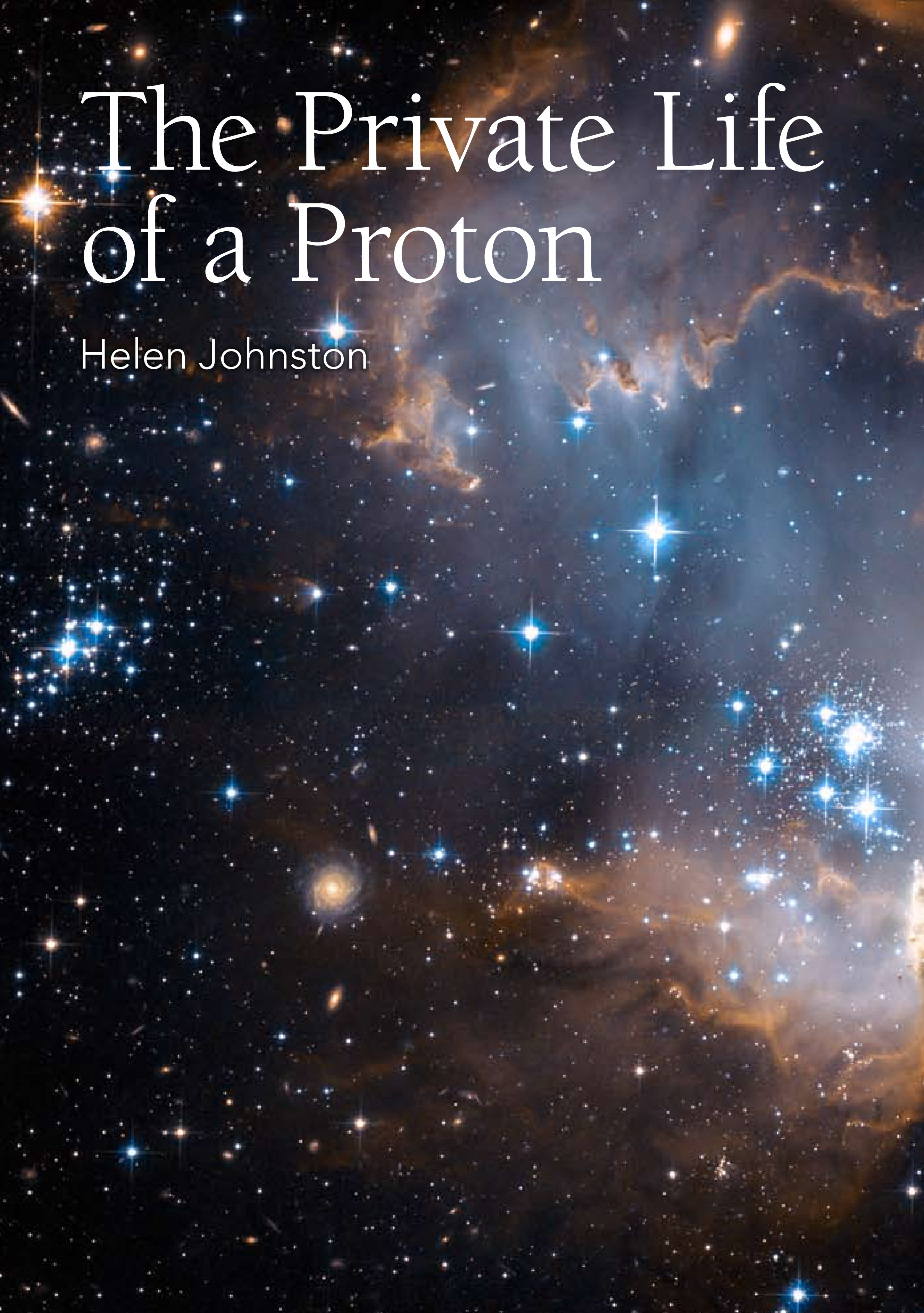
The Private Life of a Proton

Helen Johnston



Very few things are forever. Molecules re-arrange and re-make themselves constantly, in countless chemical reactions; and even atoms can be made and destroyed in the interiors of stars, forging entirely new chemical elements. Only protons are truly unchanging: every proton in every atom in the universe has been there since the very beginning[1]. But over the life of the universe, those protons may have been through many different guises. If one of those protons could tell its story, what a story that would be ...

Well, here is that story.

In the beginning, there was a proton.

Actually, it wasn't quite at the beginning. At the very beginning was the Big Bang, a moment of infinite temperature and density. The whole of the universe we see today was compressed into a region smaller than an atomic nucleus.

1 Actually, under some circumstances, protons can turn into neutrons and vice-versa. However, it takes energy to convert a proton to a neutron, so left to themselves neutrons will decay into protons but not vice-versa.

