
10. Our violent origin

Cosmology and the nuclear processes in the Big Bang

Our Universe is getting larger. The space between the galaxies is expanding so that we see distant galaxies in all directions receding from us; the more distant a galaxy is, the faster it retreats. This is not because our galaxy occupies a privileged location at the centre of the Universe; an inhabitant of another, far away, galaxy would see the same spectacle.

If we imagine viewing the expansion in reverse, we can follow it all the way back to an instant, about 15 billion years ago, when all the matter in the Universe was squeezed together. This was the moment when space and time themselves came into being. What happened at that instant, and immediately after it, has become known as the Big Bang.

The Big Bang was an event like no other. Any attempt to describe it in terms of familiar concepts can only give a vague idea. For example, it is often referred to as an explosion of matter and energy, but this is quite wrong since the word ‘explosion’ suggests matter being forced out by huge pressures from a point in a pre-existing space. At the Big Bang, the whole of space itself was stretched out, carrying pure energy with it, as if it were being sucked out of nothing. The Universe did not expand into empty space; but space itself expanded.

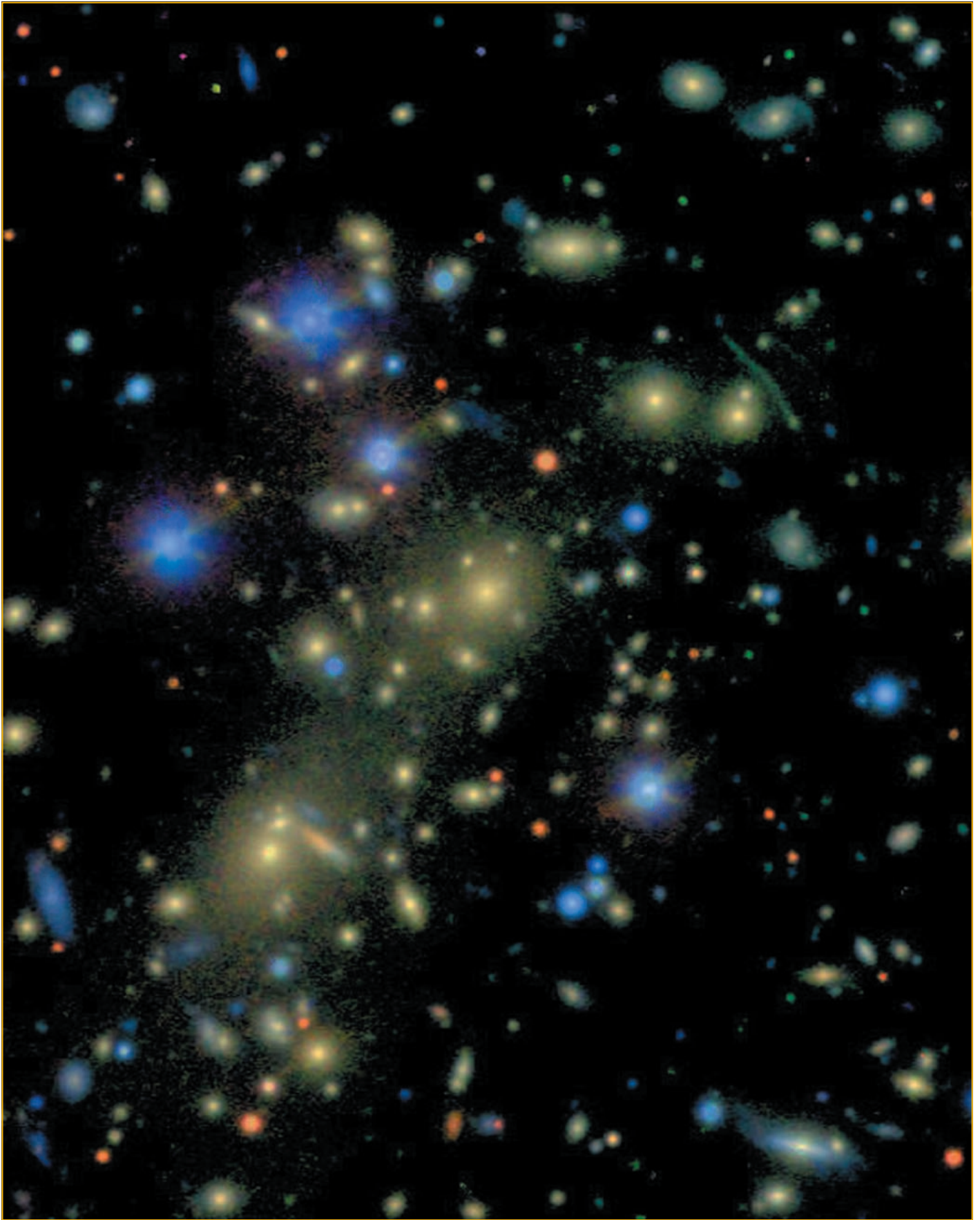
Even stranger, the Big Bang did not take place at some moment in time, but instead marked the very beginning of time. To ask what there was before the Big Bang would seem to be a meaningless question.

