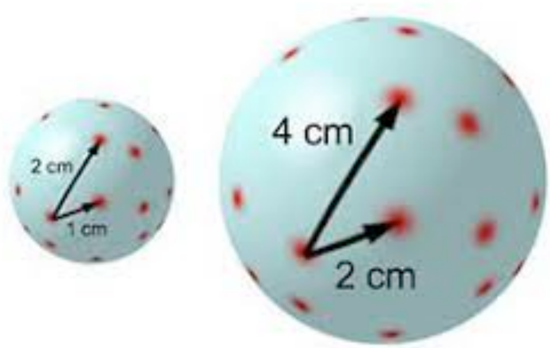


Figure 2 Expanding balloon analogy (source: Physics World)

6.1 Age of the Universe

Since the time of Newton the general consensus of the scientific community has been that the universe is static, neither expanding or contracting. Each star remains positioned at a specific point in the universe. That quickly changed. In 1925 Edwin Hubble determined the distance to the Andromeda Galaxy and several other galaxies. He measured these distances using the newly completed 100-inch Mount Wilson telescope located in the mountains above Pasadena, California. At the same time Vesto Slipher at the Lowell Observatory in Flagstaff, Arizona obtained spectra of these galaxies. He found that the spectra where the same as several elements, particularly hydrogen, measured in laboratories here on Earth, except that the spectra were red shifted to longer wavelengths. Hubble concluded from Slipher's observations that nearly all galaxies are moving away from our own Milky Way galaxy. That is, the universe is expanding. Hubble found that the speed at which a galaxy is moving away from us is directly proportional to the distance of that galaxy. A galaxy that is 90 million light years from Earth moves away from us twice as fast as a galaxy 45 million light years away. In mathematical terms

$$v_r = H_0 \cdot d = Hubble's\ Law$$

where

v_r = recession velocity (km/s)

d = distance (km)

H_0 = Hubble's constant

Hubble's constant is generally given in terms of mega-parsec (Mpc) and is

$$H_0 = \frac{70km}{s} \cdot \frac{1}{Mpc}$$

One parsec is equal to 3.262 light years (LY). In terms of light years Hubble's constant is

$$H_0 = \frac{70km}{s} \cdot \frac{1}{Mpc} = \frac{70km}{s} \cdot \frac{1}{3.262 \cdot 10^6} = \frac{21.459km}{s} \cdot \frac{1}{10^6\ LY}$$

$$H_0 = \frac{21.459km}{s} \cdot \frac{1}{10^6\ LY}$$

We can use Hubble's Law to estimate the age of the universe. Hubble's Law assumes that the universe has expanded at a constant rate since the time of the Big Bang. This assumption is not correct. The universe has not expanded at a constant rate. However, using Hubble's Law we come up with a fairly accurate estimate for the age of the universe. For example, assume that today two galaxies are 100 million light years apart. If these two galaxies are moving apart at a constant rate, then at some time in the past they had to be together at the same place. According to Hubble's Law the two galaxies are moving apart at a velocity of

$$v_r = H_0 \cdot d$$

where d is 100 million light years (10^8 LY). Thus

$$v_r = H_0 \cdot d = \left[\frac{21.459km}{s} \cdot \frac{1}{10^6\ LY}\right] \cdot 10^8\ LY = \frac{2{,}146\ km}{s}$$

Knowing the speed at which they are receding from each other, we can calculate the time it took the two galaxies to become 100 million light years apart since

$$Time = \frac{Distance}{Speed}$$

One light year equals 9.46 x 10^{12} km. The 100 million light year distance between the two galaxies is equal to 9.46 x 10^{20} km. Plugging in these values gives

$$Time = \frac{Distance}{Speed} = \frac{9.46 \cdot 10^{20}}{2.146 \cdot 10^3} = 4.4 \cdot 10^{17}\ seconds$$

Dividing by the number of seconds in a year (~ 3.2 x 10^7 s/yr) gives

$$Time = 1.375\ \cdot\ 10^{10}\ years = 13.75\ billion\ years$$

which is very close to today's estimate of 13.8 billion years as the age of the universe.

6.2 Shape of the Universe

The universe could be flat, positively curved, or negatively curved as illustrated in Figure 3. In a positively curved universe parallel lines converge. The Earth is a positively curved surface. Lines of longitude are parallel at the Earth's equator but converge to a single point at the Earth's north pole, and also at the south pole. Parallel lines in a negatively curved universe diverge as illustrated in Figure 3. In a flat universe, however, parallel lines remain parallel forever. The characteristics for each type of curvature are summarized in Table 1. Current observations, to a very high degree of precision, indicate that the universe is flat. Not only flat, but extremely flat.

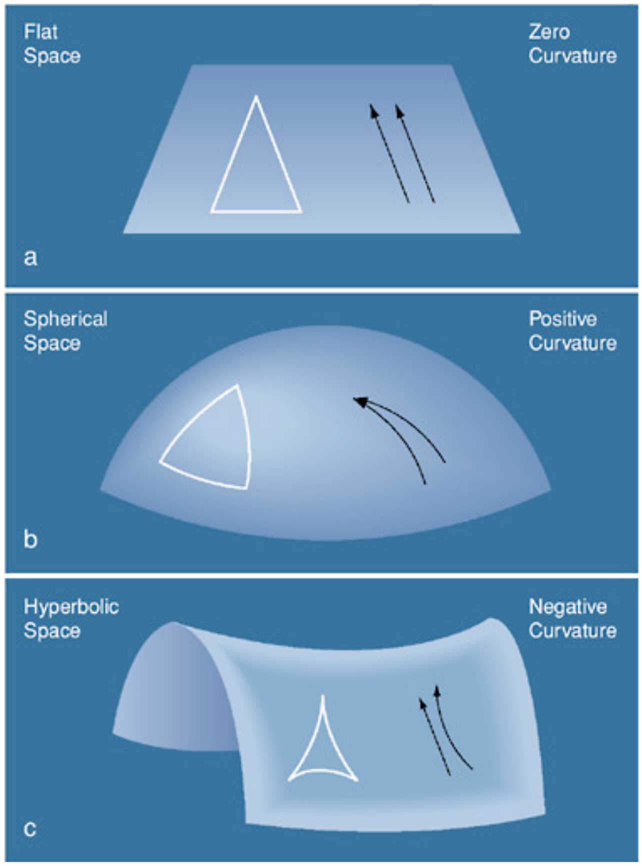


Figure 3 Shape of the Universe (source: The National Academies Press)

Shape of Universe	Spherical	Flat	Hyperbolic
Curvature	Positive	Zero	Negative
Circumference of a circle	$< 2\pi r$	$= 2\pi r$	$> 2\pi r$
Sum of angles in a triangle	$> 180°$	$= 180°$	$< 180°$
Number of galaxies	Finite	Infinite	Infinite
Starts with	Big Bang	Big Bang	Big Bang
Eventual size of universe	Finite	Infinite	Infinite
Expansion history	Expands, then collapse ending in Big Crunch	Expands forever	Expands forever

Table 1 Characteristics of various models for the universe (source: J. Richard Gott)

6.3 Center of the Universe

There is no such thing as outside the universe. Consequently, there is no outer edge to the universe. An outer edge implies that you could cross this edge (boundary) into something beyond the universe. But there is no such thing as beyond the universe so there can be no outer edge. You can travel forever in a straight line from any starting point in the universe and never reach the edge of the universe. In fact, walking forever you can never get any closer to the edge than when you started because there is no edge. This also means that there is no center to the universe since to find the center of something you must first find its edges. Without edges there can be no center. For example, the **surface** of the Earth does not have a center. If you begin at **any** point on Earth's surface and walk straight forward you will never come to an edge. Instead, you will eventually end up back at your starting point.

6.4 Dark Mater

In addition to normal matter (subatomic particles, electrons, protons, neutrons, atoms, molecules, etc.) dark matter also exists. Dark matter accounts for approximately 84% of the matter in the universe. Its presence is implied by gravitational effects that can not be explained unless more matter exists than can be seen. This evidence includes calculations showing that many galaxies would fly apart if they did not contain large amounts of an unseen matter. Other evidence include:

- Astronomical observations of the universe's current structure,
- Formation and evolution of galaxies,
- Motion of galaxies within galaxy clusters, and
- Gravitational lensing.

Dark matter is called dark because it does not appear to interact with electromagnetic fields. Consequently, it does not absorb, reflect, or emit electromagnetic radiation making it difficult to detect. Current theories are that dark matter is composed of some as yet undiscovered subatomic particles which do not interact with ordinary matter.

6.5 Dark Energy

When Einstein developed his equations of general relativity he assumed that the universe was static, neither expanding or contracting. This was the general consensus of the scientific community dating back to the time of Newton. Newton believed the universe to be static with a relatively uniform distribution of stars. Each star experienced the gravitational pull from all of the other stars. However, these gravitational forces on a star cancelled out since they were pulling equally on the star from all directions. With a net zero force each star had to remain positioned at a specific point in the universe. However, Einstein's general theory of relativity indicated that any universe containing mass, and therefore gravity, can not be static. To solve this problem, Einstein added a fudge factor, called the cosmological constant, into the general relativity equation. The cosmological constant acted as a repulsive force opposing the force of gravity. Selecting the right value for the cosmological constant resulted in the general theory of relativity predicting a static universe. Einstein realized his mistake when Hubble discovered that the universe is not static but instead expanding. Einstein called the introduction of the cosmological constant the greatest blunder of his scientific career.

Recent discoveries that expansion of the universe is accelerating has reintroduced the concept of a cosmological constant that opposes the force of gravity. Today, physicists point out that the cosmological constant is equivalent to Einstein proposing that the vacuum of empty space actually has a positive energy density.

We would expect the energy density in a complete vacuum to be zero. However, it turns out that the vacuum of empty space does have a positive energy density. In addition, it has a corresponding negative pressure of the same magnitude as its energy density. The negative pressure of empty space is uniformly distributed so we don't notice it in the same sense that we do not notice the 15 pounds per square inch of atmospheric pressure that we are consistently exposed to. The energy density and accompanying pressure of empty space is called dark energy, dark because we can not see it.

In weather systems high and low pressure regions produce hydrodynamic forces that cause winds to blow. The negative pressure of empty space does not create any hydrodynamic forces since it is uniformly distributed. However, it does have a gravitational effect. In Einstein's equations both energy density and pressure gravitate. Positive energy density is attractive. It pulls things together. Positive pressure is also attractive. But negative pressure is gravitationally repulsive. The negative pressure of empty space exceeds the gravitational attraction of empty space energy density by a factor of 3 to 1. As a result, the vacuum of empty space is gravitationally repulsive.