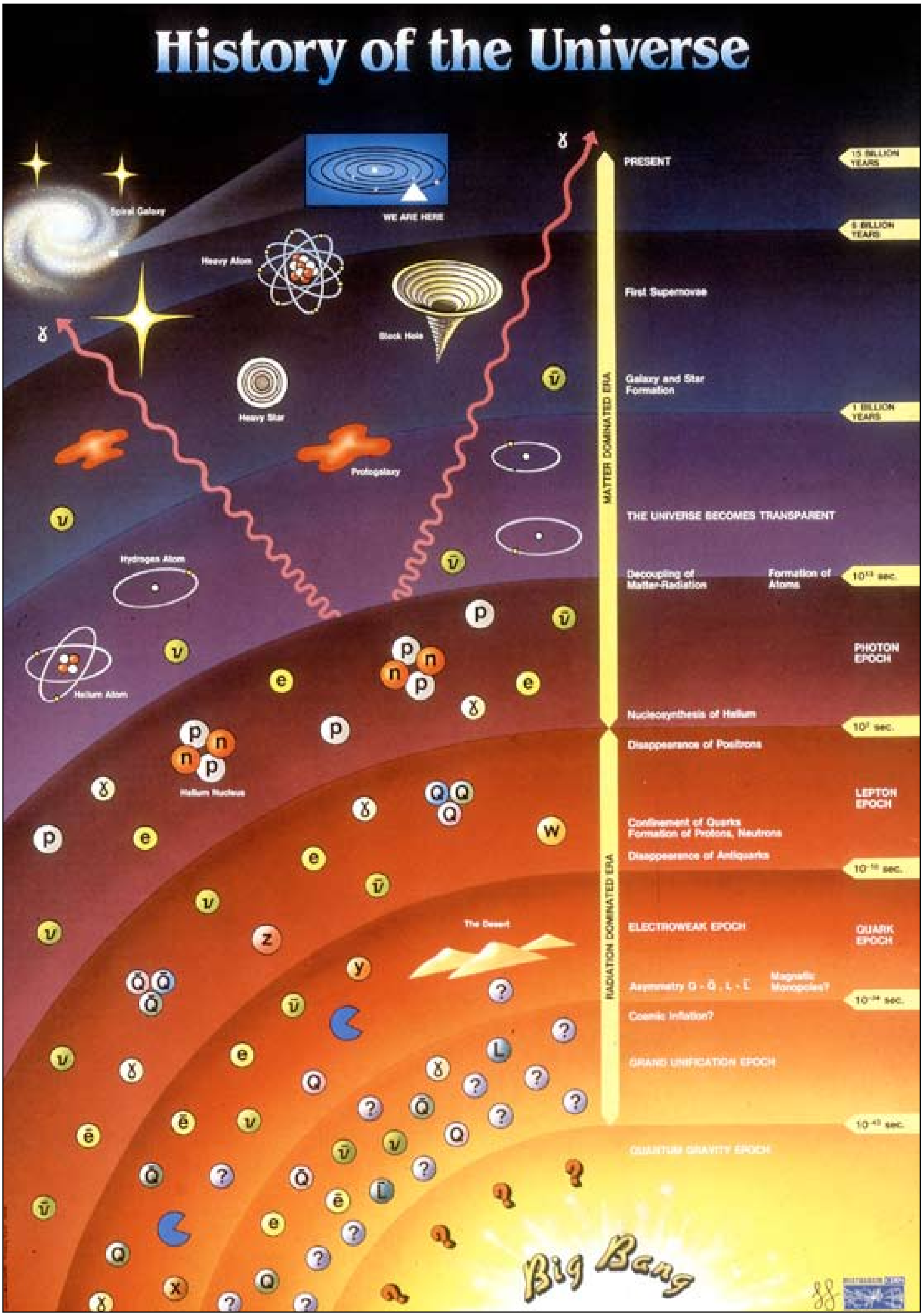


Figure 1: History of the Universe. *Microcosm CERN*

We have no laws of physics to describe what was going on under these conditions, so our description of the universe has to start a tiny fraction of a second after time zero. After that time, the universe began to expand, and as it did so, it cooled.

The story of our proton begins just 0.01 seconds after the Big Bang. Before that, the universe had been too hot and dense for protons to exist: instead, it was a seething mass of photons[2], electrons, positrons, neutrinos, quarks and antiquarks. It was not until the temperature of the universe had dropped below several million million degrees that quarks could bind together to form protons and neutrons.

This is where we meet our proton for the first time.

For a while, the existence of the proton is very transitory: every time it meets an anti-proton the two annihilate, converting their mass-energy into a pair of energetic photons. These photons then spontaneously convert the energy back into mass, producing a new proton/anti-proton pair, which speed away from each other.

There comes a time, however, when the universe has cooled just enough that the photons no longer have enough energy to produce new particles. When that happens, most of the particles and antiparticles annihilate each other one last time. Our proton was one of the few – the very few – that did not find an antiparticle. For each lucky particle, 30 million other particles did not make it. One second after the Big Bang, our proton finds itself in a universe made up of energy and matter, with essentially no antimatter.

For reasons we still don't understand, there was a tiny imbalance of matter over antimatter – for every 30 million antiparticles there were 30 million and one particles. After the annihilation had finished, only this small amount of left-over matter remained: the rest had disappeared into radiation. So about 1 second after the Big Bang, there was about one proton or neutron for every billion photons or electrons or neutrinos.

The universe is a seething maelstrom. Protons and neutrons smash into each other, moving much too fast to stick together. The entire universe still consists entirely of sub-atomic particles.

As the temperature drops, the particles start moving more slowly. Now when protons and neutrons meet, they can stick together; the strong nuclear force grabs them and binds them together into the first nuclei. All around our proton, particles are sticking together in clumps: first two, then three and four. The four-nucleon clump – two protons and two neutrons – is the most stable: a helium nucleus. But not five: when a four-particle helium nucleus is struck by another particle, the whole lot is split apart again.

By the time the universe is a bit more than three minutes old, nearly all the neutrons have combined into nuclei, while most of the protons (including ours) are still free. About 90% of the universe is hydrogen, with nearly all the rest made up of helium. There is some deuterium[3], and tiny amounts of lithium and beryllium, but nothing else. The first elements have been born, albeit without electrons: it is still too hot for the electrons to combine with the nuclei to form atoms. Shortly afterwards, when the temperature becomes too low for nucleosynthesis to take place, the production of nuclei stops. No more elements will be formed for a long time.

This story of how the first elements were formed is extremely well understood. As the universe cooled, new particles could be made out of old ones. We can measure the rates at which these reactions occur in particle accelerators, and by applying the concepts of thermodynamic equilibrium, we can predict which particles will be formed as the universe cools. It turns out that the final composition of the universe depends only on the *baryon*

2 Electrons and positrons are examples of *antiparticles*, which have the same mass but opposite electric charge. Particle-antiparticle pairs can annihilate one another and convert their entire energy into two photons. Matter is made of protons, neutrons and electrons, while antimatter is composed of antiprotons, antineutrons and positrons.

3 Deuterium is the name given to *heavy hydrogen*, hydrogen-2, whose nucleus consists of one proton and one neutron bound together. The ordinary hydrogen nucleus, hydrogen-1, has just a single proton.

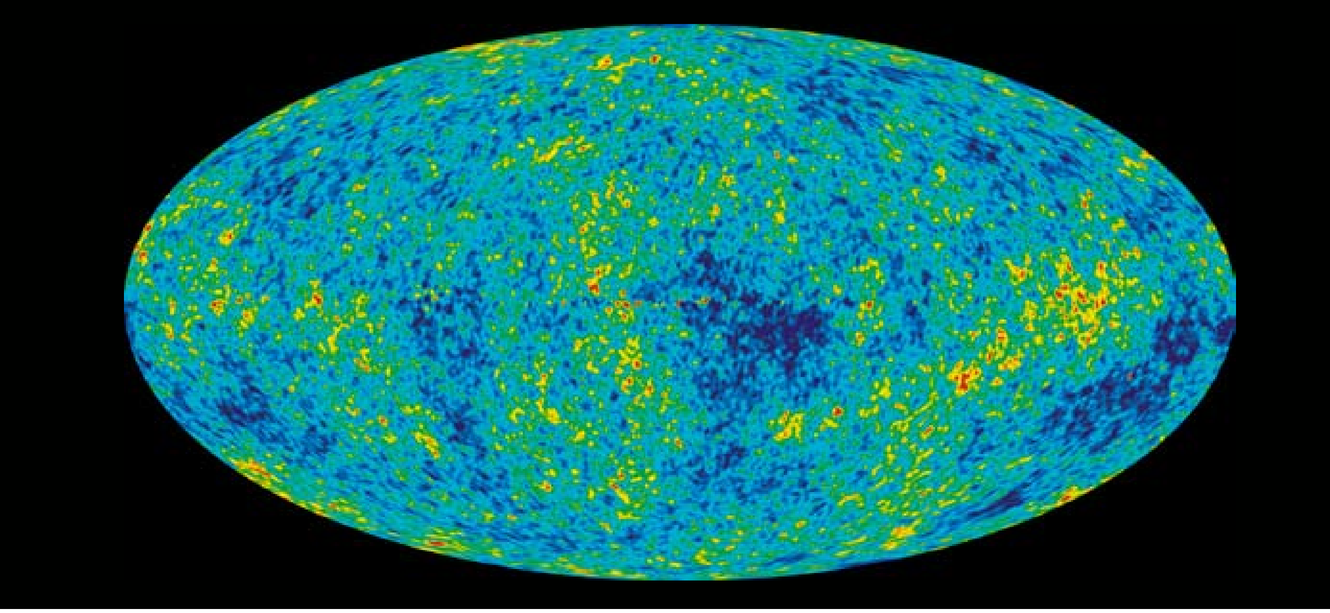


Figure 2: The cosmic microwave background, observed by the Wilkinson Microwave Anisotropy Probe (WMAP). The average temperature is 2.725 K; the colours represent tiny fluctuations (0.0001 degrees) from this mean, with red regions warmer and blue regions colder.