General relativity is currently our best theory describing the nature of space and time. Its equations predict the expansion of the Universe, but it is not just mathematical equations that scientists rely on for their evidence. There are three independent pieces of evidence for the Big Bang.

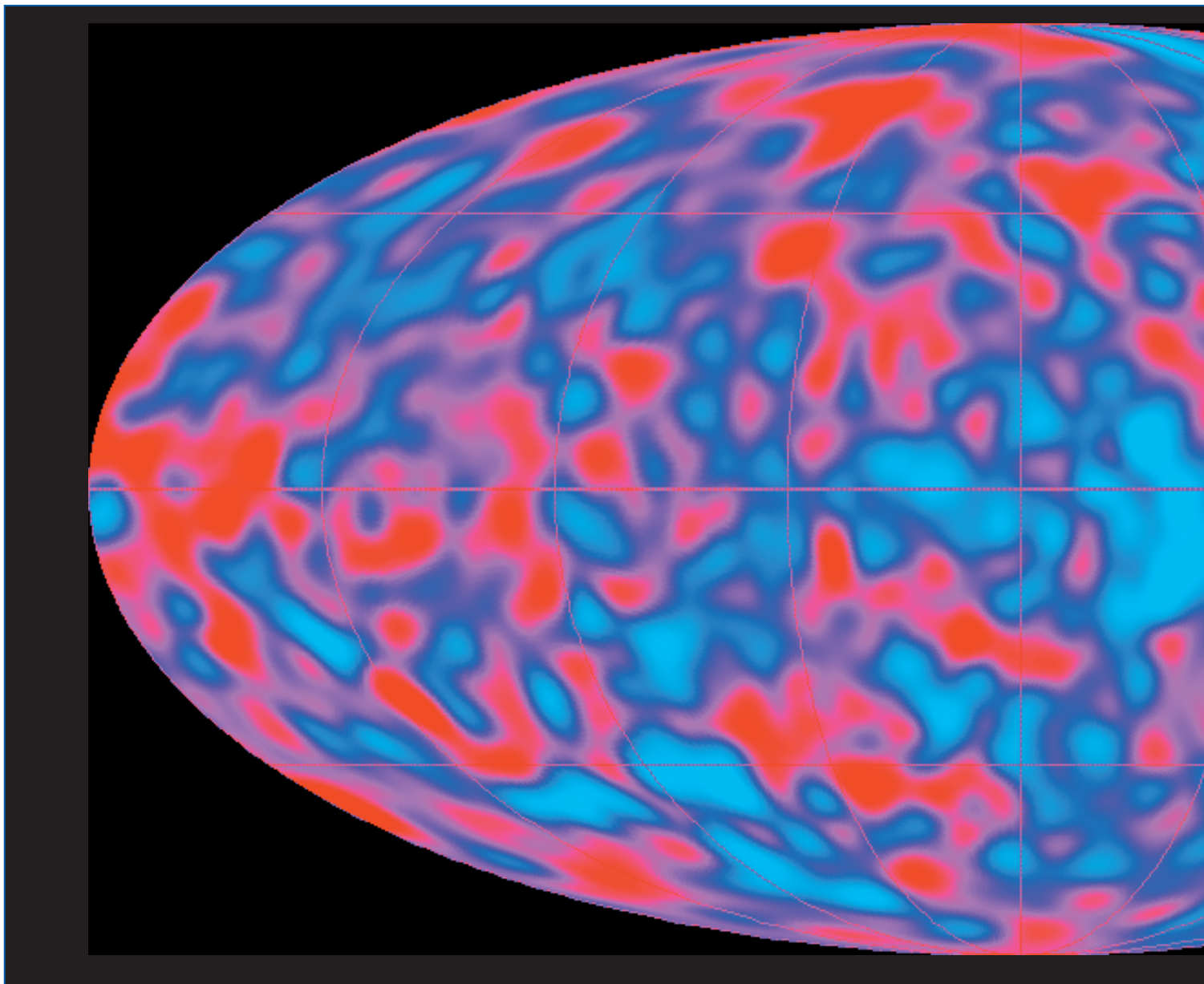
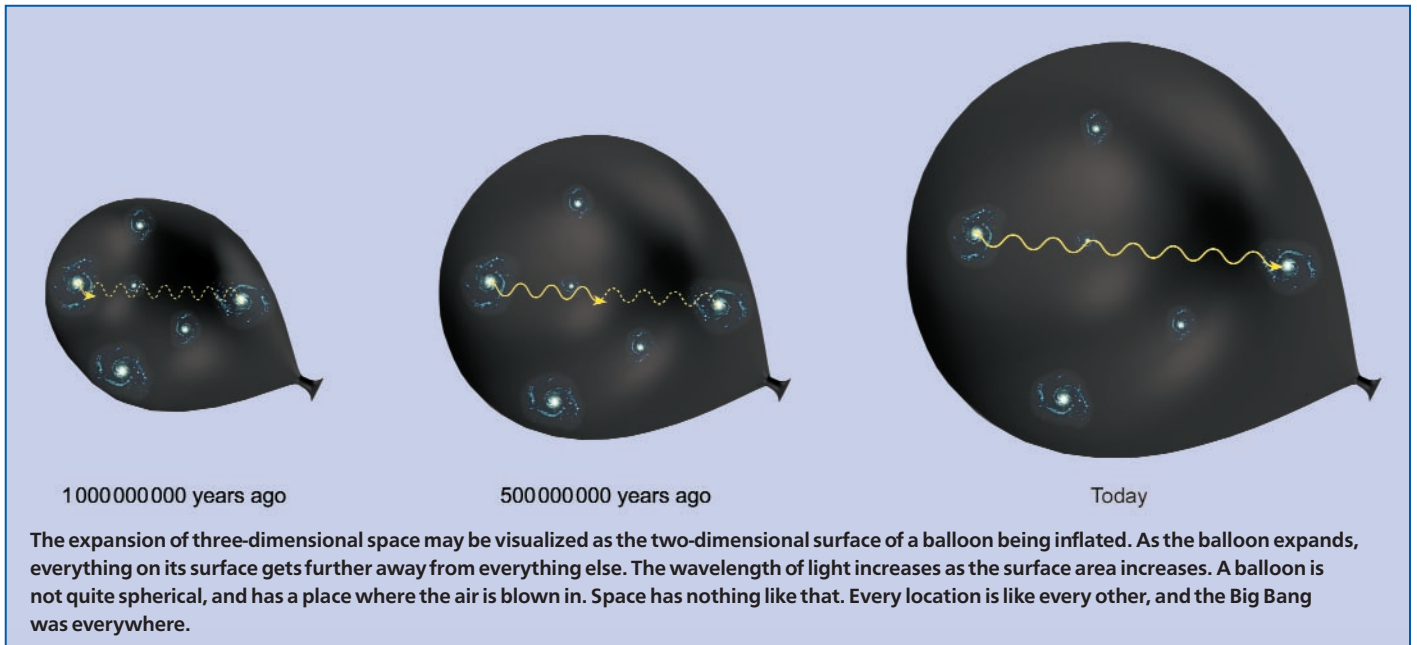
Evidence for a Big Bang

Since all galaxies are composed of the same elements, the light emitted from distant galaxies should have the same characteristic wavelengths as that from nearer galaxies. The first clue that the Universe is expanding is that light from distant galaxies has a longer wavelength than it should. These longer wavelengths suggest the galaxies are receding from us at great speeds. The wavelength of the light that reaches us from those galaxies is ‘stretched’ as the space it travels through stretches. Longer wavelengths means light is shifted towards the red end of the visible spectrum. This stretching of space is just the ongoing expansion of the Universe that started with the Big Bang.