6.6 Expansion of the Universe

Figure 4 illustrates four possible models for an expanding (non-static) universe.

Cosmological models are defined today by two parameters: Ω_m and Ω_Λ. The values of these parameters determine the expansion history of the universe, whether the universe is finite or infinite, and whether the universe will expand forever or collapse in on itself.

The first parameter, Ω_m, describes the matter density of the universe.

$$\Omega_m = \frac{8\pi G \rho_m}{3H_0^2}$$

where

G = Newton's gravitational constant

H_0 = the Hubble constant, and

ρ_m = the average density of matter in the universe today including both normal and dark matter

The numerator of this equation, $8\pi G \rho_m$, describes the density of the universe which determines the amount of gravitational attraction. The denominator, $3H_0^2$, describes the kinetic energy of expansion.

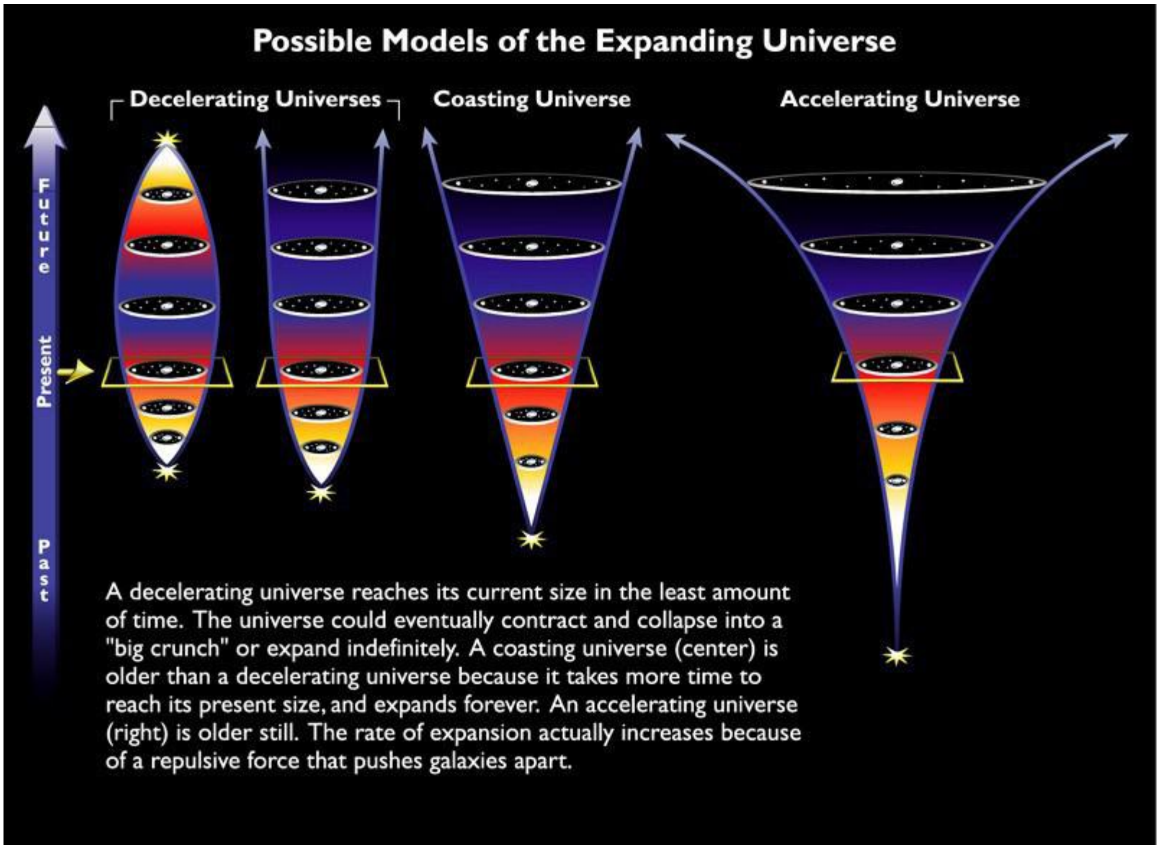


Figure 4 Expansion models for the universe (source: The Cosmic Perspective / Jeffrey O. Bennett, et all)

The second parameter, Ω_Λ , describes the vacuum energy density of the universe.

$$\Omega_\Lambda = \frac{8\pi G \rho_{vac}}{3H_0^2}$$

where

ρ_{vac} = is the average vacuum energy density.

The total matter and vacuum energy density in the universe is

$$\Omega_0 = \Omega_m + \Omega_\Lambda$$

If we assume for the moment that the vacuum energy density in the universe $\Omega_\Lambda = 0$, then the matter density Ω_m tells us whether the universe will expand forever or not. It also tells us what the shape of the universe is in the absence of dark energy.

If $\Omega_m > 1$ gravitational attraction overcomes the kinetic energy of expansion and the universe eventually collapses. This is represented by the left-hand model in Figure 4. The Big Bang occurs. The universe at first expands rapidly. But the attractive force of gravity slows the rate of expansion until it eventually stops, reverses direction, and then collapses in on itself at an accelerating rate. In this case the curvature of the universe is positive with the universe being finite in size.

If $\Omega_m < 1$ the kinetic energy of expansion overwhelms gravitational attraction causing the universe to have a negative curvature with the universe expanding forever. This case is represented by the coasting model in Figure 4.

If $\Omega_m = 1$ the kinetic energy of expansion just balances gravitational attraction causing the universe to be flat. The universe expands slower and slower forever as density goes down and the kinetic energy of expansion decreases with time. However, expansion never quite goes to zero. This is represented by the model second from the left in Figure 4.

The value of Ω_m for normal matter is around 0.03. It is estimated that about 85% of the matter in a galaxy consists of dark matter. Adding the contribution of dark matter brings the value of Ω_m to around 0.2. It is believed that there is also dark matter in the regions between galaxies. Figuring in this dark matter brings the value of Ω_m to about 0.3, much less than one. Consequently, the universe should have negative curvature and expand forever.

The density of the universe decrease as the universe expands. Expansion causes galaxies to be stretched further and further apart thus reducing the amount of mass per volume throughout the universe. Consequently, the value of Ω_m decreases as the universe continues to expand driving the universe further toward a negative curvature that expands forever.

However, all measurements indicate that today's universe is flat, not only flat but exceptionally flat. This discrepancy is resolved by dark energy. Measurements from a number of spacecraft, including WMAP and Planck, indicate that today the dark energy density $\Omega_\Lambda \approx 0.7$. Adding the contribution of dark energy, the total energy density of the universe today is very close to one meaning that the universe is flat, it will not collapse, but continue to expand at a decreasing rate. That is

$$\Omega_0 = \Omega_m + \Omega_\Lambda = 0.3 + 0.7 = 1$$

Observations of Type Ia supernovae in very distance galaxies indicate that expansion of the universe is not slowing down but instead expanding at an accelerating rate. How can this be? We know that the energy density of dark energy, Ω_Λ , is positive because a positive energy density beyond that of ordinary matter and dark matter, Ω_m , is required to make the universe flat, which we observe. That is, $\Omega_0 = \Omega_m + \Omega_\Lambda$ must be equal to 1. Consequently, dark energy pressure must be negative since only a negative pressure would produce the gravitational repulsive force required for the expansion of the universe to accelerate.

Initially, expansion of the universe was controlled by gravity. About 7.5 billion years ago the situation changed. The attractive force of gravity, weakened by continual expansion of the universe, fell behind the repulsive force of dark energy pressure as the dominate factor controlling expansion. Gravity decreases as the material objects creating it become stretched further and further apart. Under the increasing influence of dark energy pressure, slowing in expansion stopped, momentarily stabilized, and then began expanding at an accelerating rate as illustrated in Figure 5.

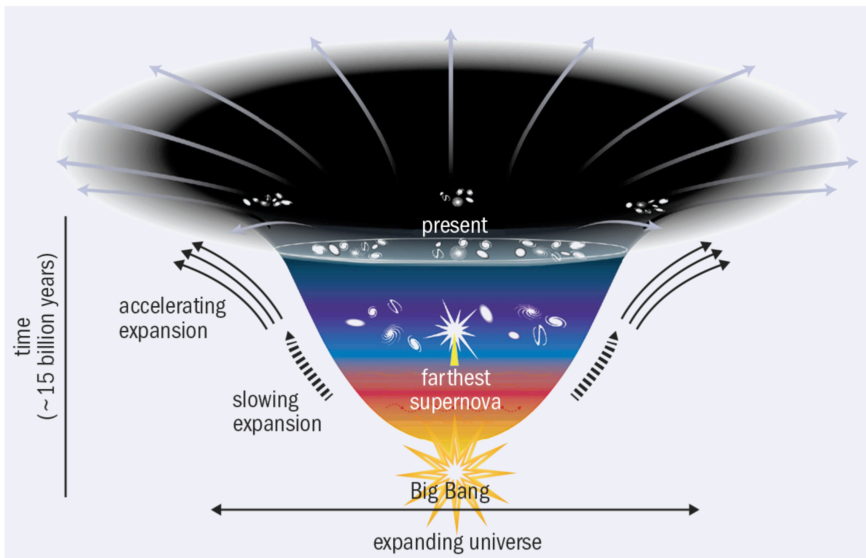


Figure 5 Universe rate of expansion (source: Physics World)

6.7 Fundamental Forces of Nature

The four fundamental forces of nature, responsible for controlling everything that happens in the universe, came into existence within the first picosecond of time. These forces are:

- The strong nuclear force,
- Electromagnetic force,
- The weak nuclear force, and
- Gravitational force.

The relative strengths of the four forces are shown in the following table in which the weak nuclear force has been arbitrarily assigned a value of 1.

Force	Relative Strength
Strong Nuclear Force	10,000
Electromagnetic Force	100
Weak Nuclear Force	1
Gravity	$7 \cdot 10^{-34}$

Table 2 Fundamental Forces of Nature

The strong nuclear force is the strongest force in nature. It holds together the subatomic particles, including up quarks and down quarks, that make up protons and neutrons. The strong force also holds protons and neutrons together in the nuclei of atoms. The strong force operates over an extremely short distance which is about the diameter of a proton. Two particles must be almost touching to be affected by the strong force. However, when two particles get close enough, the strong force "kicks in" dominating all other forces in nature. Since the strong nuclear force is one hundred times stronger than the electromagnetic force, it is able to hold together protons within a nucleus even though the positively charged protons, under the influence of the electromagnetic force, try to repel one another.