Image: NASA/WMAP Science Team

density – how many protons and neutrons there were in a given volume of the early universe. By measuring the abundance of elements like deuterium in the oldest stars, we can determine this baryon density.

It was still too hot for the electrons to combine with the nuclei to form atoms, so our proton found itself free in a sea of protons and helium nuclei, surrounded by photons and electrons.

The entire universe consisted of nothing but this ionised gas: a *plasma*. Electrons and nuclei moved freely about. Because electrons are very good at scattering photons, light cannot travel far before hitting an electron and flying off in another direction. This has the effect of making the universe opaque: light is scattered around just like being inside a fog.

Nothing else much of note happens for a long time, while the universe continues to expand. About 380,000 years later, the temperature has cooled to about 3,000 degrees. Finally, it is cool enough for electrons to combine with nuclei to form stable atoms without being ripped apart again. Once it has captured an electron, our proton is no longer a free proton. It is now the nucleus of a hydrogen atom.

This period when electrons were trapped into atoms – the *recombination era*[4] – has one important consequence. Once the photons were no longer continually bouncing off electrons, they could begin flying freely. Most have been flying freely ever since. We can observe these photons today as the cosmic microwave background. Since they began travelling, the universe has expanded by a factor of 1000, so the temperature has dropped from 3000 degrees to just 3 degrees above absolute zero.

The cosmic microwave background radiation is almost uniform in all directions. The Wilkinson Microwave Anisotropy Probe (WMAP) was a satellite launched in 2001 to measure the tiny variations in the temperature of the radiation: the temperature over the sky ranges from 2.7251 to 2.7249 degrees Kelvin.

The universe is completely dark. There are no stars; nothing is hot enough to produce any visible radiation. There is no source of light anywhere.

Once the temperature of the universe had dropped below 3000 K, the wavelength of the average photon making up the background

4 Actually, it should be called the "combination era", since the electrons and nuclei had never been united before.

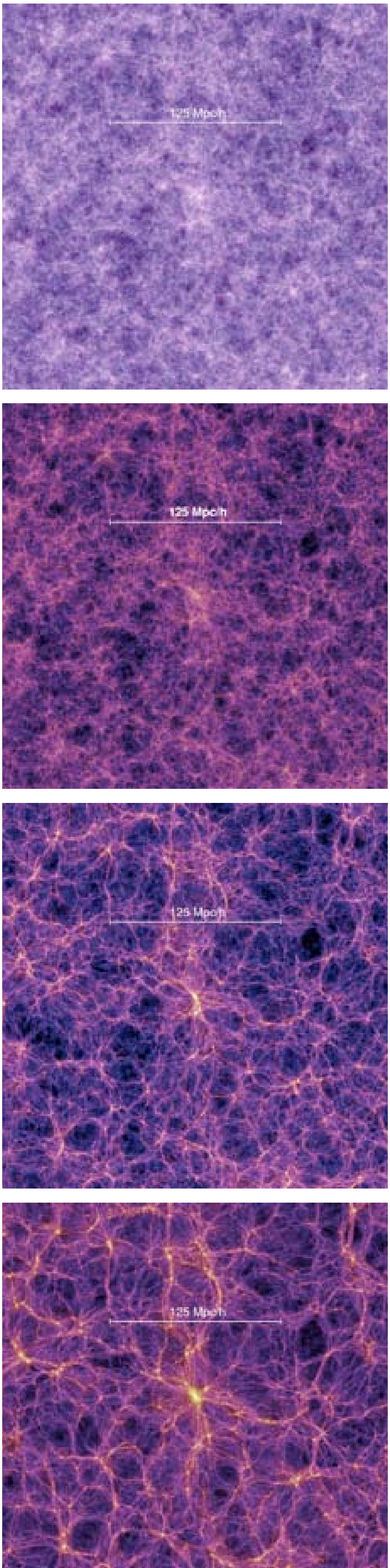


Figure 3: Snapshots of a very large volume of space in the Millennium Simulation, which followed the formation of galaxies and clusters. The yellow points represent individual galaxies.
Images: G.Lemson and the Virgo Consortium

radiation had shifted into the infrared. Nothing in the universe was emitting visible light.

This *cosmic dark age* lasted for perhaps a hundred million years.

Our hydrogen atom moves aimlessly as part of the gas that makes up the universe; almost, but not quite, completely uniform. By random chance, in some regions the atoms are slightly closer together than in other regions. This means they have slightly more mass, so their gravity pulls in more material, so they get denser still. By such means, little by little, the universe gets lumpier.

In the dark, things were happening. The matter was distributed almost but not quite evenly through the universe: we still see the imprint of these tiny fluctuations in the background radiation. As time went on, the clumps of matter grew; gravity was assembling the components of the universe. The physics of how this happened is extremely complicated: we need supercomputer simulations to understand how structures grew. These simulations show that the matter develops into a web of filaments, with voids separating the denser regions. We see these filaments today in maps of galaxies. The 2dF Galaxy Redshift Survey, which was done at the Anglo-Australian Telescope, measured the distances to nearly a quarter of a million galaxies, enabling astronomers to make a three-dimensional map of the universe. The distribution shows clusters and filaments, separated by vast voids almost devoid of galaxies.

For a long time, our hydrogen atom drifts. For millions of years the drift is barely perceptible, but gradually it becomes apparent that the gas is getting denser, and that it is drifting in a particular direction. The gas cloud containing our hydrogen atom is now stretched out like a long thread. Then at last, something has changed. Millions of light years away in the direction the cloud is drifting, there is light: the first light that has been

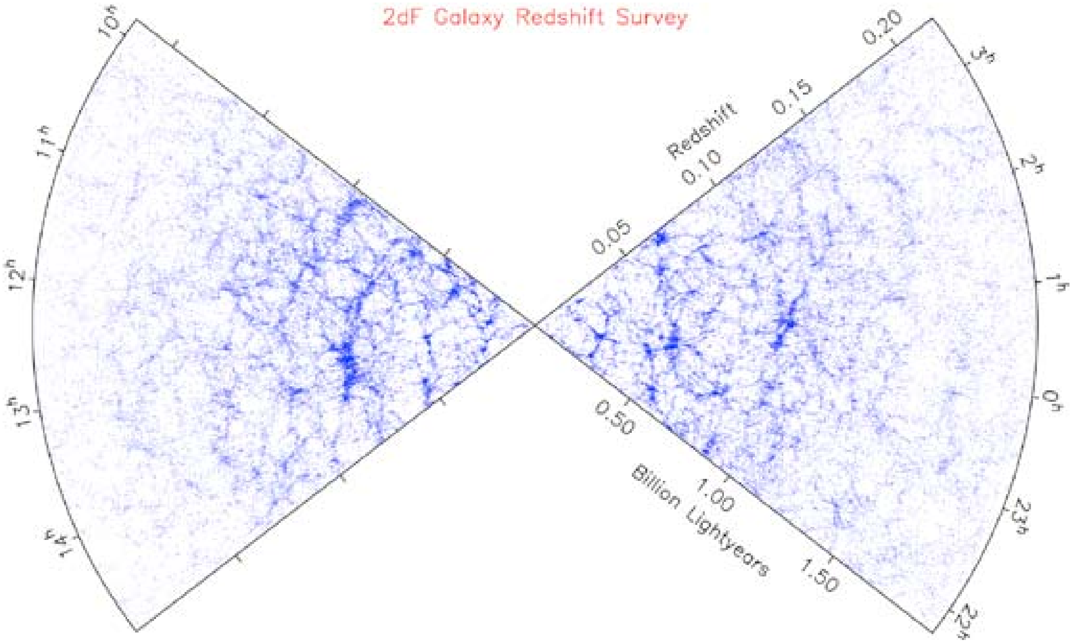


Figure 4: A slice of the universe from the 2dF Galaxy Redshift Survey: each dot is a galaxy. *Matthew Colless*

seen since the universe cooled below 3,000 degrees. Far ahead, one of the first stars in the universe is shining.

