2. The Universe Is Expanding and Evolving

We now know that the entire universe is both expanding and evolving. These two remarkable facts have been established beyond doubt over the past century.

The simple observation that the sky is dark at night indicates that the universe cannot be infinite and unchanging, comprised of an infinite number of unchanging stars. If that were so, then the stars (which have finite sizes) would overlap in every line of sight, and the sky would be as bright as the surface of the Sun in all directions. This is known as 'Olbers' Paradox'. The darkness of the night sky rules out an unchanging universe that is infinite in space and time.

In astronomy we directly observe the distant past, and can therefore directly study the evolution of the universe. This is possible due to the finite speed of light. It takes time for light to travel from one place to another, from a distant galaxy to us. Therefore when we look out into the distant universe, we also look back in time. The most distant galaxies we see are now being observed as they were over 13 billion years ago – their light has taken that long to reach us.

As mentioned above, the distant universe looks very different from the nearby universe. In contrast to the familiar nearby spiral and elliptical galaxies, the faint distant galaxies have irregular forms beyond imagination. It was a totally different world. Smaller and much more chaotic in appearance, they were young galaxies still in the process of formation. We now know from spectroscopy that these faint galaxies are indeed the most distant (see below), so the early universe was certainly very different from the nearby universe of bright galaxies. From straightforward observations such as these it is already clear that the universe has significantly evolved.

P. Shaver, *Cosmic Heritage*, DOI 10.1007/978-3-642-20261-2_2,

The Expansion of the Universe

In 1917 Albert Einstein applied his new equations of general relativity to the universe as a whole. He found, to his discomfort, that they implied that the universe had to be changing with time – either expanding or contracting. The orthodox view at that time was that our galaxy was the entire universe, and the small motions of the stars indicated that it was neither expanding nor contracting. Einstein therefore felt that he had to somehow make his equations consistent with a static universe. He did so by adding what nowadays might be called a 'fudge factor' to the equations – a constant, which became known as the 'cosmological constant'. With this, his equations did indeed produce a static universe, to his satisfaction.

A few years later a young American astronomer by the name of Edwin Hubble started to work at Mount Wilson Observatory in California, using the 100-inch telescope, the largest in the world at that time. He set out to study the mysterious spiral nebulae. There was much debate at the time as to whether these were within our galaxy or outside. He was able to examine what appeared to be individual stars in the Andromeda Nebula, and found that some of them were varying in brightness with a fixed period, similar to the stars known as Cepheid variables in our galaxy. It was already known that there is a relationship between the periods and the luminosities of Cepheids; if you measured the period (the time between peaks in brightness, using photographs taken over several months), you knew the luminosity. And knowing both the intrinsic luminosity and the measured apparent brightness of the star (i.e. the brightness as measured here on Earth), you could determine its distance using the inverse square law (a star of a given luminosity appears four times fainter if it is moved two times further away). In this way Hubble was able to determine the distances to several nebulae. It was clear that they were outside of our galaxy – they were themselves distant galaxies. That was in itself a huge discovery.

But it was only part of the story. Hubble, Georges Lemaître and others also knew, from spectroscopic measurements of the nebulae, how fast these galaxies were moving away from (or towards) us. By 1929 it was clear that almost all of the galaxies are moving away from us, and that the speed of recession (the redshift) increases with the distance to the galaxy. This became known as Hubble's Law. The expansion of the universe had been discovered.

When Einstein heard about this, he said that inserting the cosmological constant into his equations had been "the biggest blunder of my life". His equations in their original form had predicted a changing universe (either expanding or contracting) – which would have been an amazing theoretical prediction if he had left the equations as they were – but he had made his universe static by inserting the constant. In 1931 Einstein finally removed the cosmological constant from his equations, which became the theoretical and mathematical framework for the expanding universe concept.

The idea that all of the galaxies in the universe are moving away from us, and at speeds that are proportional to their distances from us, is very striking, and can be misleading. You might at first think that we're 'at the centre', but we're not. The galaxies are not themselves moving in this way through space; instead, in Einstein's theory it is space itself that is expanding, and the galaxies are just going along for the ride. All galaxies throughout the universe are moving away from each other. And the further apart any two galaxies are, the faster they are moving away from each other. Observers in each galaxy may naïvely think that they are at the centre of this expansion, as all galaxies appear to be moving away from them, but there is actually no 'centre'.