The electromagnetic force is the next strongest force. The electromagnetic force holds together atoms binding the cloud of negatively charged electrons to the positively charged nucleus. The electromagnetic force also binds together atoms into molecules and molecules into all of the more complex structures that we are accustom to including trees, oceans, and our human body. The electromagnetic force is the primary force underlying most of engineering, physics, chemistry, and biology. The electromagnetic force has an infinite range. The electromagnet force between two electrically charged objects is inversely proportional to the square of the distance separating them, but never goes to zero. Two electrons on opposite sides of a galaxy still repel each other even though the force between them is infinitesimally small. The electromagnetic force causes most large objects in the universe to be electrically neutral. If an object is electrically positive, it will over time attract and capture a sufficient number of electrons to become electrically neutral. A negatively charged object will eventually eject enough electrons to also become electrically neutral. This is so because everything in nature attempts to achieve the lowest possible energy state, which for material objects is electrically neutral.

The weak nuclear force has the shortest range of all the forces. Its range of influence is only about 1% the diameter of a proton. It is extremely unlikely that two particles will get close enough to interact via the weak force. That is, the probability of this occurring is very small, but not zero. Thus, reactions that occur as a result of the weak force occur at an extremely slow rate. The weak force is, however, responsible for radioactive decay and, under certain conditions, the transformation of a proton into a neutron and similarly the reverse conversion of a neutron into a proton. The transformation process between protons and neutrons enables the production of all elements other than hydrogen. Radioactive decay provides much of the heat required to keep the Earth's nickle-iron core molten. A molten nickle-iron core is extremely important since it is responsible for Earth's significant magnetic field that largely shields Earth's atmosphere from erosion by the solar winds emanating from the Sun.

Gravity is incredibly weak in comparison to the other three forces, and yet it is the most important. In relative terms, the strength of gravity is only $7 \cdot 10^{-34}$ compared to the weak nuclear force, the next smallest force. However, the range of gravity is infinite and it attracts **all** types of matter. Thus, gravity accumulates! The gravity associated with a small particle attracts other particles and they attract it, forming a larger body. The gravitational force associated with a large body is the sum of the gravitational forces of each of its component particles. As a body grows in size, so does its gravitational force pulling in more and more material, leading eventually to the development of planets, stars, and galaxies. Gravity holds together solar systems, galaxies, and galactic clusters. It makes stars and planets rounds. It holds us, the oceans, and most other things that we are familiar with to the surface of the Earth. It causes weaken buildings to collapse, mountains to erode, and ultimately determines the fate of the universe. Thus, despite its intrinsic weakness, the infinite range of gravity and its attraction force exerted on all forms of matter cause gravity to dominate all other forces on a large scale.

6.8 Evolution of the Universe

Evolution of the universe beginning with the Big Bang is illustrated in Figure 6.

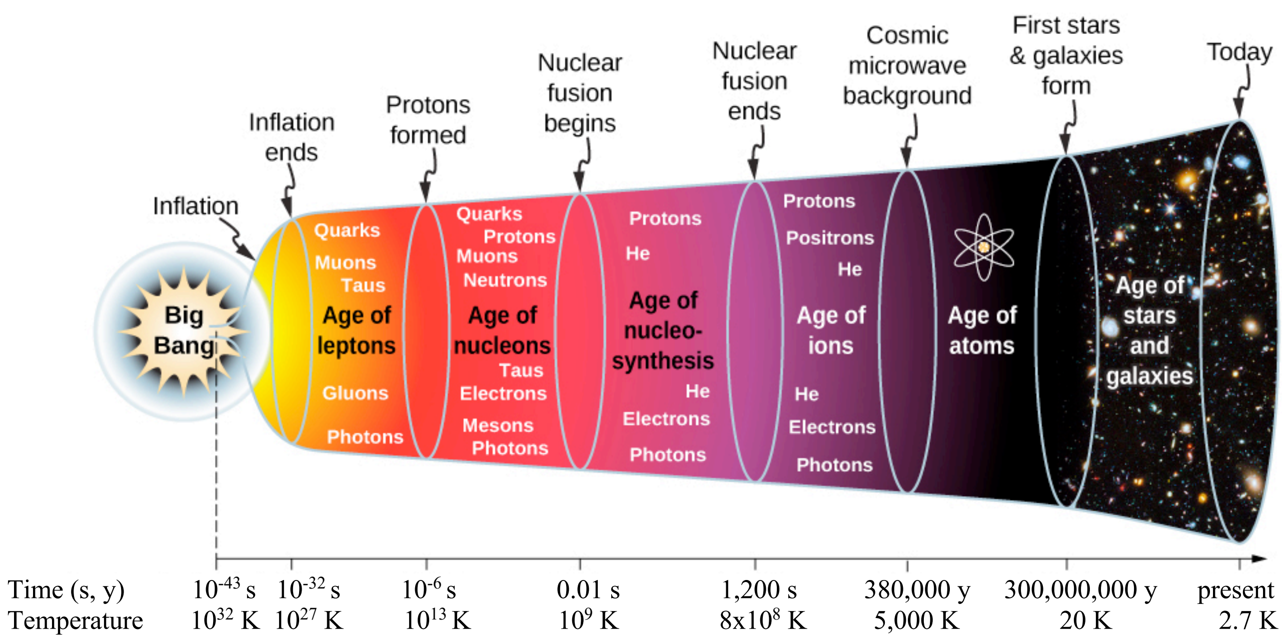


Figure 6 Big Bang Timeline (source: author / civilsdaily)

6.8.1 Planck Epoch

We do not understand what happened at the beginning of the Big Bang (at time $t = 0^+$), but our knowledge of physics is good enough to determine, with a fair degree of confidence, what happened from that point on. In fact, we are pretty sure that we understand what happened from 10^{-45} seconds onward.

The Planck Era is defined as the time from t = 0 to 10^{-43} seconds. 10^{-43} seconds is the closest that current physics can get to the absolute beginning of time. Not much is known about the Planck Era. It is believed that the four fundamental forces of nature (the strong nuclear force, electromagnetic force, weak nuclear force, and gravity) all had about the same strength and possibly where unified into one single fundamental force. The size of the universe at 10^{-43} seconds was about $10^{-35}\ meters$ and had a temperature of over $10^{32}\ °K$. The diameter of proton is $8.5\ x\ 10^{-16}\ meters$. During the Planck Era the universe was incredibly small (much smaller than a proton), extremely hot, and dense!

6.8.2 Grand Unification

The gravitational force separated from the other three fundamental forces during the Grand Unification epoch from 10^{-43} to 10^{-35} seconds (Figure 7). The other three forces remained unified in a single force (the grand unification).

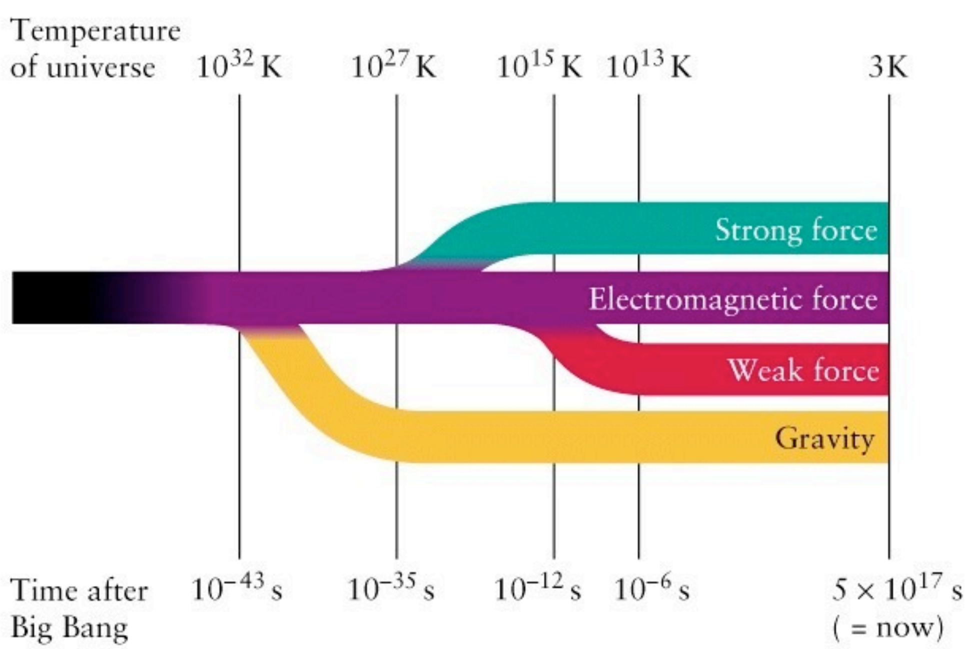


Figure 7 Separation of the 4 Fundamental Forces (source: wonders-of-the-cosmos.tumblr.com)

6.8.3 Inflation Epoch

From 10^{-35} to 10^{-32} seconds the universe expanded at an extremely rapid exponential rate. It is estimated that the universe expanded from about the size of a proton, 8.5×10^{-19} km, to over a light year across, $9.46 \times 10^{+12}$ km in less than 10^{-20} picoseconds, a rate far beyond the speed of light.

The rapid inflation was accompanied by separation of the strong nuclear force from the remaining two forces (the electromagnetic force and weak nuclear force) as illustrated in Figure 7.

6.8.4 Electroweak Epoch

The period from 10^{-32} to 10^{-12} seconds is known as the Electroweak Epoch. The electromagnetic and weak nuclear forces were still unified through most of this period. The weak nuclear force and the electromagnetic force separated toward the end of this period, at around 10^{-12} seconds, a picosecond after initiation of the Big Bang. The temperature of the universe at 10^{-12} seconds was around 10^{15} ºK (Figure 7).

During this period energy transformed into photons of gamma ray light. A photon is a packet of energy in the form of a particle with zero mass that travels as the speed of light. A photon **is** a particle of light (see the "Wave Particle Duality" chapter in the Appendix). Gamma rays are the highest energy highest frequency form of light, way above the energy and frequency of ordinary visible light.