Eventually, the first objects which produced light were born. This light not only illuminated the darkness, but also stripped the electrons off the atoms in the interstellar gas again. We are still not sure which objects were responsible for this *cosmic re-ionisation*. They had to be objects producing large numbers of energetic photons: hydrogen is ionised by radiation with wavelengths shorter than 91.2 nm, which are ultraviolet photons. The most likely candidates are either quasars or the first stars. Quasars are supermassive black holes, which are accreting gas from a swirling disk and sending narrow jets of high-speed particles and radiation towards us. We know the universe was already re-ionised by the time the universe was 1 Gy old[5], at a redshift of 6, because quasars at higher redshift have all their blue light absorbed by neutral hydrogen gas, while quasars at lower redshift do not. Re-ionisation almost certainly did not happen all at once; instead, bubbles of ionised gas formed around stars (or quasars). As the number of bright objects grew, the bubbles merged together and cleared up the "fog" of neutral hydrogen, allowing the blue light to travel freely.

Evidence is beginning to suggest that it was stars that first re-ionised the universe. The most distant quasars yet observed already show the presence of elements heavier than hydrogen and helium, which means (as we shall see) that there must have already been massive stars before these quasars were born.

Composed only of hydrogen and helium (and a tiny amount of lithium), these first stars would have been very different from the stars forming today. Theory predicts they would not only have been much hotter than stars forming now, but also that they could have been much more massive. Stars forming today cannot be more massive than about 150 times the mass of our Sun. Beyond that mass, the star produces so much radiation that the outward pressure of

5 *Redshift* describes how much the wavelength of the light which reaches us has been stretched by the expansion of the universe since it left the source. More distant objects have higher redshifts, and so when we observe an object at high redshift, the light has been travelling since a long time in the past. The relation between redshift and age of the universe is given in Table 1, see end of chapter.

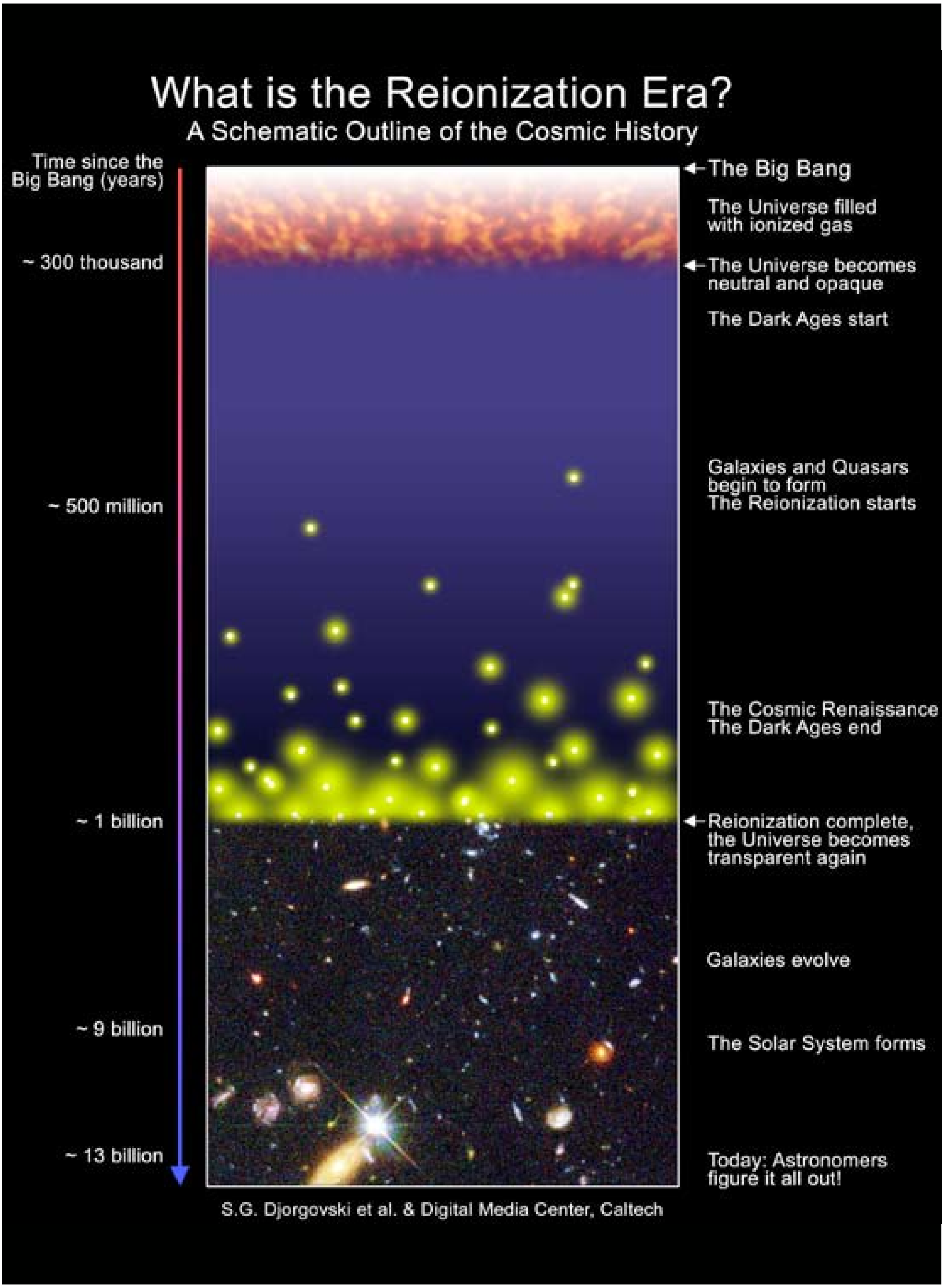


Figure 5: Cosmic reionisation in the history of the Universe. *S. G. Djorgovski et al., Caltech. Produced with the help of the Caltech Digital Media Center.*