To understand this, it is helpful to imagine an expanding balloon which has dots all over its surface. We live in a universe with three spatial dimensions. Imagine instead that you live on the two-dimensional surface of the balloon. To you, it is a flat surface. Now imagine how you see the dots as the balloon is blown up: they are all moving away from each other (and from you), with the rate of separation proportional to the separation itself, but none of the dots is 'at the centre'. There is no 'centre' and no 'outside' in this two-dimensional world – the entire universe is expanding.

The expansion of the universe can be extrapolated back to 'the beginning', when the distances between galaxies would have been zero. The universe was once in an extremely compressed state, and originated in what the famous astrophysicist and cosmologist Fred

Hoyle once facetiously called a 'Big Bang' (he was a proponent of the competing 'steady state theory', which was abandoned several decades ago as the evidence for the Big Bang became conclusive). The Big Bang name has stuck, and the Big Bang theory has been the conventional scenario for cosmology for many decades now. According to this theory, if we extrapolate far enough back into the past, the density of matter and the 'curvature' of space become infinite – a so-called 'singularity'. This is the 'beginning' of the Big Bang. However, while we can determine how long ago it occurred, we can say nothing about 'the beginning' itself, or about any 'before'. This provocative and fundamental issue will be discussed in Chap. 5.

The present age of the universe (the time back to the 'beginning') can be computed from the current rate of expansion and the density of the universe. Recent discoveries and modern satellite measurements, described below, add independent new techniques and precision. The best 'cosmological' determination of the present age of the universe is 13.7 billion years. This age agrees well with that determined by astrophysical methods using stars. Combining the observed properties of the oldest clusters of stars ('globular clusters') with our theoretical understanding of stellar evolution gives ages in the range 11–13 billion years. White dwarf stars gradually cool and fade with time; the faintest white dwarfs can therefore give a measure of age. Radioactive dating has also been used to estimate the ages of old stars. All of these astrophysical methods give results that are consistent with the cosmological age of 13.7 billion years.

Is the Big Bang model consistent with Olbers' Paradox? Yes, because the Big Bang universe is both finite in age and expanding. The finite age means that we can only see a finite number of stars, which have existed for less than the age of the universe. And the expansion has caused the brilliant light given off by the Big Bang to be diluted and redshifted from the optical/infrared part of the electromagnetic spectrum to the millimetre band, where it is observed today.

The expansion of the universe has been established beyond doubt. And the implication is that there was a time when the universe was very small and dense. Even if we cannot say anything about the instant of the Big Bang itself, we can certainly say a lot about this hot, dense phase, as the next two sections will show.

Afterglow of the Big Bang

How can we possibly have any idea of what the early universe was like? In its compressed state 13.7 billion years ago, our universe was extremely dense, hot and uniform. But precisely because it was so hot and uniform, the physics involved would have been simple; it was basically a hot 'soup' of fundamental particles and forces. With only a few variables and virtually no complexity, it is relatively easy to compute the properties of that early phase. The physics of the early universe just a small fraction of a second after the Big Bang was already known to us half a century ago; its properties were being explored in the 1940s, when the atomic bomb was being developed.

A fairly obvious test of the reality of the early hot phase of the universe would be the observation of an afterglow. Even, now, 13.7 billion years after the event, there should still be a cool, fading 'relic radiation' left over, which we might be able to detect. That radiation would have cooled as the universe expanded, and would have been increasingly shifted towards the red end of the spectrum. By now it should be only several degrees above absolute zero, and concentrated at microwave (millimetre) wavelengths.

George Gamow, Ralph Alpher and Robert Herman were studying the early universe in the late 1940s. They computed that the temperature of the relic radiation as observed today (called the Cosmic Microwave Background, or CMB) could be as low as 5 degrees Kelvin (5 K, or −268°C). A temperature of absolute zero on the Kelvin scale means zero thermal energy – no motions whatsoever – it's as low as you can possibly go, so 5 K is very, very cold. The Kelvin scale is used throughout this book, but you can always subtract 273 to get degrees Celsius (°C).