The energy E of a photon is equal to

$$E = h \cdot f = h \cdot \frac{c}{\lambda}$$

c = the speed of light (c = 299 792 458 m / s)

h = Planck's constant (h = $6.62607004 \times 10^{-34}$ m^2 kg / s)

f = frequency in Hertz

λ = wavelength in meters

6.8.5 Quark Epoch

From 10^{-12} to 10^{-6} seconds, in a period of one microsecond, the universe cooled from around 10^{15} to 10^{13} ºK (Figures 6 and 7). At these temperatures elementary particles and anti-particles began to form through a process called pair production. Particles and anti-particles are the same except they have opposite electrical charges. Because of their opposite charges, a particle and anti-particle will annihilate each other if they collide. A particle and an anti-particle are formed when two extremely energetic photons collide annihilating the two photons. In the process energy of the photons is converted into mass (the particle and anti-particle) accordance to Einstein's equation $E = mc^2$. In this case E is the energy of the colliding photons and m is the mass of the matter-antimatter pair formed by the collision.

Elementary particles are the basic building blocks of all matter. They are collectively known as Fermions. Elementary particles have no internal structure. For example, an electron is an elementary particle since it has no internal structure. An electron is an electron. In contrast, protons and neutrons are not elementary particles. Protons and neutrons both have internal structures composed of various types of quarks which are bound together by the strong nuclear force.

Fermions are divided into two types

- Quarks, and
- Leptons

Quarks interact with the strong nucellar force, leptons do not.

Fermions consist of twelve particle, six quarks and six leptons, grouped into three generations. Each generation consists of two quarks and two leptons as shown in Table 3. The characteristics of each particle type is known to a high degree of certainty, with the exception of the neutrinos. For example, the mass of an electron is known to a precision of better than one part in 10 million. In addition, each particle of a given type is absolutely identical to all other particles of that type. They are indistinguishable. If this were not so, for example if one electron was ever so slightly different than another electron, atoms would collapse and life would not exist. We also have good reason to believe, but no definitive proof, that Table 3 is the complete list of Fermion elementary particles.

The six quarks are named up (u), down (d), charm (c), strange (s), top (t), and bottom (b). These fanciful names have nothing to do with their properties. They are simply fun names. None are more charming or strange than any of the others. Quarks combine together to make hundreds of larger particles. The two most important are the proton and the neutron.

	Generation Number			
Particle	**1**	**2**	**3**	**Charge**
Quarks:	u - (up)	c - (charm)	t – (top)	+ 2/3
	d - (down)	s – (strange)	b – (bottom)	- 1/3
Leptons:	e – (electron)	μ – (muon)	τ – (tau)	- 1
	v_e – (electron neutrino)	v_μ – (muon neutrino)	v_τ - (tau neutrino)	0

Table 3 Elementary Particles

Leptons are not affected by the strong force. They include the electron, muon, and tau all with a charge of -1. Muon and tau leptons are more massive versions of an electron. A muon is 207 times heavier than an electron, while a tau is 3,500 times heavier.

Leptons also include three types of neutrinos, the electron neutrino, muon neutrino, and tau neutrino all of which have no electric charge. The characteristics of neutrinos are well known except for their mass which is very small, probably less than one billionth the mass of a proton. It is difficult to determine the mass of neutrinos because they are so light and ghostly. The interaction between neutrinos and other particles is so weak that a neutrino can pass through a thousand miles of steel without hitting anything.

The particle generation number does not mean that one set of particles are the descendants of a previous generation. Instead, the generation number refers to their relative masses. A generation 3 particle has a greater mass than its corresponding generation 2 particle. In turn, a generation 2 particle is more massive than a generation 1 particle. Because of their greater masses, the life of generation 2 and 3 particles is extremely short. Consequently, generation 2 and 3 particles are extraordinarily rare in nature. They are so rare that generation 2 and 3 particles are of little importance in the evolution of the universe. All material that we encounter throughout the universe (including stars, planets, ourselves) are made of first generation charged fermions!

Each type of particle has an associated anti-particle. An anti-particle is the same as its corresponding particle except that it has the opposite electrical charge. For example, a positron (an electron anti-particle) is the same as an electron but has a charge of +1 instead of -1.

In the early universe, particles and antiparticles constantly collided, annihilating each other, and producing pairs of photons in the process. After annihilation, nothing remained of the original particle and antiparticle, no residual charge, no residual matter, no residual anything. It was all transformed into energy in the form of two photons. Photons in turn collided producing more particle – antiparticle pairs and so on. The chaotic process of pair production and annihilation continued as the universe expanded further, eventually cooling to the point where colliding photons no longer had enough energy for pair production. When pair production stopped, particles and antiparticles that annihilated each other were no longer replaced. The annihilation of particles and antiparticles should have been complete leaving the universe filled with only radiation, photons with too little energy to produce particles. Had this happened there would be no galaxies, stars, planets, no us in the universe. This almost happened, but not quite. For every electron in the universe today there were 10 billion and **one** electrons in the early universe, but only 10 billion positrons. This one-part-in 10-billion excess of electrons over positrons meant that when electron-positron annihilation came to an end, some electrons were left over, enough to account for all the electrons in all the atoms in the universe today. The same occurred with quarks and antiquarks. When the annihilation stopped, a few quarks were left over. At this point, all of the matter (elementary particles) needed to build the universe had been created in a period of one microsecond.

6.8.6 Formation of Protons and Neutrons

At time equal to 10^{-6} seconds the universe had cooled to around 10^{13} degrees kelvin, cool enough to permit up and down quarks to combine (stick together) under the strong nuclear force forming protons and neutrons. The composition of protons and neutrons are shown in the following table.

Particle	# Up Quarks: Charge = +2/3	# Down Quarks: Charge = -1/3	Total Charge
Proton	2	1	+1
Neutron	1	2	0
Electron	An elementary particle		-1

Table 4 Atomic Particles

Formation of protons and neutrons was not a simple process. At these high temperatures collisions between protons, neutrons, electrons, neutrinos, and quarks caused frequent transmutations of protons into neutrons and visa versa.

Neutrons are slightly more massive than protons. Because of their higher mass more energy is required to produce neutrons resulting in fewer neutrons being created than protons.

- Neutron mass = 1.674927×10^{-27} kg
- Proton mass = 1.672622×10^{-27} kg

The formation of protons and neutrons lasted for about 10 milliseconds, stopping when the universe cooled below 100 billion degrees (10^{11} ^{o}K). When the formation process stopped, the concentration of protons verses neutron was 7 protons for every neutron.

6.8.7 Nucleosynthesis

At about 1 billion degrees kelvin protons and neutrons had cooled down enough to begin sticking together forming the first simple atomic nuclei, a process called nucleosynthesis. This occurred in the first few minutes of time. The simplest nuclei is hydrogen consisting of a single proton. The next more complicated nuclei is deuterium consisting of one proton and one neutron. Beyond that, a helium nuclei consists of two protons and two neutrons while a lithium nuclei has 3 protons plus 3 or 4 neutrons depending on the isotope. Since there were so few neutrons, one neutron for every 7 protons, only 1 proton in 7 could unite with a neutron to form a deuterium nuclei. In atomic form a deuterium atom, also known as heavy hydrogen, consists of a single electron orbiting a nucleus composed of one proton and one neutron. Deuterium can only be made by the Big Bang. Stars can not make it.

Only a small fraction of deuterium, about one deuterium to 40,000 hydrogen nuclei, remained as deuterium. The rest quickly combined in pairs to form helium nuclei. Again, a helium nuclei consists of 2 protons and 2 neutrons. Consequently, out of every 16 nucleons (14 protons + 2 neutron) four nucleons (2 protons + 2 neutrons) became a helium nuclei while the remaining protons became 12 hydrogen nuclei.

At this point the universe was too hot to form complete atoms, a complete atom consisting of a nucleus plus orbiting electrons. Instead, the universe was filled with ions; positively charged hydrogen nuclei (protons), helium nuclei, a few lithium nuclei, plus a large number of negatively charged electrons. Electrons at billion degree temperatures contain enormous energy. If an electron was briefly captured by a proton, forming a neutral hydrogen atom, the energetic electron quickly broke free from the atom turning the atom back into a positive ion.

After about 20 minutes the temperature of the universe had dropped below 800 million degrees kelvin. At this temperature nuclei could no longer form. Nucleosynthesis stopped. At the end of nucleosynthesis roughly three-quarters of the universe by mass was hydrogen and one-quarter helium. In addition to hydrogen and helium, the universe contained very small amounts of lithium (several parts in ten billion compared to hydrogen) and small amounts of remaining deuterium (one part in ten thousand). The remaining 100 or so chemical elements, including increasing concentrations of helium and lithium, where and still are produced in the stars. But the concentrations of these elements are only a few percent of the overall mass in the universe. In terms of number of atoms, 98% of the universe today is composed of hydrogen. In terms of mass, 71 % of the universe is hydrogen, 27% is helium and 2% by mass is everything else.

6.8.8 Photon Epoch

The universe gradually cooled from 800 million degrees to around 5,000 ^{o}K over the next 380,000 years. To put this in perspective, the core of the Sun has a temperature of 15.8 million degrees kelvin. The photosphere, what we perceive as the Sun’s surface, has a temperature that ranges from 6,500 to 4,400 ^{o}K. 4,400 ^{o}K is the temperature of the photosphere’s outer edge, the part of the photosphere furthest from the Sun’s core.

During the Photon Epoch the universe was filled with a hot plasma, an opaque soup of electrons and protons (hydrogen nuclei) plus heavier nuclei of deuterium, helium and trace amounts of lithium. The energy of the universe at this time was dominated by photons. High energy photons continuously ionized any neutral atoms that happened to form. If an electron was briefly captured by a proton, forming a neutral hydrogen atom, it was quickly hit by one of the trillions upon trillions of high-energy photons knocking the electron free from the hydrogen atom.

Photons interact strongly with electrons. In this hot soup of particles, photons could not travel very far before colliding with electrons scattering the photons in all directions. Scattering caused the universe to be opaque, a “dense fog”. (See the chapter on “Wave Particle Duality” in the Appendix.)

6.8.9 Recombination/Decoupling

The universe changed dramatically 380,000 years after the big bang. By then its temperature had dropped to around 5,000 ºK allowing the electromagnetic force to join negatively charged electrons with positive nuclei forming neutral atoms. This process is called recombination. At 5,000 ºK and below, photons no longer had enough energy to ionize the atoms that were forming.

Neutral hydrogen, as well as helium and lithium atoms, do not scatter photons nearly as much as free electrons. The universe suddenly became transparent as free electrons were combined into neutral atoms. The fog lifted. From that time, 380,000 years after the big bang, photons have traveled freely in straight lines throughout the universe as illustrated in Figure 8.