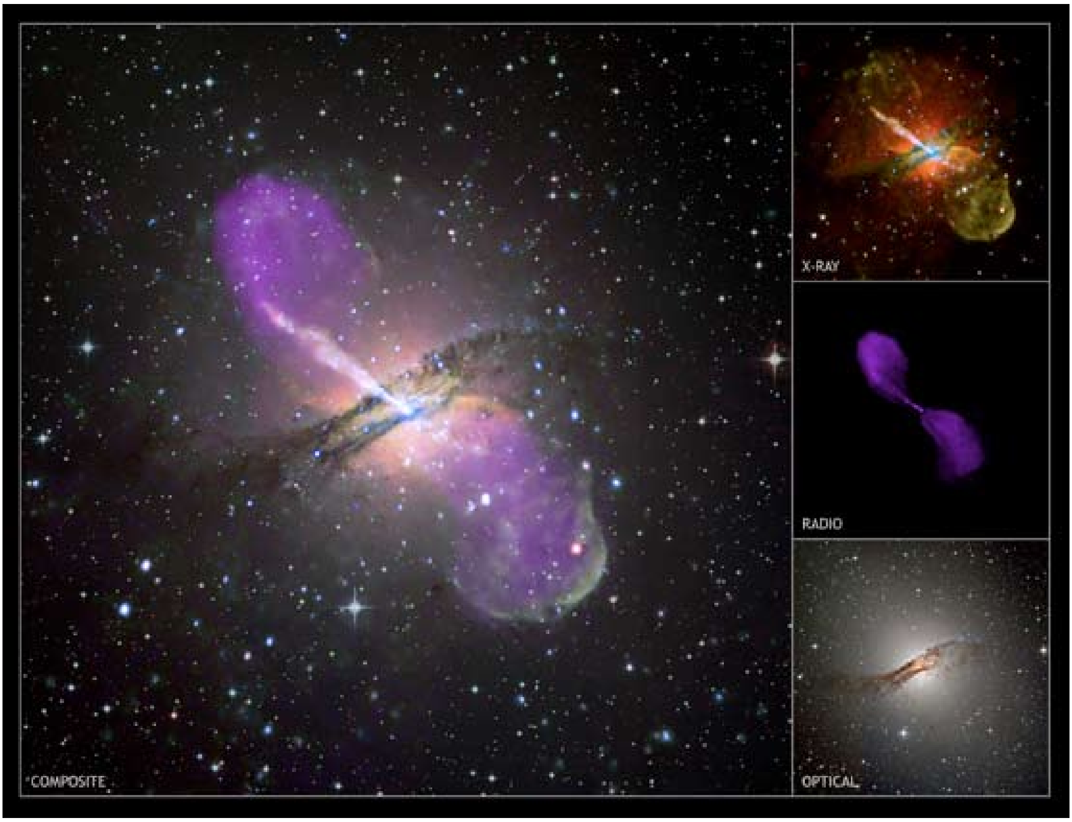


Figure 6: The radio galaxy Centaurus A, showing twin jets of matter being ejected from the central black hole. These jets can be seen at X-ray and radio wavelengths.
NASA/CXC/SAO

the radiation exceeds the inward pull of gravity, and the star tears itself to pieces. The very first stars, however, could potentially grow to be much more massive: several hundred, perhaps even up to a thousand solar masses. Such stars would have extremely short lifetimes – a million years or less – after which they would explode, seeding the interstellar medium with heavy elements. Their collapsing cores may even have provided the seeds which grow into the massive black holes we see at the centres of quasars and galaxies.

The region towards which our hydrogen atom is falling is now perceptibly a protogalaxy. At its centre is a black hole, formed from the embers of one of the dying first stars. Since its formation it has grown considerably, by merging with other black holes, and by sucking down enormous quantities of gas. Surrounding it is a cloud of stars formed from the gas that continues to accumulate. The gas cloud containing our proton gradually swirls towards the centre of the growing galaxy. As smaller clumps come too close and are pulled in, some of the gas is flung completely away, doomed to swirl forever in the almost empty regions of intergalactic space. Other gas finds itself being hurled towards the centre of the galaxy. There it is pulled into a swirling, super-heated accretion disk around the black hole, where it will eventually disappear into the event horizon and be lost forever, or else squirted at nearly the speed of light right out of the galaxy in twin jets. Our proton avoids both of these fates; instead, it finds itself near the centre of a dense cloud, which gets denser as more gas collides with it and compresses it.

Whether they were formed in the first stars, or collapsed directly from the gas, or grew from seeds of primordial black holes created

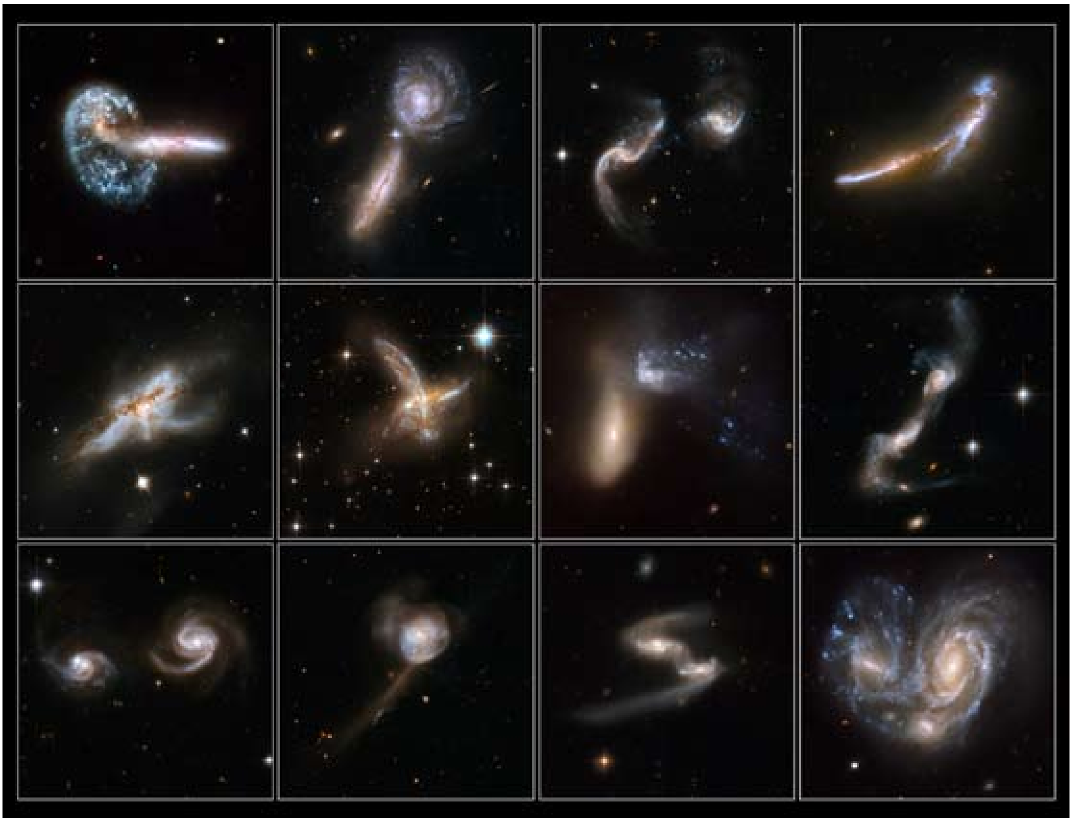


Figure 7: A series of interacting galaxies observed by the Hubble Space Telescope.
ESA/Hubble

in the first instants of the Big Bang, we know that massive black holes already existed and were growing less than a billion years after the Big Bang. The most distant quasar currently known has a redshift of 6.43, so it was formed when the universe was only 0.87 Gy old. Radio galaxies are also powered by supermassive black holes, but the jet is seen side-on, so we see radio emission from the jets. Radio galaxies are known at redshifts of up to 5.19, when the universe was just over 1 Gy old. So the black holes must have been formed very early on in the universe. Did they exist first and then galaxies grew around them? Or did the galaxy and the black hole both form together? We still don't know. We do know, however, that almost every galaxy has a massive black hole at its heart, and that the bigger the galaxy, the bigger the black hole. This suggests that the growth of the galaxy and the black hole are somehow intimately linked.