The definitive detection of the CMB was serendipitous. Arno Penzias and Bob Wilson were working at Bell Telephone Laboratories in New Jersey in the mid-1960s, in part to measure the potential background contamination that could affect satellite communications. They worked hard to reduce any radio noise generated by their equipment, and went so far as to delicately remove two pigeons and their droppings from their antenna. But their measurements still showed an excess of 3.5 K, which they could not account for. Meanwhile, in Princeton, just 40 km away, Robert Dicke and his colleagues were using a small radiotelescope to search specifically for the CMB. When Penzias was eventually informed about Dicke's work, he phoned him immediately in puzzlement about his results, and after the phone call Dicke said to his team "Boys, we've been scooped!" Penzias and Wilson were awarded the Nobel Prize in physics for their momentous discovery.

The temperature of the CMB has now been measured with extremely high accuracy. It is 2.725 K. The radiation is constant over the whole sky to an astonishing precision of one part in a hundred thousand. Its spectrum (the distribution of its intensity as a function of wavelength) was found to be very special indeed – it is almost exactly that corresponding to thermodynamic equilibrium, as would be expected for heat radiation coming from an early universe of constant temperature and density (this type of spectrum is called a black-body spectrum, and the observed radiation has the most perfect black-body spectrum known to man). The prediction and discovery of the CMB are considered to be conclusive evidence for the Big Bang theory.

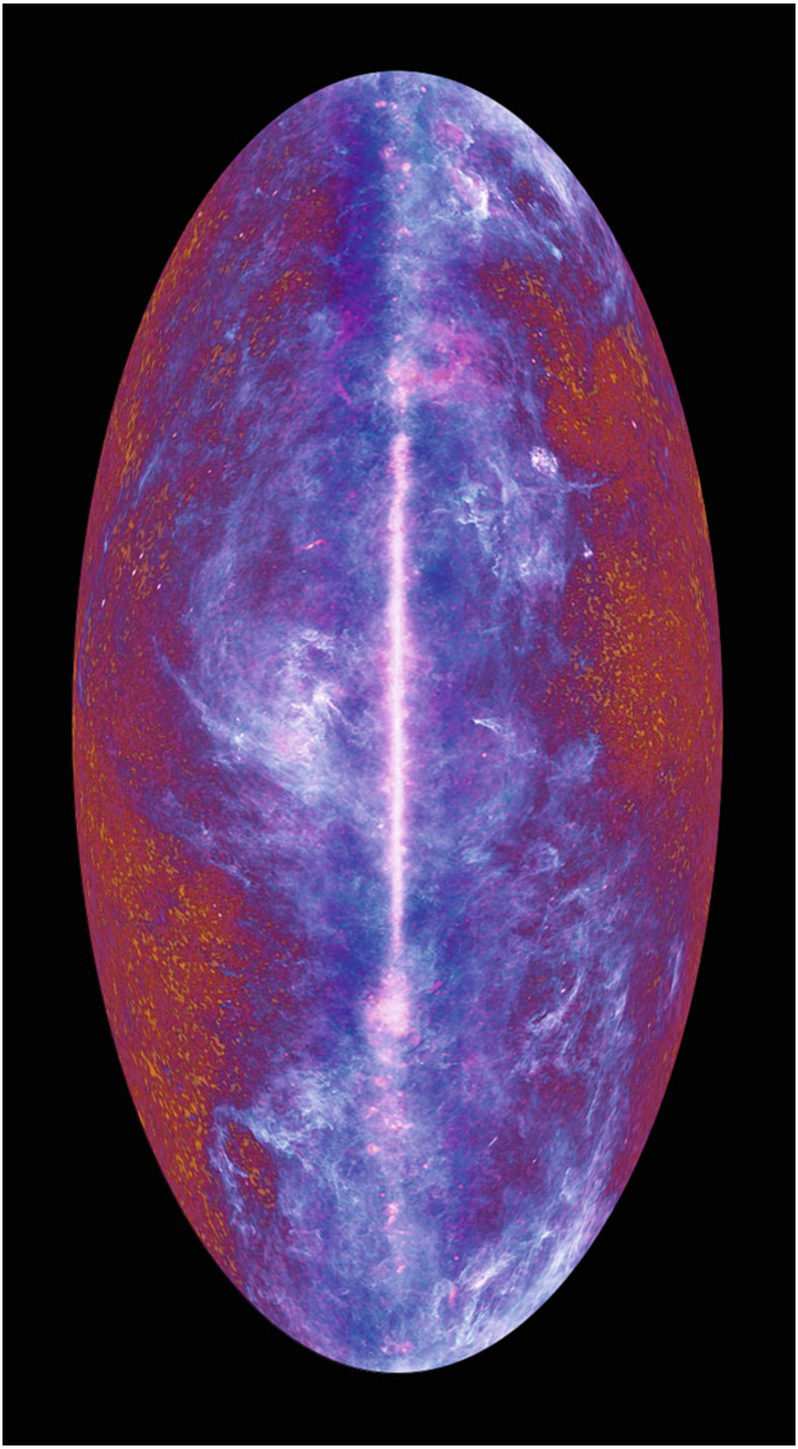
The CMB that we see is an image of the relic radiation as it was at a very specific epoch. This is why it has such well defined properties, rather than being a blur. It comes from the 'surface of last scattering'. Before that time, the radiation (carried by massless particles called photons) scattered off electrons (negatively charged particles of matter), producing an opaque fog. When the universe had expanded and cooled to about 3,000 K, the electrons were able to combine with positively charged protons to form electrically neutral hydrogen atoms, in a process called recombination. This resulted in a decoupling of matter and radiation, and the radiation was finally able to travel freely through space. The universe became transparent. Thus the CMB we see is a snapshot of the surface of last scattering, which occurred 380,000 years after the Big Bang. It's like a distant wallpaper covering the entire sky behind all the stars and galaxies. This is important, as it means that we can clearly see any structures (irregularities in the distribution of matter) that may be imprinted on it. They would show up as a pattern of regions, some very slightly warmer and others very slightly cooler than the average temperature.