The green panel in Figure 8 illustrates the early universe. Photons, the black wiggly lines, were constantly scattered in all directions as they collided with electrons, the white dots. Scattering of photons caused the universe to be opaque. 380,000 years after the big bang, the blue panel, the universe became transparent as electrons and nuclei formed into neutral atoms, freeing photons to travel throughout the universe with little or no scattering. The process of freeing photons from constant scattering by electrons is referred to as decoupling.

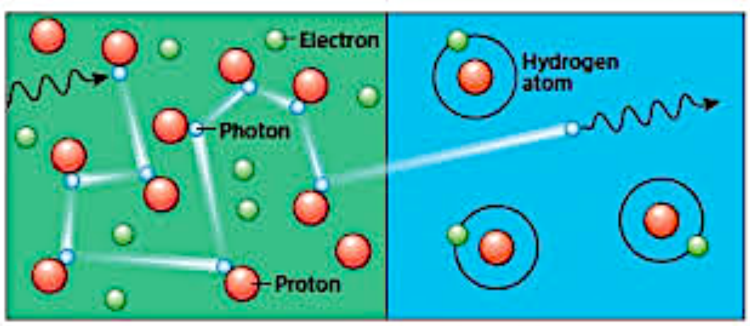


Figure 8 The universe turns transparent (source: astronomy.com)

6.8.10 Dark Age

The period from 380,000 to 300 million years is referred to as the Dark Age. This was the age before the first stars. Although abundant photons existed, the universe at this time was literally dark with no stars having formed to give off light. Activity in the universe had tailed off dramatically, energy levels were very low, and little of note was happening.

6.8.11 Star and Galaxy Formation

Star formation began 300 to 500 million years after the Big Bang. Gravity amplified slight irregularities in the primordial hydrogen and helium gas that filled the universe. Pockets of gas formed and grew into huge dense clouds under the influence of gravity. One by one these clouds collapsed under their own gravitational weight becoming hot enough at their cores to trigger thermonuclear fusions. In each case, energy from the nuclear reaction flowed outward stopping the gravitational collapse. In the process a stable star formed radiating a broad spectrum of light from inferred, through visible light, to extreme ultra-violate and x-rays. After the formation of stars, the universe was no longer dark.

The first stars were composed entirely of hydrogen and helium, the only material available in the universe at that time. These stars were massive, hundreds of times the size of our Sun, and had life spans that were very short, typically less than a 100 million years. The thermonuclear fusion of hydrogen into helium within the core of a supermassive star had to "burn" at a ferocious rate in order to keep the star from collapsing in on itself under it own enormous weight. The star's core compressed as hydrogen was consumed driving core temperatures and pressures high enough to initiate thermonuclear fusion of helium into carbon. The core compressed further as the supply of helium diminished increasing core temperatures to 600 million degrees, hot enough to fuse carbon into oxygen, neon, and magnesium. The cycle continued until at temperatures of several billion degrees iron, cobalt, and nickel formed. At this point the core was so dense that it could not be compressed any further. Thermonuclear reactions in the core stopped. When that happened, the star collapsed. Outer regions of the star came crashing down into the core producing a massive supernova explosion. In the process, atomic nuclei were ripped apart forming free protons and neutrons which were captured by other nuclei forming heavy elements like gold, lead, and uranium. Remnants of exploded stars formed huge gas nebula containing trace amounts of elements that had been produced in the stars (Figure 9). These nebula became the birth place for second and third generation stars. These stars were, and still are, composed primarily of hydrogen and helium but also have trace amounts of other elements present in the nebula. For the first time solar systems, consisting of planets orbiting a central star, became possible due to the material that had been produced by the first generation of stars.

Second and third generation stars includes not only massive stars but also yellow dwarf stars like our Sun (a third generation star) and even smaller red dwarf stars.

Yellow dwarf stars live for 10 billion years or more as the thermonuclear reactions within their cores proceed slowly fusing hydrogen into helium. A yellow star reaches the end of its life as the hydrogen within its core becomes depleted. Gravitational forces compress the core causing temperatures and pressures to rise triggering thermonuclear fusion of helium into carbon. Energy released by this reaction expands the star into a red giant. When the Sun becomes a red giant its size will engulf the orbits of Mercury and Venus resulting in a scorched Earth becoming the closest planet to the Sun. Despite its now bloated size, the red giant is not massive enough for thermonuclear fusion of carbon to occur. When the helium fuel in its core is consumed, the star collapses into an extremely dense white dwarf about the size of Earth. The outer layers of the original star dissipate into space forming a planetary nebula surrounding the white dwarf (Figure 10).

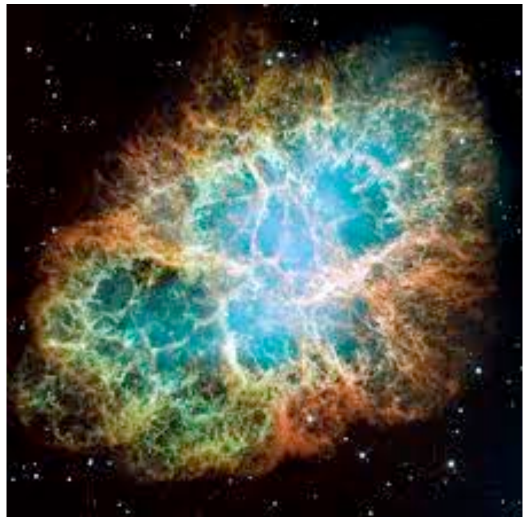


Figure 9 Supernova remnant (source: Wikipedia)

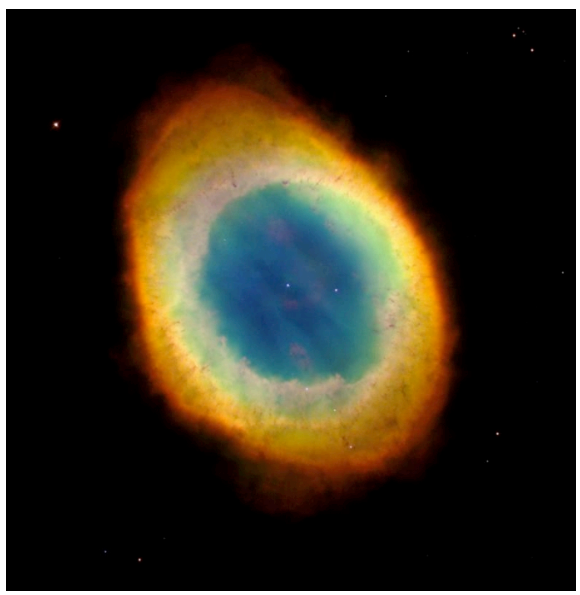


Figure 10 Planetary nebula with white dwarf star at its center (source: John Dutton PennState)

Red dwarf stars range in size from roughly $\frac{1}{10}th$ to $\frac{1}{2}$ the size of our Sun. A red dwarf is large enough to produce a core temperature of over 10 million degrees, sufficient for thermonuclear fusion of hydrogen into helium. A red dwarf lives an extremely long life on the order of six to twelve trillion years. However, a red dwarf does not have sufficient mass to generate the temperatures and pressures necessary to fuse helium into carbon. When the thermonuclear fusion of hydrogen in its core is complete, it collapses slowly over several hundred billion years into a white dwarf star.

The first galaxies formed about 1 billion years after the Big Bang as gravitational forces pulled stars closer together. In turn, gravitational forces pulled galaxies into groups, clusters, and superclusters until today the universe is filled with trillions of galaxies (Figure 11).

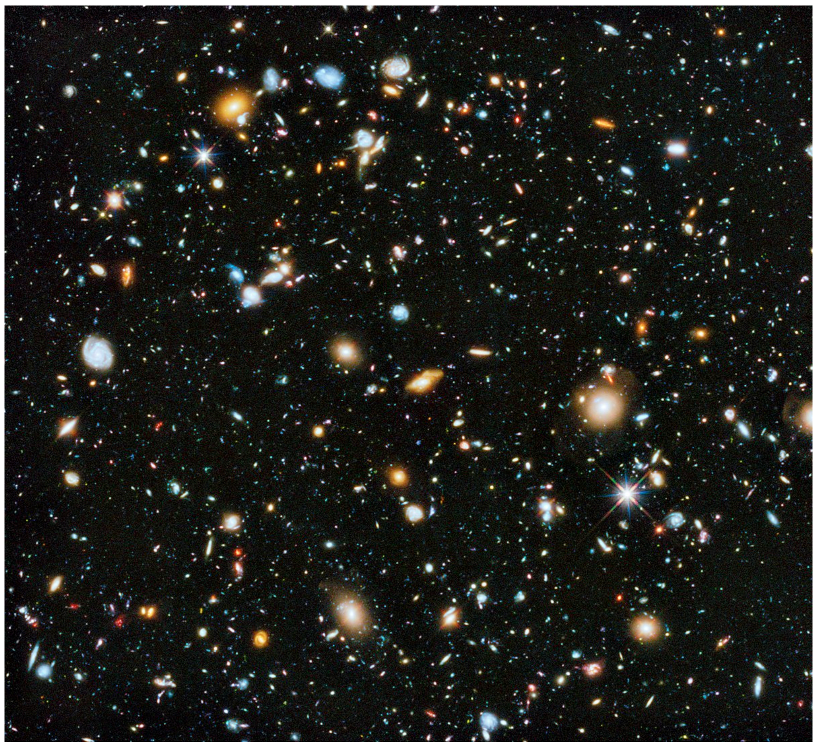


Figure 11 Universe filled with galaxies (source: NASA)

6.9 Cosmic Microwave Background Radiation

We should be able to see light from when the universe became transparent 380,000 years after the big bang, and we can!

At that time the universe radiated as a blackbody at a temperature of around 5,000 ^{o}K. Blackbody objects, which are often not black in color, radiate energy over a range of wavelengths determined entirely by their temperature (see the "Wave Particle Duality" chapter in the Appendix). Stars radiate as blackbodies as well as humans and most other things that we are familiar with. Figure 12 shows the blackbody curves for three types of stars, a very hot blue star, a medium temperature yellow stars like our Sun, and a cool red star.