One way to visualize this expansion is to imagine blowing up a balloon with spots painted on it. No one spot would occupy the centre of the surface of the balloon, just as no one galaxy occupies the centre of the Universe. Concentrating on one spot and observing how other spots move in relation to it as the balloon is blown



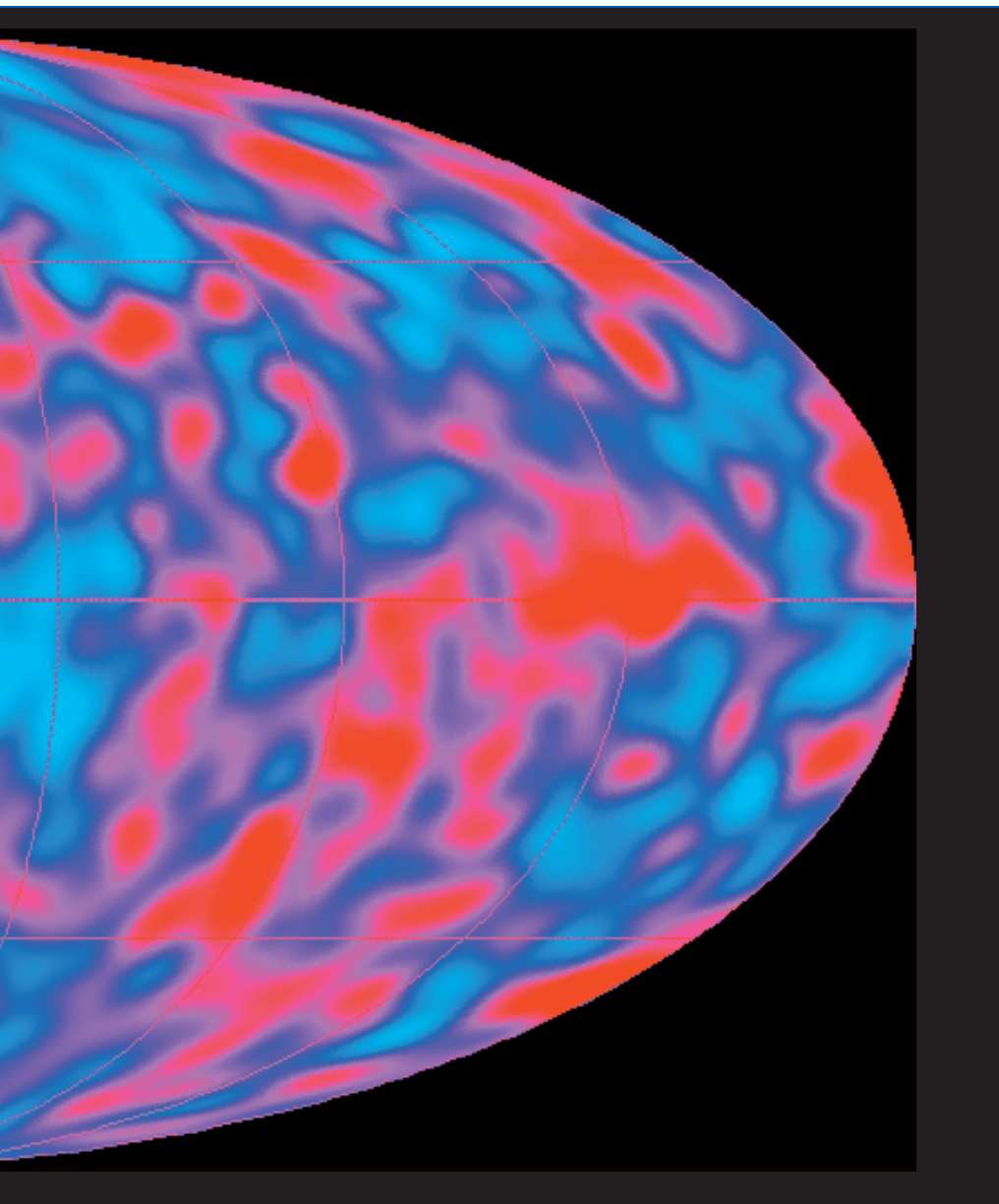
Light from this distant cluster of galaxies, 1ES 0657-558, has taken about 6 billion years to reach us. When the light began its journey, the Universe was only about 60% of its current size. In other words, the distance between galaxies was only 60% of what it is now. Not only the Universe has stretched, the emitted light has too: wavelengths of light have increased by about 30%. Galaxies in this cluster appear 30% redder than they were when the light was emitted. (Courtesy European Southern Observatories.)