And structures there had to be. It was widely believed that the CMB could not be perfectly smooth. If it were, then no galaxies, stars or planets could ever have formed in our universe. But if there were even tiny irregularities in the distribution of matter in the early universe, the slightly denser regions could accrete matter from less dense regions by simple gravitational attraction (even though the overall universe was expanding). They would increase in mass and density and decrease in size until, after hundreds of millions of years, they became so massive and dense that they formed the galaxies, stars and planets that we know today.

What could be the origin of these irregularities – these so-called 'primordial fluctuations'? The most widely held view is that these were random 'quantum' fluctuations (described in Chap. 4) from the very, very early universe that were stretched to macroscopic scales by a brief period in which the universe expanded by an enormous factor. These initial fluctuations grew with time, and became the seeds of an extraordinary pattern that evolved. Overlapping density waves were produced, similar to the overlapping ripples on a pond when a handful of pebbles is thrown in. A pattern caused by overlapping shells is not necessarily easy to see straightaway, but it can be clearly detected using statistical analysis. Cosmologists were able to predict the characteristic size of the waves, which would provide a 'standard ruler' for length scales in cosmology: about 0.6 angular degrees in the CMB, which in today's universe corresponds to about 500 million light-years (5 billion trillion kilometres).

These are amazing predictions. Could they be verified by observations? After many attempts the fluctuations were finally detected in a statistical analysis of an all-sky survey made using NASA's Cosmic Background Explorer satellite in 1992, at a level of 10^{-5} (one hundred thousandth) of the total intensity (another Nobel prize). It was fortunate that the fluctuations were found at this level; if they were much fainter they would have been swamped by fluctuations in the interstellar medium of our own galaxy, and we would never have known about them. As it turned out, they have become a treasure trove of information about the early universe and its large scale properties.