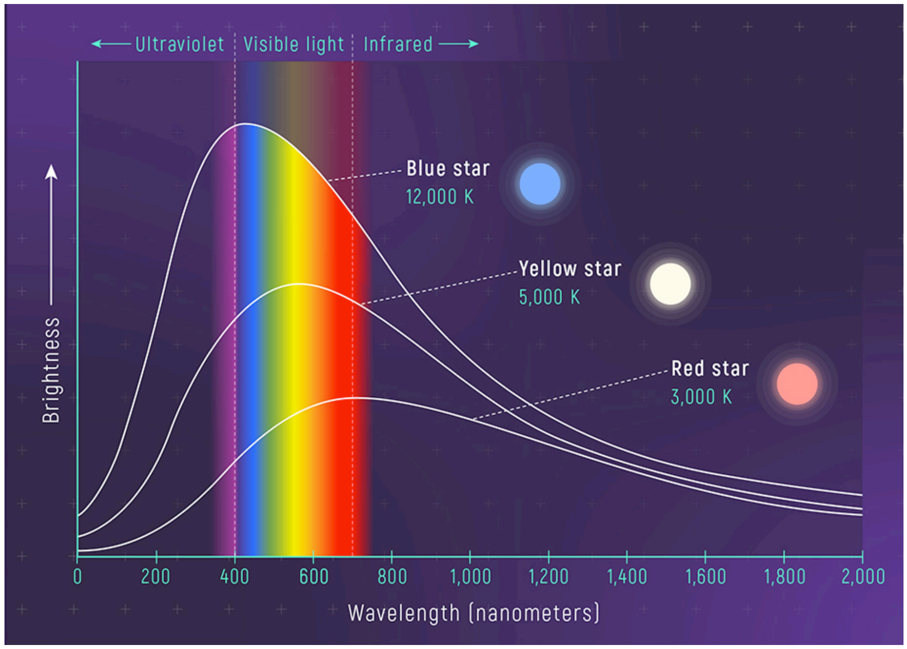


Figure 12 Blackbody spectrum of stars (source: NASA)

In Figure 12 the blackbody curve for a very hot 12,000 °K star peaks in the blue range of the spectrum at a wavelength around 400 nanometers (nm), which is why very hot stars are blue in cooler. These stars also radiate lesser amounts of energy at both shorter and longer wavelengths. For example, a blue star radiates a significant amount of energy at 200 nm as well as at 1,000 nm. However, the energy radiated goes to zero at very short wavelengths (< 50 nm) and at very long wavelengths (> 2,000 nm). Medium temperature stars like our Sun (a yellow star) peak at longer wavelengths, specifically at 580 nm for the Sun. Cool red stars peak at still longer wavelengths in the red part of the spectrum around 700 nm, which is why cool stars are red in color. Notice in Figure 12 that the energy radiated (the brightness) of the blue star is significantly greater than the yellow star. In turn, the brightness of the yellow star is greater than that of the red star. The blackbody curves for cool objects always peak at longer wavelengths and radiate less energy than hot objects. However, the shape of all blackbody curves are the same. They are defined by an equation developed in 1900 by German physicist Max Planck (see the "Wave Particle Duality" chapter in the Appendix).

The blackbody radiation curve for a human is shown in Figure 13. At a body temperature of 98.6 °F (310 °K) the human blackbody curve peaks at 9,550 nm, far to the right of the curves shown in Figure 12. A comparison of the blackbody curve for the Sun, at a temperature of 6,000 °K, to that of a human with a temperature of 303 °K is shown in Figure 14. In this figure the brownish-orange curve is the blackbody curve for the Sun and the maroon curve to the right is that for a human. The blackbody peak wavelength of a human (9,550 nm) is 16 times longer than that of the Sun (580 nm) while the energy output of a human ($10^{7.2}$) is a million times less than the Sun ($10^{13.5}$). However, the shape of the human blackbody curve is the same as that of the Sun.

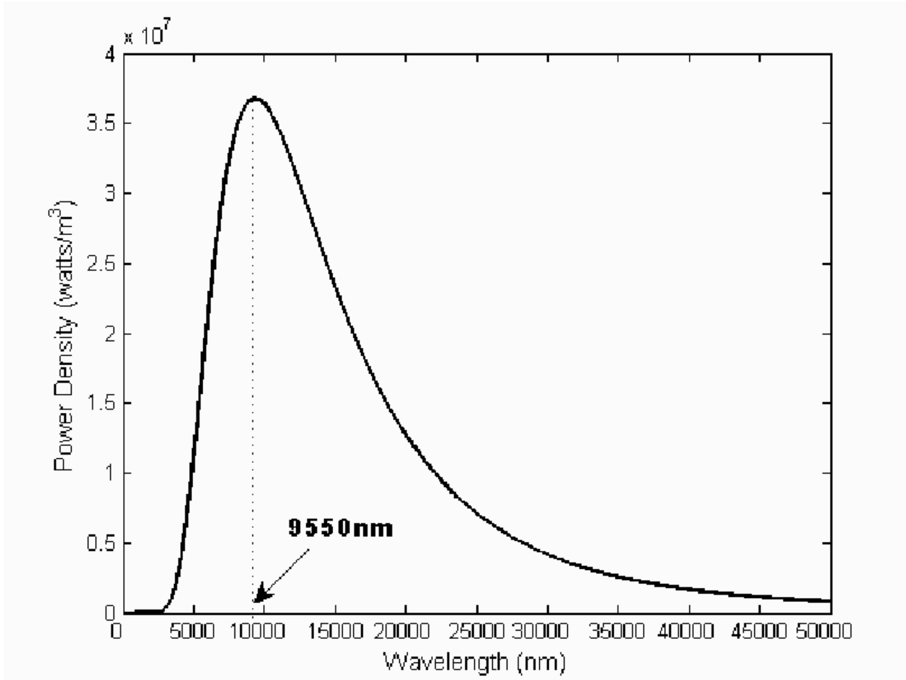


Figure 13 Blackbody radiation curve for a human (source: researchgaate.net)

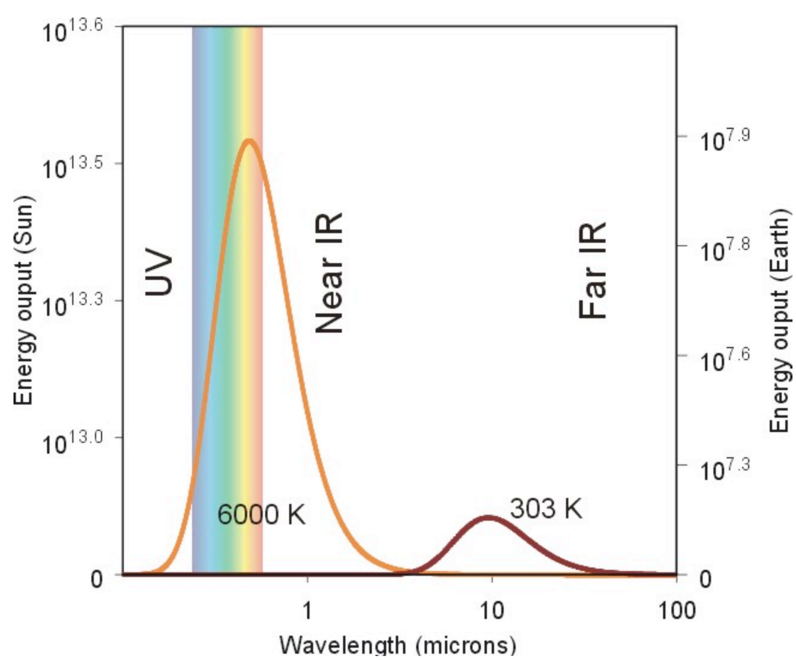
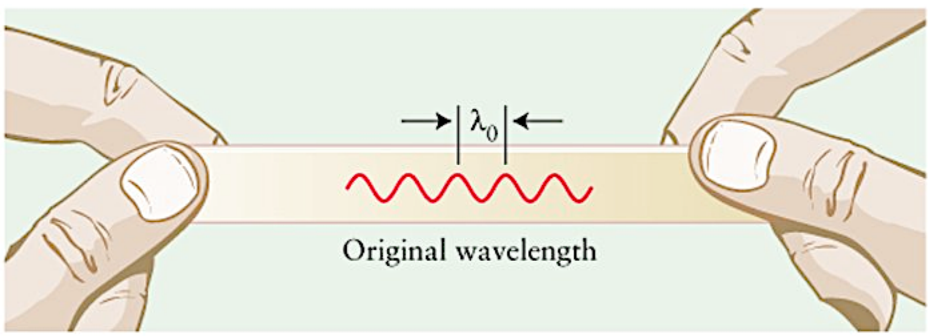


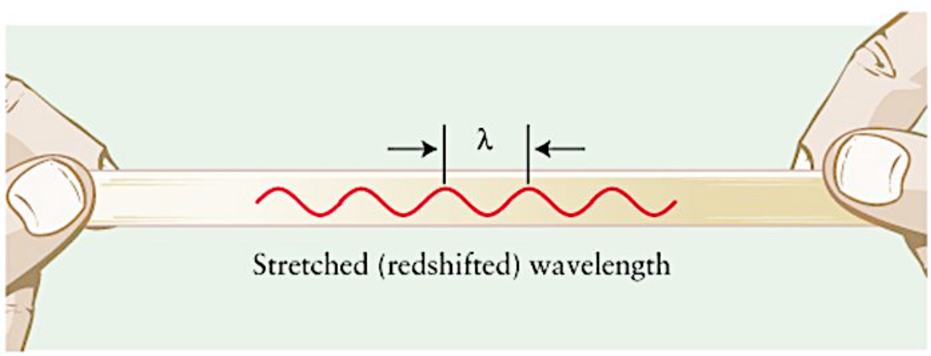
Figure 14 Blackbody curve of Sun vs human (source: learningweather.psu.edu)

There were no stars or galaxies 380,000 years after the big bang. Stars and galaxies had not yet formed. The temperature of the universe at that time was around 5,000 ºK, about the same temperature as the surface of our Sun. Consequently, the blackbody radiation curve for the 380,000 year old universe was similar to that of the yellow star shown in Figure 12 with a wavelength around 600 nm.

The universe expanded by a factor of about 2,000 from the time it was 380,000 year old till now 13.8 billion years later. As it expanded the universe cooled by the same factor from 5,000 ºK to around 2.5 ºK, close to but not quite absolute zero. At the same time the wavelength of blackbody energy radiated when the universe was 380,000 years old was stretched out by a factor of 2,000, from 600 nm to approximately 1.2 mm, as the universe expanded. A wavelength of 1.2 mm is in the microwave radio segment of the electromagnetic spectrum. Wavelength stretching is illustrated in Figure 15.



(a) A wave drawn on a rubber band ...



(b) ... increases in wavelength as the rubber band is stretched.