However they began, the evidence suggests that both the galaxy and the black hole at its heart grow as a result of the merging of galaxies. Everywhere we look, we see signs of galaxies in the process of colliding, or showing evidence of collisions in the not-too-distant past. And the further back we look, the more common these collisions seem to be. When galaxies collide, the stars almost never collide: their physical size is so small compared to the vast distances between them that they just pass freely past each other. However, the enormous gas and dust clouds in both galaxies do collide: the gas is compressed, which triggers more star formation. Meanwhile, some of the gas and stars are flung out in huge tidal tails, while some is sent spiralling towards the centre of the galaxy, where it can feed the black hole.

Our own Milky Way galaxy contains the debris of many dwarf galaxies it has swallowed up in the past, and it is currently in the process of devouring a few more; the Magellanic Clouds will be devoured within the next few hundred million years.

Over millions of years the gas cloud gets denser and colder, and our proton (now a hydrogen atom) finds itself in a molecule for the first time: two hydrogen atoms are bound together as molecular hydrogen, H_2.

The interstellar gas is the raw material from which stars form. A cloud of gas has a tendency to collapse under its own gravity, but this inward pressure is resisted by the gas pressure. This is sufficient to resist the collapse until a critical threshold is passed, when the collapse becomes unstoppable. This threshold mass depends on the temperature and density of the cloud, with colder and denser clouds more likely to collapse. So stars tend to form in the coldest, densest regions of gas; these regions are called *giant molecular clouds*.

A typical giant molecular cloud might be 50–100 light years across and contain a million or more solar masses of material. The gas is now not just the pristine material made in the first few minutes after the Big Bang; the first stars polluted the interstellar gas with heavy elements when they exploded. So by the time this second generation of stars begins to form, the gas cloud already contains small amounts of (amongst other things) carbon, nitrogen, oxygen, and other elements. Astronomers can measure the proportion of heavy elements in the spectra of stars, and find that older stars have significantly lower proportions than younger stars. In our own galaxy, these *low-metallicity stars*[6] are found primarily in the Galactic bulge and in globular clusters, while younger, more metal-rich stars like our Sun are found in the disk of the galaxy.

When the giant molecular cloud starts to collapse, it continues under its own momentum. More and more gas falls inwards as the collapse accelerates. Multiple clumps develop in the cloud, as denser-than-average regions pull in more and more gas. Eventually the cloud fragments into hundreds of small dense globules, each of which will eventually become a star. The collapse is fastest near the centre of each globule where, inside a cocoon of gas and dust, the dense core of gas is getting hotter as the kinetic energy of the accreting matter is converted into heat. As the density increases the cloud becomes opaque, trapping the heat within the cloud. This then causes both the temperature and pressure to rise even more rapidly – the collapsing cloud is now a *protostar*.

The cloud containing our proton has been accumulating mass, getting denser and more massive as more gas falls in. Once the runaway collapse has started, the gas containing our proton begins its long fall towards the dense knot that will become the newborn star. The gas heats up as it falls; first

6 To an astronomer, every element other than hydrogen and helium is called a *metal*, so oxygen and carbon are described as metals. Only the first generation of stars, made from the primordial gas of hydrogen and helium, was *metal-free*.

Figure 8: The young star cluster NGC 602 in the Small Magellanic Cloud, showing hot young stars just emerged from their birth cloud.

NASA, ESA, and the Hubble Heritage Team the molecules are stripped apart, then the electrons are ripped from the atoms. When the collapse finally ends, our proton finds itself near the centre of a young, massive star, about 25 times the mass of our Sun.

The collapse only comes to an end when the star finds a source of energy to balance the inexorable inward pull of gravity. That source is nuclear fusion: when the temperature at the core reaches about 15 million degrees, hydrogen nuclei can begin to fuse together to form helium, just as they did in the first few minutes after the Big Bang. Energy is a product of that fusion, so as each set of four hydrogen nuclei fuses into helium via a series of nuclear reactions, energy is produced which increases the temperature and pressure of the star's core enough that it can resist the inward pull of gravity. A star has been born.

Our proton sits near the core but not in it. Here, where our proton sits, a bit less than a quarter of the way out from the core, the temperature is lower. Unprotected by their electron shells, protons regularly collide, but their positive charge means they just bounce off each other. It is only deep in the core, more compressed by the great weight of the star, that the nuclei are moving fast enough to collide and form new elements: first deuterium, then helium.

This conversion produces enough heat to support the immense mass of the star against the inexorable pull of gravity.

As long as the star can continue fusing hydrogen to helium in its core, it can maintain its equilibrium against the pull of gravity. The star stays like this for 6.6 million years, steadily converting the hydrogen in its core to helium: the star is a *main sequence star*. Outside the core, where our proton sits, no fusion is taking place: the material of the star is still the same as the original gas cloud from which it was born: mostly hydrogen, with some helium and some trace amounts of other elements left over from previous generations of stars.

For six and half million years, nothing much has changed for our proton. Enormous quantities of radiation flood past every second, produced in the core and flowing through the star to its surface, there to shine into space.

But this situation cannot last. Eventually the time comes when the hydrogen in the core is exhausted. When that happens, the core can no longer support itself against gravity, so it starts to collapse. When it does so, it heats up, and hydrogen just outside the core finds itself hot enough to fuse into helium for the first time. This sudden increase in energy forces the outer layers of the star to swell up dramatically: the diameter of the star increases by a factor of 200. The outer layers, being so much larger, also cool dramatically, so the star becomes enormously large and red: a *red giant star*. If this star replaced our Sun, it would stretch past the orbit of Jupiter.

Meanwhile, the helium core is still collapsing and heating up. Eventually, it becomes hot enough for helium to fuse: this takes much higher temperatures, about 100 million degrees. But eventually the helium is also exhausted: then the collapse re-commences. The cycle repeats: each time a fuel is exhausted, the core begins to collapse once more, which heats it up even higher, so that even heavier elements can fuse, which produces more energy to support the star. The fusion of these nuclear fuels goes faster and faster as the atomic number increases, both because there are fewer atoms to fuse, and less energy is released each time.

At last something changes. The pressure beneath our proton drops, and it starts to fall inwards. The fall is stopped as the gas beneath is more compressed, but now the temperature is higher. Several times this collapse and halting happens, with the temperature increasing each time. At last the day comes when, instead of bouncing off other protons, the particles collide and stick: our proton is now part of a deuterium nucleus. Almost immediately, this fuses with two more particles to form first helium-3 and then helium-4. Later, after more collapse of the core, this helium-4 nucleus fuses with two others to form a carbon-12 nucleus.