The statistical detection was obviously tantalizing, and many scientists were eager to measure the fluctuations in detail. Several



One of the most amazing images ever made of the sky. This is an all-sky image obtained by the Planck team using the Planck spacecraft of the European Space Agency (ESA). The plane of our own galaxy (the Milky Way) is the thin strip extending across the entire image. Above and below it are plumes and filaments belonging to the galaxy. The mottled red background at the top and bottom is the afterglow of the Big Bang, seen as it was when the universe was just 0.003% of its present age. The orange 'spots' are primordial structures that later evolved into stars and galaxies.

hastily built ground based telescopes were able to detect the strongest 'acoustic peak'. A particularly intriguing experiment was a balloon-borne instrument called Boomerang that drifted with the air currents circling the South Pole while staring at one region of sky for a long period of time. It succeeded in making a high-sensitivity map in which the individual fluctuations and patterns were actually visible for the first time. During this time NASA was busy building a follow-up mission: the Wilkinson Microwave Anisotropy Probe (WMAP). Launched in 2001, it has mapped the microwave sky with unprecedented sensitivity and resolution. The detailed agreement of the predicted and observed ripples in the CMB is absolutely astonishing. Even finer detail and new observational horizons will become possible with data from the European Space Agency's Planck spacecraft launched in 2009.

Stimulated by these astounding discoveries, astronomers have searched huge, uniform databases from ground-based surveys of millions of galaxies looking for the equivalent of the CMB ripples in the distribution of galaxies in the 'local' universe. They have succeeded in finding that there is indeed an excess of galaxies separated by the distance (500 million light-years) that corresponds to the cosmological ripples. This provides an amazing link between the local universe and the very distant universe, and a stunning confirmation of predictions made about the early universe and its evolution to the present.

Yet another test can be provided by measurements of the CMB temperature when the universe was at intermediate ages, older than when the CMB was formed (when its temperature was about 3,000 K) but younger than it is today (when its temperature is 2.725 K). The temperature at a given epoch can be measured by observing the ratios of certain atomic and molecular spectral lines. It should decrease at the same rate that the universe expands, and the few measurements made so far seem to indicate that it does.

An added bonus of the observations of the CMB is the accurate measurement of the motion of our galaxy relative to the distant universe. The CMB is a bit warmer on one side of the sky than it is on the other. This is known as the CMB dipole anisotropy. The difference between the two hemispheres is 0.003 K (one thousandth of the total intensity of the CMB) – small, but huge in comparison with the fluctuations described above. It is due to a global Doppler effect – the fact that our local group of galaxies is moving at 627 km per second relative to the reference frame provided by the CMB, so one side of the sky appears redshifted and the other side blueshifted. This motion is a result of the gravitational attraction of other relatively nearby galaxies. Motions such as these in the local universe are being mapped in three dimensions using large galaxy surveys.

Creation of the Elements

The elements, essential for life as we know it, were created in two totally different epochs: (1) in the first minutes, across the entire universe, and (2) billions of years later, in the cores of stars.

When the very early universe was undergoing rapid expansion and cooling, it went through a fleeting moment when the conditions were similar to those in the interiors of stars, and elements could form. That fleeting moment started just seconds after the Big Bang, and lasted just minutes. The process is called Big Bang nucleosynthesis (BBN). Nucleosynthesis is the process of synthesizing the nucleus of one atom from the nuclei of others. Only the first few elements in the periodic table (the so-called 'light elements' or 'primordial elements' – hydrogen, deuterium, helium and lithium) could be formed in this period.

BBN gives the only explanation for the abundances of the light elements. Stars can produce only about one tenth of the helium present in the universe today. Deuterium is actually destroyed in stars. And the BBN predictions are very clear and precise. Again, it was Gamow, Alpher and Herman who first studied this in detail.

The physics of this early phase is well understood. It started when the universe was about one second old, when its temperature was down to 10 billion degrees, at which point stable atomic nuclei could form from the binding together of their constituent particles, protons and neutrons (a neutron is a subatomic particle with no electric charge and a mass slightly greater than that of a proton). Hydrogen nuclei are just protons; deuterium nuclei formed from the fusion of protons and neutrons, and helium nuclei from the fusion of deuterium nuclei.

This phase of the universe lasted for just minutes, and then it was gone. The window of opportunity for the production of elements in the early universe had then passed. The universe continued to cool as it expanded, and the temperature was no longer sufficient to support nucleosynthesis. No elements heavier than helium were able to form, except for trace amounts of lithium, so the light elements were the only ones in the universe for a very long time. The heavier elements would have to wait until the first stars formed, hundreds of millions of years later.