Figure 15 Cosmic Stretching (source: University of Alberta)

In this figure the expanding universe is represented by a rubber band. Figure 15a illustrates the universe when it was 380,000 years old. The red sinewave drawn on the rubber band illustrates blackbody energy radiated at that time with a wavelength of λ_0. Figure 15b shows the universe sometime later when it has expanded, simulated by stretching the rubber band. The original wavelength λ_0 has now been stretched by the expanding universe to some longer wavelength λ.

In 1948 doctoral students Ralph Alpher and Robert Herman predicted that the universe today should be filled with thermal radiation left over from the Big Bang. Using arguments similar to those above, they calculated that the temperature of this radiation today should be around 5 ^oK . However, by the 1960's this prediction was largely forgotten.

In August 1960 the Echo-1 satellite was launched. Echo-1 was one of the many experimental satellites launched in the very early days of space exploration. It was a metalized sphere (a balloon) inflated in orbit to a diameter of about 100 feet. The purpose of Echo-1 was to test the feasibility of long-distance communications via Earth satellite. Echo-1 did not contain any electronics for relaying radio signals. Instead, it was purely a passive device designed to reflect radio signals back to Earth. During the testing, 2.39 GHz microwave signals transmitted from the NASA Goldstone facility in California's Mojave Desert, reflected off the satellite, and were received at AT&T's Holmdel, New Jersey facility. A 6 meter (20 ft) horn antenna at Holmdel (Figure 16) was meticulously designed and constructed to avoid picking up any terrestrial microwave signals that might otherwise interfere with the very weak signals reflected from Echo-1. In addition, the receiver was cooled with liquid helium to 4 ^oK to suppress any interference that the receiver itself might generate. Echo-1 achieved its design objectives. Microwave signals from Goldstone were reflected off of Echo-1 and received at Holmdel.

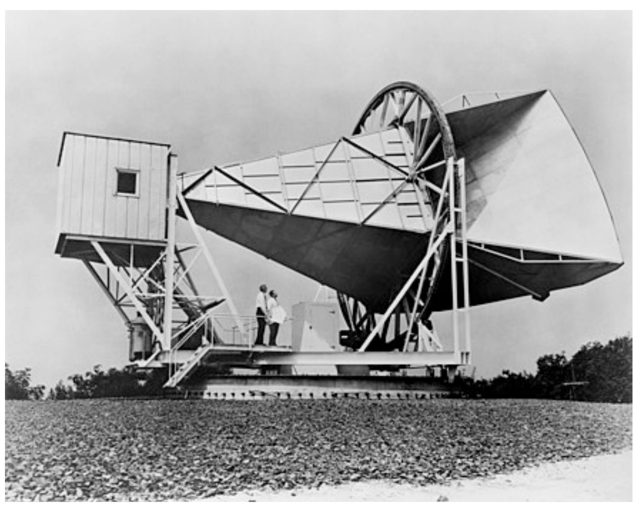


Figure 16 Horn antenna at Holmdel, New Jersey (source: wikipedia)

On July 10, 1962 AT&T and NASA launched the world's first active communications satellite (Telstar) to further test the feasibility of using Earth satellites for long distance communications. The beach-ball sized satellite is shown in Figure 17. Unlike Echo-1, Telstar was an active device containing electronics needed to receive signals transmitted to it, reconstitute the integrity of those signals, and transmit them back to Earth. The mission was a brilliant success including, among other things, transmitting the world's first transatlantic television signal. The satellite kept sending data until February 1963 when its transmitter finally failed. The success of Telstar caused Echo-1 and its related technology to become obsolete.

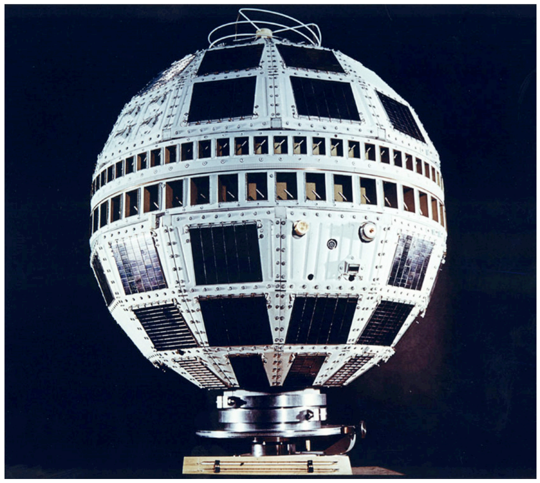


Figure 17 Telstar Communications Satellite (source NASA)

In 1964 Bell Laboratory scientists Arno Penzias and Robert Wilson (Figure 18) obtained permission to use the super sensitive Holmdel horn antenna and receiver to map the sky at microwave wavelengths. To their surprise they discovered a mysterious noise that emanated from every region of the sky. The noise was 100 times more intense than they expected and was present day and night. They were certain the noise did not come from Earth, the Sun or our galaxy since it emanated from all parts of the sky. They carefully checked their equipment, removed some pigeons nesting in the antenna and cleaned out accumulated droppings. However, the noise remained. They concluded that the noise must be coming from outside our own galaxy, although they were not aware of any radio sources that would account for the noise.

In the early 1960s Bob Dicke, Jim Peebles, Dave Wilkinson, and Peter Roll of the Princeton University physics department came to the same conclusion that Ralph Alpher and Robert Herman came to in 1948. We should be able to see (detect) light coming from the time when the universe became transparent. They also concluded that this radiation should have a peak blackbody wavelength in the microwave band, perhaps around 1 millimeter. To test their theory they began building a microwave telescope on the rooftop a Princeton University building. When they heard the results obtained by Penzias and Wilson, they were convinced that their prediction of a cosmic microwave background radiation had actually been discovered by Penzias and Wilson. Two papers were written. The Princeton paper predicted the existence of the cosmic microwave background (CMB) radiation. The Penzias and Wilson paper documented the discovery of the radiation. Both papers were published back-to-back in the Astrophysical Journal in May 1965. Penzias and Wilson were awarded the 1978 Nobel Prize in Physics for their discovery.

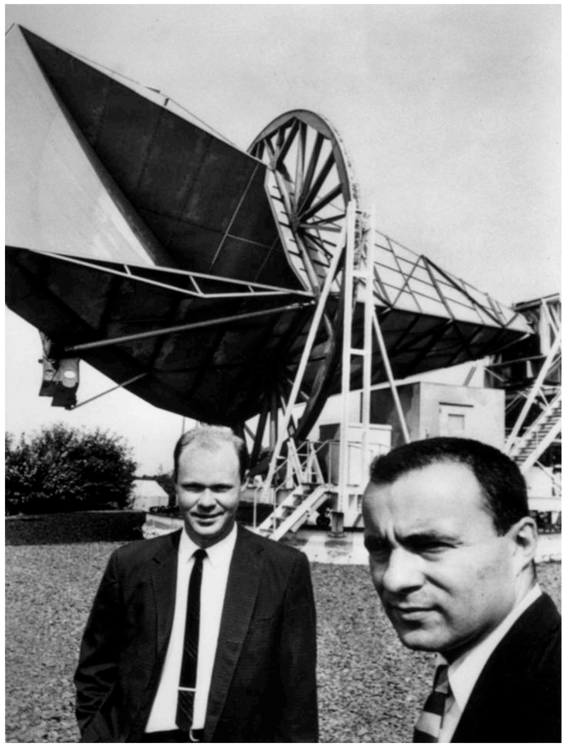


Figure 18 Robert Wilson (left) and Arno Penzias (right) - (source: jila.colorado.edu)

The original 1948 paper by Alpher and Herman predicted that the peak temperature of the CMB blackbody spectrum should be about 5 ^oK. Penzias and Wilson found the temperature to be 3.5 ^oK which is the number that they published in their 1965 paper. Since then the peak CMB blackbody temperature has been refined to 2.725 ^oK at a wavelength of 1.9 mm with a peak frequency of 160.4 GHz. The CMB blackbody spectrum is shown in Figure 19.

Discovery of the CMB radiation convinced the astronomical community that the Big Bang model is correct. Other models describing the beginning of the universe can not explain the CMB radiation.

Since 1964 the COBE, WMAP and Planck spacecraft have confirmed the existence of the CMB radiation and refined its parameters.

The Cosmic Background Explorer (COBE) satellite, Figure 20, was launched November 18, 1989 to make precise measurements of the cosmic background radiation. The spacecraft carried three instruments, a Far Infrared Absolute Spectrophotometer (FIRAS), A Differential Microwave Radiometer (DMR), and a Diffuse Infrared Background Experiment (DIRBE). The Far Infrared Absolute Spectrophotometer compared the spectrum of the cosmic microwave background radiation with a theoretical blackbody radiation. The Differential Microwave Radiometer precisely mapped the cosmic radiation. The Diffuse Infrared Background Experiment was used to search for cosmic infrared background radiation.

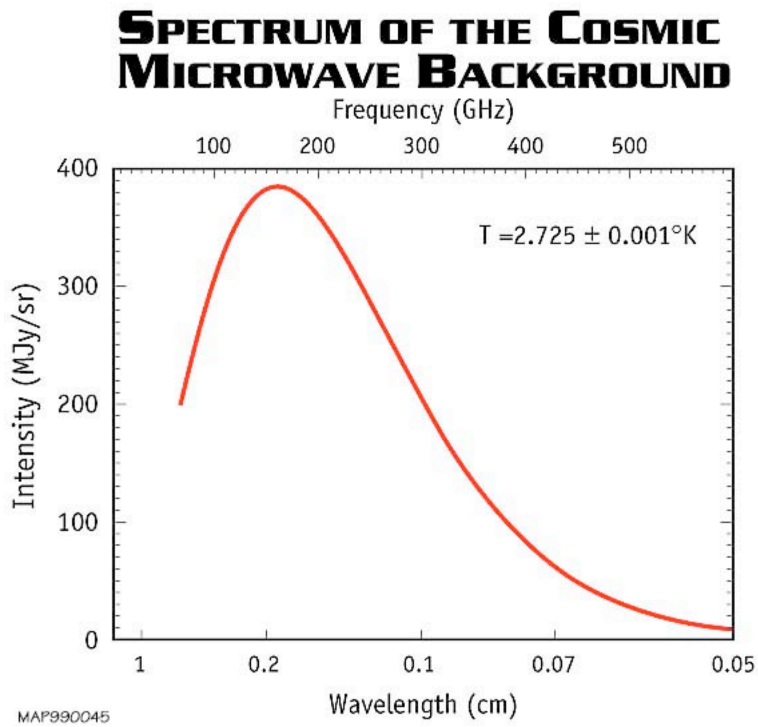


Figure 19 CMB spectrum (source: arstechnica.com)