Once silicon has fused to iron, however, there is no next step. Iron is the most stable nucleus, and does not release energy when it is fused: adding anything else to the nucleus costs

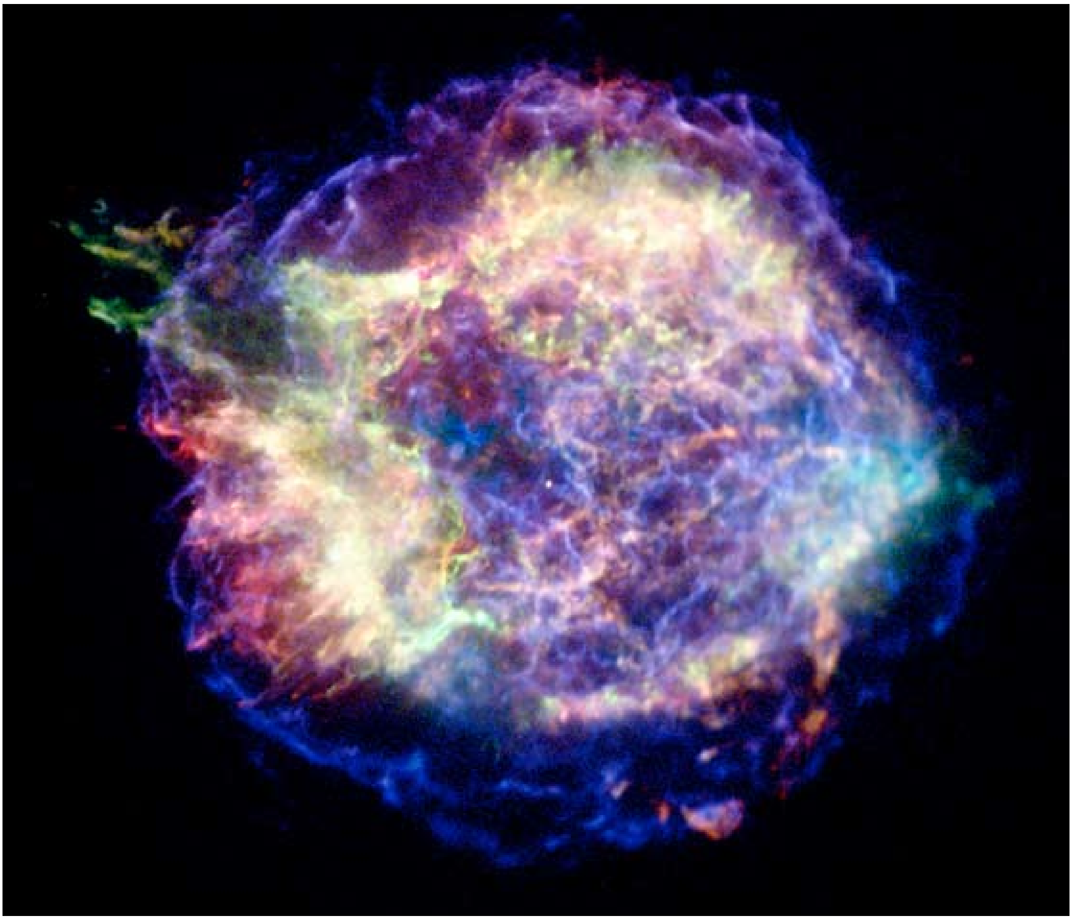


Figure 9: Chandra X-ray image of the supernova remnant Cassiopeia A.
NASA/CXC/SAO

energy instead of producing it. The star has reached the end of the line, and can no longer support itself. Gravity has won.

The core of the star collapses inwards. The inwards pressure forces electrons and protons in the core to combine to form neutrons. These neutrons are squeezed so tightly together that in less than a second the whole core of the star, weighing about one and a half times the mass of our Sun, is compressed to a sphere only 15 km in diameter: it has become a *neutron star*.

Meanwhile, the outer layers of the star are still falling, oblivious to what is happening to the core. When these layers meet the newborn neutron star, they bounce off it so hard that they are ejected outwards again at a substantial fraction of the speed of light. This creates a shock wave which blasts the whole envelope of the star outwards at tremendous speed. When this blast wave reaches the surface of the star, it becomes visible as an enormously expanding fireball: a *supernova*.

Sitting in the layer of carbon, our proton (in its carbon nucleus) has no warning of the catastrophic events that have taken place deep below it in the core of the star. The first sign that something has changed is that the pressure beneath the layer suddenly drops; the star begins to collapse. With nothing supporting it from beneath, the outer layers of the star, including the carbon atom containing our proton, begin to fall inwards. Seconds later, however, the blast wave exploding outwards through the star roars past, and the gas is exploded outwards. All around, nuclei are being fused with other nuclei to form heavier elements, and bombarded by a flood of neutrons in the wake of the blast. Within seconds, elements up to uranium are formed, in the crucible of a supernova explosion.

Our carbon nucleus is swept outwards as part of an expanding shell of gas. As it expands, the shell cools, and after about a hundred thousand years stops glowing. The remnant of the star, now light years behind, is visible for a few million years as a pulsar, then it too fades. The gas from the explosion, no longer discernible as a shell, mingles with the interstellar medium.

Without supernova explosions, there would be no heavy elements from which to form (amongst other things) rocky planets. Recall hydrogen, helium and a tiny bit of lithium were the only elements formed in the Big Bang, and until the first stars formed nearly a billion years later, they were the only elements in the universe. Once the first stars had been born, heavier elements like carbon and oxygen were created in their cores, but these elements were locked up, inaccessible beneath layers of unburnt hydrogen. Supernova explosions not only liberate these elements into interstellar space, but are also responsible for creating all the elements heavier than iron in the explosion itself[7]. All the stars in our Galactic neighbourhood, including the Sun, have about 1% of their mass composed of elements heavier than helium. All these elements must have come from earlier generations of massive stars which lived their lives, then exploded as supernovae, seeding the surrounding gas with the new elements. This gas, now enriched with heavy elements, can then be incorporated into new stars.

Eventually, our carbon atom finds itself in another cloud of cold, dense gas. A nearby supernova triggers the collapse of this cloud. Again, the gas is drawn inwards to where the densest regions are pulling in ever more material, eventually to reach high enough temperatures that nuclear fusion begins and stars are born.

Figure 10: Protoplanetary disks around stars in the Orion Nebula, from HST.
NASA, ESA, and the Hubble Heritage Team

7 There is a tiny number of elements that are formed in different ways, like beryllium, formed when cosmic rays split heavier nuclei in the interstellar medium, or molybdenum, formed in the atmospheres of red giant stars. Every other element in the periodic table is made inside stars.