Overall, the abundances (by mass, relative to hydrogen) predicted for the primordial elements were 25% helium, 0.01% deuterium, and 10^{-10} (a tenth of a billionth) lithium. The relative abundance of helium is determined purely by the physics, and is independent of the initial conditions of the universe. It is an extremely robust prediction, and is just what we see in the universe today. The predicted abundances of the other primordial elements also agree well with observations of the universe today.

A variety of methods has been used to measure these abundances. Helium lines are easily seen in the spectra of stars, emission nebulae and planetary nebulae. Deuterium can best be studied by observing isolated gas clouds in the distant universe that are themselves almost primordial, and do not contain stars. These are intergalactic clouds, and we can study them by observing the absorption they cause in the spectra of even more distant quasars that happen to lie behind them. Lithium can be studied in the spectra of old stars, but this is somewhat less certain because of processes in the stars themselves.

There is an important overall check. The primordial element abundances should all be consistent both with each other and with a key cosmological parameter that is related to the density and temperature of the early universe. This parameter has been determined to high accuracy using the WMAP observations discussed above, and it agrees well with the predicted and observed abundances of the primordial elements.

Finally, a recent and important confirmation that the helium was formed in the very early universe, long before the first stars existed, also comes from the WMAP observations. The effect of the primordial helium shows up in the fluctuations of the CMB. As the CMB is observed as it was 380,000 years after the Big Bang, and the first stars weren't formed until the universe was hundreds of millions of years old, this provides direct supporting evidence that the helium was indeed formed in the early universe.

It is amazing to think that we can make such precise and verified statements about such an early phase in the history of the universe – just minutes after the Big Bang. Keep in mind that, while we look back in time as we look out into the universe, we can only see as far back as the microwave background. The universe at ages less than 380,000 years is totally opaque to us across the entire electromagnetic spectrum – we can't see it at all. The short phase when the primordial elements were formed, just minutes after the Big Bang itself, is completely shrouded from our view. Nevertheless we can determine the events of that time from our knowledge of physics, and we know exactly what happened, as proven by abundances measured in the universe today. An incredible success.

However, today's universe contains more than just the light elements. The rest of the elements – the 'heavy elements' – are made in stars.

In total, 94 naturally-occurring elements exist on Earth. Some of these are (in order of the atomic number, which is the number of protons in the nucleus of an atom): hydrogen, helium, lithium, beryllium, boron, carbon, nitrogen, oxygen, fluorine, neon, sodium, magnesium, aluminium, silicon, phosphorus, sulphur, …. iron, …. gold, …. uranium, …. plutonium, ….). Iron is special in that it has the lowest mass per nuclear particle of all the elements. This means that the fusion (joining together) of the nuclei of light elements to make heavier ones (which produces energy) can only work up to iron, because beyond that point no further energy is released. Similarly the fission (breaking apart) of the nuclei of heavy elements to make lighter ones (which also produces energy) can only work as far down as iron. This is a fundamental distinction in nucleosynthesis. Hydrogen bombs are based on the fusion process, and atomic bombs are based on the fission process.

How do stars create elements? Fred Hoyle first outlined the overall process of nucleosynthesis in stars in 1946. A star is born from its parent molecular cloud when its central temperature and density are sufficient for hydrogen fusion reactions to begin. The contraction of the protostar then comes to an end, and a long-term balance is achieved between the force of gravity pulling inwards and the pressure from the hot star pushing outwards. This balance produces the virtually constant, sharply-defined bright sphere that is a star. The star has then reached maturity and has become a so-called main-sequence star.

What determines the minimum and maximum masses of stars in the first place? The lower end is determined by the requirement that the core temperature reaches the 10 million Kelvin necessary for nuclear fusion. If a protostar has a mass less than 0.08 solar masses, it is prevented by basic physics from collapsing sufficiently to reach the required temperature. The result is a brown dwarf star. As 0.08 solar masses is only about 80 times the mass of Jupiter, these objects fill the 'gap' between planets and stars. The upper end of the stellar mass scale is caused by outward radiation pressure in huge and luminous stars ultimately overcoming the gravitational infall of matter. The most massive stars are well over a hundred solar masses. Such massive stars are rare, representing less than one in every hundred thousand stars.