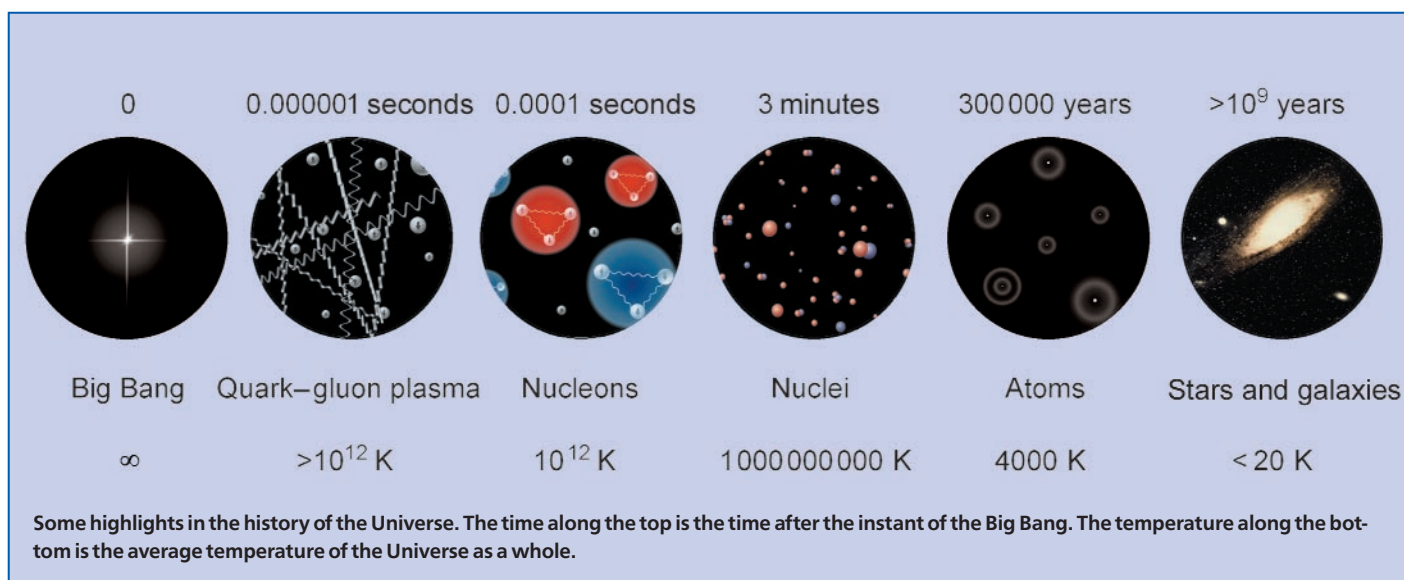
up shows every other spot recedes from it. The further away another spot, the faster it recedes, just like distant galaxies. Like all analogies, this one should not be taken too literally: the surface of the balloon is only two-dimensional.

The second piece of evidence for the Big Bang is the existence of microwave radiation approaching Earth from every direction in space. George Gamow first predicted the existence of this radiation long before it was actually observed. It is the 'afterglow' of the Big Bang. It has a temperature of less than three degrees above absolute zero (absolute zero is 273 degrees Celsius below freezing, about -459 degrees Fahrenheit), and consists of low energy photons. These photons existed about 300,000 years after the Big Bang, and remained when the Universe cooled sufficiently for them not to continue interacting strongly with matter.