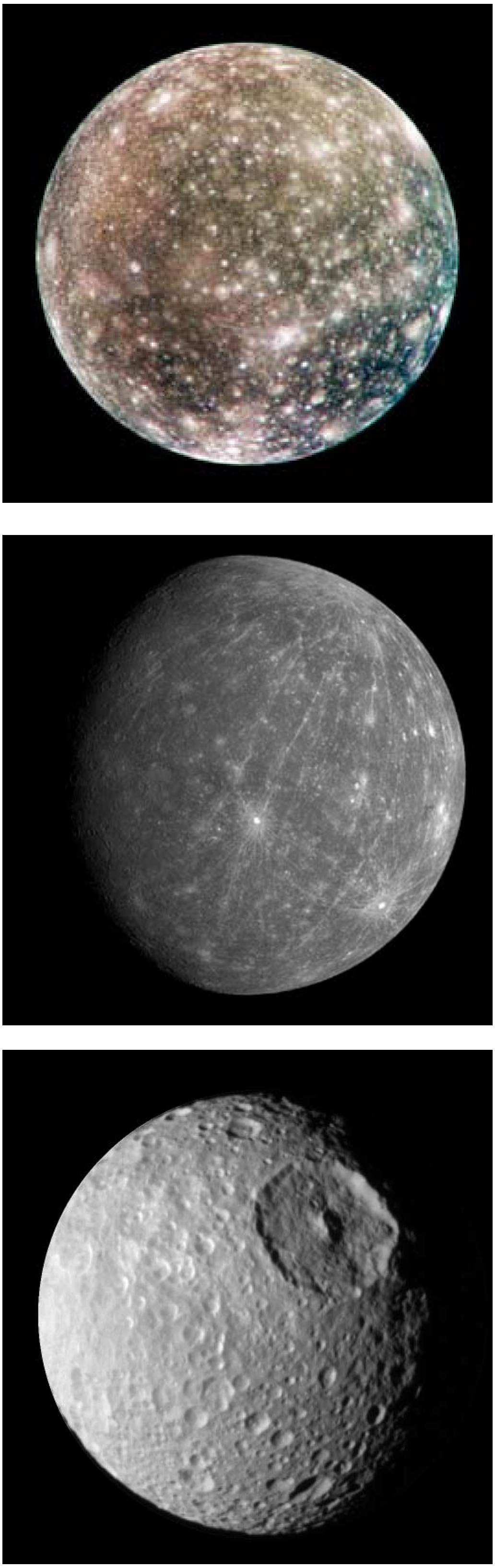


Figure 11: Every old surface in the Solar System bears witness to having been battered by impacts of all sizes. From top to bottom: Callisto, Mercury and Mimas.

This time, our carbon atom is not in the dense centre of the cloud, so by the time the new star begins to shine, it is trapped in an icy body at the outer edges of a giant disk swirling around the star.

As the centre of the cloud collapses, the outer regions flatten into a disk surrounding the protostar. The Hubble Space Telescope has taken pictures of these disks in regions like the Orion Nebula, showing that they are common around young stars. It is from a disk like these that the Solar System formed.

In the inner regions of the disk, dust and particles condense out, then stick together, bumping and colliding and growing in size until the fragments, now called *planetesimals*, have grown to about 1 km in size. Now their gravity starts assisting with their growth: the larger they grow, the more matter they attract. The largest planetesimals sweep up all the matter within their reach, until we are left with a hundred or so proto-planets, each the size of our Moon or larger, orbiting the infant Sun. Over the next hundred million years or so, this number was reduced to the current handful of planets as the proto-planets cross orbits and collide in giant impacts. Every old surface in the Solar System bears witness to having been battered by impacts of all sizes.

Orbiting beyond the outermost planets were the left-over planetesimals, which never coalesced into a planet. We still see this disk of left-over bodies as the *Kuiper Belt*, a region beyond the orbit of Neptune containing probably 70,000 or more small icy bodies more than 100 km in diameter. Pluto and the newly-discovered dwarf-planets like Haumea and Makemake are just the largest members of the Kuiper Belt.

Six hundred million years after the planets formed, something is happening in the endless cold at the edge of the Solar System. As they orbit, the icy bodies feel new and

Figure 12: The near side of the Moon, taken by the Galileo spacecraft on its way to Jupiter. The dark areas are the maria: impact basins filled with lava from ancient volcanic eruptions.

different pulls; orbits that were previously stable are perturbed. Chaos ensues; some bodies are flung outwards, but many others are hurled inwards, towards the inner solar system. The icy rock containing our carbon atom is one of them. It hurtles towards a small rocky world circled by one large moon...

Simulations of the formation of the planets suggest that Uranus and Neptune probably formed much closer to the Sun than they are now. The four largest planets interacted with each other and with the disk of icy planetesimals which circled beyond them. The orbits slowly expanded, until after about 700 million years, the orbit of Saturn came into 2:1 resonance with Jupiter, which means that Jupiter orbited the Sun exactly twice for every one of Saturn's orbit.

This made the orbits of Uranus and Neptune unstable, and their orbits expanded outwards into the disk. Planetesimals were scattered in all directions; some were flung outwards, and some were sent careening into the inner Solar System. This *late heavy bombardment* left scars on most planets and satellites in the solar system. It produced the great basins of the *maria* on the Moon, and may have contributed to the atmospheres of the inner planets. None of the rocks brought back from the Moon were older than 3.9 billion years, which is 600 million years younger than the age of the Solar System.

Any atmospheres the terrestrial planets had at the beginning would have been lost during the worst of the heavy bombardment. As the rate of impacts began to ease, however, the planets began to cool. Gases trapped in the hot rocks were gradually released, and combined with the volatiles (water, carbon dioxide etc.) brought by comets and asteroids from the outer solar system to gradually build up an atmosphere. On Earth, once the temperature dropped below 100° C, water vapour could condense out and the oceans begin to form.

Only inside stars can transmutation of elements take place, because only inside stars do we find the enormous temperatures required. Outside a star, a proton in the nucleus of an atom is almost certain to stay there forever. However, atoms can form an enormous variety of molecules with other atoms, and molecular bonds can form and break at much lower temperatures. Carbon in particular forms bonds with many elements, and can form molecules of great complexity.

We don't know how long it was after the late heavy bombardment before conditions were right for life to form, but the evidence suggests it wasn't long. The earliest evidence for life comes from the study of isotope ratios of carbon-12 to carbon-13 in rocks from 3.8 billion years ago, suggesting that life arose a mere 100 million years after the late heavy bombardment stopped.

The cataclysm of the impact that delivered our carbon atom to the Earth has subsided; the vaporised material from the icy planetesimal has mixed with the existing atmosphere. Sometime later, our carbon atom joins with two oxygen atoms to form carbon dioxide, the principal component of the atmosphere of the young Earth. Soon it finds itself dissolved in the newly-formed oceans. The energetic UV radiation encourages many different compounds to form and re-form, so our carbon atom goes through a continual cycle of new configurations: methane, ammonia, simple amino acids.

One day, a completely new type of molecule emerges, built around our carbon atom. This molecule and its descendants will eventually transform the planet itself, changing its atmosphere, its surface, its oceans. It is a molecule that can reproduce itself. Our proton has made the next step in its long voyage, from galaxies to genes...

Further reading:

Here are some suggestions for popular-level books covering some of these ideas.

- "The First Three Minutes: A Modern View Of The Origin Of The Universe" by Steven Weinberg (Basic Books, 1993)
- "Big Bang" by Simon Singh (Fourth Estate, 2004)
- "The Birth of Stars and Planets" by John Bally and Bo Reipurth (Cambridge UP, 2006)
- "Cosmic Catastrophes: Exploding Stars, Black Holes, and Mapping the Universe" by J. Craig Wheeler (Cambridge UP, 2007).
- "The Story of the Solar System" by Mark A. Garlick (Cambridge UP, 2002)

Table 1: Redshift and lookback time

Redshift	Fraction of current age	Time since Big Bang (in Gy = 10^9 years)	
1100	0.0028%	380,000 y	CMB
20	1.3%	0.2 Gy	Reionisation
10	3.5%	0.5	
5	8.8%	1.2	Peak of galaxy formation
2	24%	3.3	
1	57%	5.9	
0.5	63%	8.6	
0.2	82%	11.3	
0	100%	13.7	Now