As the lifetimes of stars and the various changes and events that occur throughout their lives depend crucially on their masses, to make things simple we consider just the two extremes, low-mass stars and high-mass stars, with initial masses of less than two solar masses and greater than eight solar masses respectively. A star like the Sun has a main-sequence lifetime of about 10 billion years, compared with just millions of years for very massive stars (perversely the stars with the most fuel have the shortest lifetimes, because they burn fastest).

We start with the low-mass stars. Stars on the main sequence live relatively steady and uneventful lives. They spend their time converting hydrogen to helium. This involves bringing positively charged protons together into the same nucleus, which is not easy because similarly-charged particles repel each other. A very high temperature in the star's core is required to make this possible. In that environment particles are moving in high-speed chaos, and sometimes come close to each other in spite of the electromagnetic repulsion. When they are close enough, another force, called the strong force, overwhelms the electromagnetic force and binds the two particles together. Aside from converting hydrogen to helium, this process results in the net production of energy, because a helium nucleus is slightly (0.7%) less massive than the original four hydrogen nuclei that made it, and the mass difference is converted into energy in accordance with Einstein's famous equation $E = mc^2$, which states that mass is equivalent to energy.

A self-sustaining balance prevails between gravity, the energy produced in the core, and the energy released into space. Eventually, however, the hydrogen in the stellar core becomes depleted, the core begins to shrink, and the star begins to move off the main sequence. The core is now almost entirely helium, but its shrinkage permits the surrounding shell of hydrogen (which is also shrinking) to become hot and dense enough to start hydrogen shell burning ('burning' in this context always means nuclear burning – conversion into other elements through either fusion or fission; in this case it is fusion from hydrogen to helium). This proceeds faster than the main sequence hydrogen burning, and causes an increase in thermal pressure which expands the outer layers; the star becomes a subgiant, and eventually (after a billion years) a red giant. The outer layers of the star experience a weaker pull of gravity, and large amounts of mass escape in stellar winds. This situation persists until the still-shrinking core reaches a temperature of 100 million Kelvin, hot enough for helium-to-carbon burning.

Helium burning starts another and dramatic phase in the star's life. It heats the core excessively, releasing a huge amount of energy in what is called the helium flash. Within seconds the situation is 'corrected', and the total energy production falls sharply. The star becomes a 'normal' helium-burning star, and begins a quieter phase as a horizontal branch star. When the core has been totally transformed into carbon, shell burning around the core (this time of both helium and hydrogen) again causes the star to expand. The helium burning causes a number of thermal pulses of the star during a new red giant phase, and more mass is ejected from its outer envelopes. However, these stars are coming to the end of their lives, as they can never reach the temperatures of more than 600 million Kelvin required for fusion reactions in their carbon cores.

The large sizes of these stars mean that gravity has only a weak hold on the outer layers, and large amounts of matter flow out with the stellar wind. Strong convection during the pulses from the carbon cores dredge up large amounts of carbon, creating what are called carbon stars. The winds from these stars are by far the most prolific producers of carbon – essential for life as we know it.

The matter ejected by these winds, forming what are known as planetary nebulae, disperses into the interstellar medium within a million years. What is left of this star's eventful history is nothing but the cooling carbon core of the star. This remnant is a white dwarf star. It will eventually cool over the far distant future, and ultimately just disappear from view.

High-mass stars are even more spectacular than their low-mass counterparts. Their lives may be short, but they are certainly exciting. High-mass stars are also extremely important, as only they can produce the full range of heavy elements that our lives depend on. They begin their lives just as low-mass stars do, but the nuclear processes are somewhat different and much faster, because of the higher temperature and pressure. The hydrogen in the core is consumed in just several million years, and the subsequent helium burning lasts only a few hundred thousand years. Successive elements are burned more and more quickly, with the core shrinking, surrounded by shells of different elements, and the outer layers continuing to inflate to supergiant scales. The reactions can become quite complex, with heavy nuclei fusing with each other, leap-frogging the buildup to heavier elements. Neutrons can be released, fusing with heavier nuclei to form some of the rarest and heaviest elements. The final result of this frenetic process is the buildup of iron in the core.