The third, and just as important, line of evidence comes from nuclear physics. The relative proportions of hydrogen, helium and lithium fit very closely with the predictions of theoretical models of the Big Bang. However, the nuclei of these elements were not around at the very beginning. In fact, not even the nucleons themselves existed at the start.



An image of the sky by COBE, NASA's Cosmic Background Explorer. The cosmic microwave background radiation predicted by Gamow is incredibly uniform, varying from one direction in the sky to another by only a few parts per million. The colours represent regions of the sky where the intensity is a little greater (red) or less (blue) than the average. When the radiation began its journey 300,000 years after the Big Bang it was not microwaves but visible light. Its wavelength has increased by a thousand times, just as the Universe has itself expanded a thousand times. (NASA)



Just after the beginning

The earliest meaningful time that can be comprehended with today's physics is the unimaginably short time of 10^{-43} seconds after the Universe came into being, when the temperature was over 10^{27} degrees. At this time it was expanding steadily. At 10^{-35} seconds, the Universe had grown to just 10^{-27} metres and the temperature had fallen to about 10^{27} degrees. At this moment it is thought that the expansion underwent a phenomenal acceleration. Exactly what happened is still the subject of debate among physicists, but it is believed that space itself rapidly inflated, carrying matter within it at a stupendous rate. During this 'inflation', the size of the presently visible Universe increased by a factor of at least 10^{25} from 10^{-27} metres to one centimetre (the factor may well have been as much as 10^{50} or even 10^{100}). This inflation had finished by 10^{-32} seconds.

Creating protons and neutrons

After the period of inflation, the Universe expanded at a much more sedate pace. By one millionth of a second after its birth, the temperature had fallen to below 10^{12} degrees and the nuclear ingredients, protons and neutrons, began to form.

Many properties of nucleons can be explained by assuming they are bundles of three quarks held together by gluons. The quarks come in six different types (flavours), only two of which are used in creating nucleons. Protons consist of two 'up' quarks, each of charge $+2/3$ and a 'down' quark with charge $-1/3$, giving an overall charge of $+1$. Neutrons have two down quarks and one up quark, making them neutral overall. The force-carrying gluons are electrically neutral.

There are strong reasons for believing that no single free quark or free gluon will ever appear in the laboratory. If enough energy is put into a proton to knock out one of its constituent quarks, instead of freeing it the energy creates a new particle that is itself made up of more than one quark. This is exactly what happens in collisions studied using particle accelerators.

The situation was different during the early Universe when all the matter was extremely compressed and hot. At one millionth of a second after the Universe came into existence, when the temperature was a million, million degrees, the boundaries between individual nucleons did not exist. Consequently, quarks and gluons could move freely in the quark–gluon plasma.

As the Universe continued its expansion, and the density and temperature fell, the quarks would have begun to arrange themselves into threesomes held together by gluons, and the nucleons were formed.

A quark–gluon plasma

The brief period before one millionth of a second into the Big Bang is not the only time that the quark–gluon plasma existed. In 2000, scientists at CERN in Switzerland published evidence, gathered from many years of experiments, strongly hinting that a quark–gluon plasma can be formed briefly when heavy nuclei collide head-on at very high energies, generating extremely high pressures and temperatures. These are just the conditions required for the boundaries between nucleons to dissolve, momentarily producing the quark–gluon plasma. This work is being continued at the Relativistic Heavy Ion Collider (RHIC) in the USA using even higher energies. It is intriguing to think that perhaps this unique state of matter has been produced just twice in the history of the Universe: first about a millionth of a second into the existence of the Universe, and then again briefly on planet Earth, 15 billion years later.

Making the light elements

Just after the Big Bang, although protons and neutrons attracted each other through the nuclear force, they did not immediately bind together to form deuterons. When the nucleons were first formed, the temperature was still too high and, for every nucleon there would have been several billion gamma ray photons that would have caused the disintegration of any deuterons as soon as they formed. Nuclei had to wait until the Universe was one second old before making even a fleeting appearance. At this time, the temperature had dropped to 10 billion degrees, but even at this temperature, deuterons are so flimsy that they are broken up almost immediately.

After about one minute, the Universe was cool enough for the deuterons to last long enough to have a reasonable chance of combining with a further proton or neutron to form a nucleus with three nucleons: either the hydrogen isotope ^3H (tritium), or the helium isotope ^3He . Both these light nuclei resist breaking up and can readily absorb a nucleon to form the much more stable ^4He nucleus.