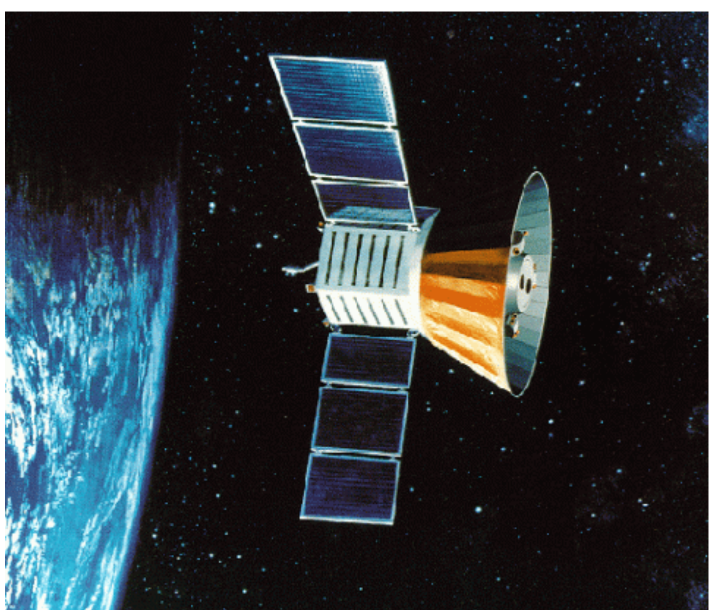


Figure 20 Cosmic Background Explorer (COBE) satellite (source: NASA)

The base module of the satellite contained the attitude control, communications and power systems. The experiment module was located inside the conical Sun shield. The satellite rotated at 1 rpm and was oriented so that the Sun was always to the side permitting the conical Sun shield to protect the instruments. The satellite's circular polar orbit 900 km above the Earth permitted the instruments to complete a scan of the celestial sphere every six months.

The COBE mission precisely measured and mapped the cosmic microwave background with a precision of 0.005%, see Figure 21. Minute temperature variations, depicted in Figure 21 as varying shades of blue and purple, are linked to slight density variations in the early universe. These variations are believed to have given rise to the structures that populate the universe today. These structures include individual galaxies, clusters of galaxies, and vast empty regions of space. The results of the COBE mission confirmed the Big Bang theory and eliminated many competing theories about the Big Bang. The COBE mission was concluded on December 23, 1993.

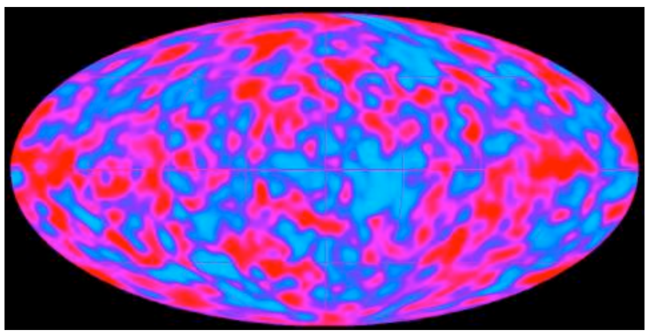
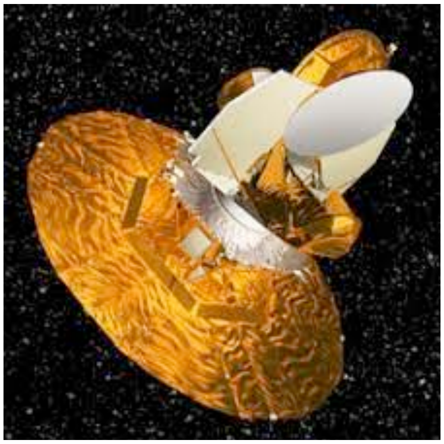


Figure 21 Cosmic Microwave Background radiation (source: NASA)

The Wilkinson Microwave Anisotropy Probe (WMAP), Figure 22, was launched on June 20, 2001 and orbited the Sun near the second Lagrange point of the Earth-Sun system. There are five Lagrange points (Figure 23) where gravity from the Sun and Earth balance the orbital motion of a satellite producing ideal parking orbits for satellites circling the Sun. The second Lagrange point is a million miles from Earth in the direction opposite the Sun as shown in Figure 23. From this position WMAP spent 9 years making fundamental measurements of the cosmos including the microwave background radiation.

The WMAP mission determined, to a high degree of precision, the age of the universe as 13.77 billion years old, the epoch when the universe became transparent 380,000 years after the Big Bang, the "lumpiness" of the universe, and strongly confirmed the Big Bang theory. WMAP observations also support the rapid inflation of the universe in its earliest moments when it underwent a dramatic expansion growing by more than a trillion trillion-fold in less than a trillionth of a trillionth of a second. In addition, WMAP observations verify the current flatness of the universe.



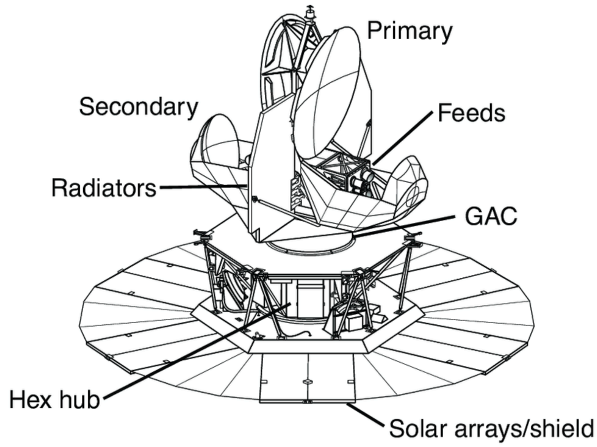


Figure 22 WMAP spacecraft (source: ResearchGate)

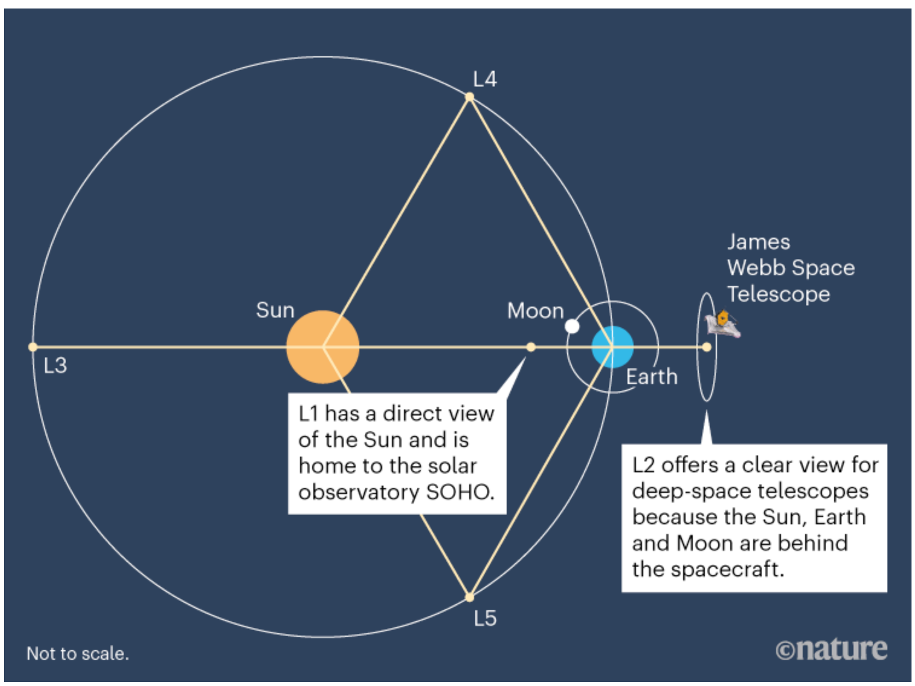


Figure 23 Second Lagrange point (source: Nature)

WAMP observations have confirmed that only 4.6% of the universe is comprised of normal matter. A much greater fraction, 24% of the universe, is composed of dark matter that has gravity but does not emit any light. The largest fraction of the universe, 71%, is composed of dark energy which is a source of anti-gravity that is causing the universe to expand at an accelerating rate.

The European Space Agency (ESA) Planck spacecraft (Figure 25) was launched on May 14, 2009 into solar orbit at the second Lagrange point. From 2009 to 2013 Planck mapped the anisotropies of the cosmic microwave background at microwave and infrared frequencies. The mission substantially improved upon observations made by the NASA Wilkinson Microwave Anisotropy Probe (WMAP) including the average density of ordinary and dark matter in the universe and the age of the universe. The mission found that the universe is 13.798 ± 0.037 billion years old. It also found that the universe contains $4.82 \pm 0.05\%$ ordinary matter, $25.8 \pm 0.4\%$ dark matter, and $69 \pm 1\%$ dark energy. It also measured the Hubble constant to be 67.8 ± 0.77 (km/s)/Mpc.

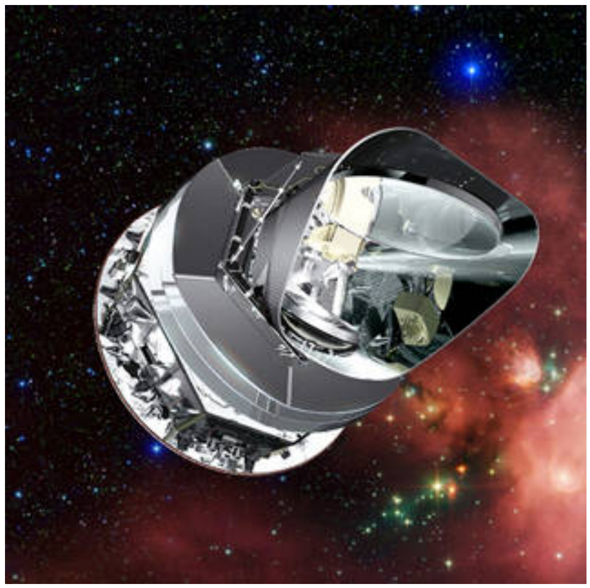


Figure 24 Planck spacecraft (source: ESA)

	WMAP Spacecraft	Planck Spacecraft
Ordinary Matter	4.6 %	4.82 %
Dark Matter	24 %	25.8 %
Dark Energy	71.4 %	69 %

Table 5 Composition of the universe

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