As mentioned above, iron is unique and critical, as neither its fusion into heavier elements nor fission into lighter elements releases energy. An iron core means no more energy output. Catastrophic core collapse takes place, followed immediately by a supernova explosion that enriches the surrounding interstellar medium with all the newly created elements. While iron is the heaviest element that can be formed in the usual processes of stellar nucleosynthesis, the extreme conditions in this brief but violent explosive nucleosynthesis create most of the elements heavier than iron. The temperatures reached in these explosions are higher than those in any star, and processes such as neutron capture (which require energy input) create the very heavy elements. Without supernova explosions we wouldn't have most of the copper, silver, iodine, platinum, gold, lead, uranium, and many other heavy elements that are part of our daily lives.

Stellar nucleosynthesis is established beyond doubt. The processes all follow directly from well-known nuclear physics, and many if not most have been verified directly or indirectly from man-made thermonuclear explosions. Detailed and sophisticated computer modelling gives excellent agreement with the wide range of types exhibited by the stars themselves. Observational evidence includes the detailed distribution of the elements across the Periodic Table, including the excess of nuclei with even numbers of protons as predicted, and the fact that young stars contain more heavy elements than do old stars (the oldest contain very little). The heavy elements comprise about 2% of the total mass in the universe today, up from zero percent before the first stars existed: the buildup of heavy elements by nucleosynthesis in stars is clear.

Thus, as we have seen, while the light elements were produced in the Big Bang, the heavier elements are produced in stars. The heavier elements accumulate in the interstellar medium, so stars born later start out already containing elements from previous generations of stars. In this way the heavy elements are continually built up over time. These elements include those of organic chemistry (carbon, nitrogen, oxygen, etc.). The very atoms we're made of were created either in the early universe or in stars.

Evolution of Galaxies from the Dark Ages to Here and Now

We can now study galaxies at all stages of evolution directly. Because of the finite speed of light, we can see the entire history of galaxies laid out on the sky in front of us in one glance. We are presently simultaneously seeing galaxies as they were 13 billion years ago, 10 billion years, 6 billion years ago, 5 billion years ago, 3,2 and 1 billion years ago, 300,000 years ago, 50,000 years ago – all of these at once. Absolutely every epoch, simultaneously, right now in the sky, right there in front of us.

With huge samples of millions of galaxies, astronomers are now mapping out the detailed history of galaxies – every billion years, every million years, whatever interval you choose – the whole history of the universe spread out on a single graph. It's fantastic. 'Detailed history' here means the evolution of the stars in galaxies, the evolution of the gas in galaxies, the evolution of the structure of galaxies, how the galaxies interacted with each other as a function of cosmological time, and many other properties.

By studying similar types of galaxies at different epochs and different types of galaxies at the same epoch, we have multiple views of the history of the universe. Putting it all together is an absolute feast – and it has just become possible over the last two decades thanks to deep surveys of the sky that reach some of the earliest galaxies, novel and clever types of surveys of galaxies at intermediate epochs, and huge surveys at relatively recent epochs covering large areas of the sky. The HST, large ground-based telescopes, super-powerful instruments on many telescopes that can observe thousands of galaxies simultaneously, and super-powerful computers have made this possible. It is truly another scientific revolution.

From this chapter it should be abundantly clear that the universe is indeed expanding and evolving. The observed expansion, the abundances of the light elements, the relic radiation with its near-perfect blackbody spectrum, the fluctuations in the microwave background that led to the formation of stars and galaxies, the production of the heavy elements in stars, and the detailed evolution of galaxies that is now observed across the history of the universe – all of these provide incontrovertible evidence for the expansion and evolution of the universe. The first three have long been referred to as the pillars of the Big Bang Theory, and certainly more pillars now come from our knowledge of the evolution of stars and galaxies. All this gives us great confidence in our understanding of the physics of the universe at an early period in its history, and in Big Bang cosmology in general.

http://www.springer.com/978-3-642-20260-5

Cosmic Heritage
Evolution from the Big Bang to Conscious Life
Shaver, P.
2011, VII, 268 p. 7 illus. in color., Softcover
ISBN: 978-3-642-20260-5