The nuclear reactions leading to ^4He took place in a rapidly changing environment. The density was falling fast as the Universe expanded, so nuclei collided less frequently. The rapid drop in temperature meant there was less energy for charged nuclei to tunnel through the barrier between them. Neutrons are uncharged and so have the advantage of not having to tunnel through the barrier caused by the electric repulsion of the nuclei, but working against them is the fact that they steadily undergo beta decay, turning them into protons.

These changes meant such nuclear fusion reactions ceased after a few minutes and no more new nuclei could be made. The primordial matter formed a few minutes after the first instant of the Big Bang had just a small number of isotopes in proportions that remained fixed for many millions of years. Only when stars began to form did other quite different element-making processes occur.

The proportions of the primordial isotopes can be predicted by theory. The overwhelming part (76% by mass) consisted of hydrogen (single protons) with the remainder (24% by mass, or about 9% by number of atoms) being helium (two protons and two neutrons). There were also tiny, but significant, traces of other

isotopes: a few tens of parts per million consisted of deuterium, slightly less of the helium isotope ^3He , and just a tenth of a part per billion of the lithium isotope ^7Li . No stable nuclei with five nucleons exist in nature, and the only stable nucleus with 6 nucleons (^6Li) had to wait until much later to be formed.

These predictions depend upon the density both of matter and photons at the time the processes were taking place. Most of the predictions seem to fit quite well with modern observations. For instance, ^7Li can be detected at the surface of very old stars lying at the edge of our galaxy which have not been contaminated by the ashes of exploding stars, and the amount of deuterium can be measured by the absorption of light from very distant galaxies as it passes through clouds of primordial gas that have not yet condensed into stars.

The Big Bang elements leave no scope whatever for the formation of heavier nuclei necessary for the rich and complex world in which we live or for the evolution of life. This has been made possible by the billions of years of nuclear reactions occurring within stars. Consequently, today there is somewhat less hydrogen (70% by mass) than there was in the early Universe, while the amount of ^4He has increased to 28% due to stellar fusion. In addition, a vital 2% of heavier elements has appeared.

The Big Bang, nucleon density and modern cosmology

Many questions remain unanswered: will the Universe expand forever or will the expansion stop some day, to be followed by contraction ending with a Big Crunch? Perhaps, as recently suggested, the expansion of the Universe is actually accelerating. Cosmologists debate these questions intensely. One key factor is just how much matter exists in the Universe. Astronomers find this a very difficult question to answer, but the abundance of primordial isotopes provides a clue. The present density of nucleons in the Universe depends on the density of matter and radiation at the time the primordial elements were being formed, and nuclear physics provides a way of deducing this primordial density.

Nuclear processes that took place in the first few minutes, in particular the amount of deuterium that was produced, depended crucially on how densely concentrated the nucleons were. The deuterium in existence today is primordial – made in the first few minutes after the Big Bang. This is known because any new deuterium created by reactions within stars is immediately destroyed by further reactions. Thus, if the amount of deuterium in existence today is measured, we can learn about the conditions at the time the primordial elements were made, which in turn provides a clue as to how much total matter there is today.

It turns out that the amount of deuterium is not exactly what is expected, but very close. It is not known if this is a consequence of problems with the measurements, which are difficult, or if cosmology is less of an exact science than some cosmologists would like to think. Maybe there are still a few surprises to come from nuclear physics.

These are exciting times, and nuclear physicists, astronomers and cosmologists, working together, will no doubt find an answer in the coming years. In doing so, we shall achieve a firmer understanding of the history of the Universe and also of its future.

Three possible ways in which the Universe might end. The picture is symbolic since the Universe does not have an 'edge'.

Left: if the density of the Universe is greater than a critical value, then it will eventually stop expanding, and will contract under the force of gravity, ending in the 'Big Crunch'.

Centre: if the density is neither too little nor too great, then the expansion of the Universe will gradually slow down. This is called the 'Flat' Universe.

Right: if the density is less than the critical value, it will expand for ever. This is called the 'Open' Universe. (Julian Baum)

