Contemplating the Origin of Matter in the International Year of Chemistry

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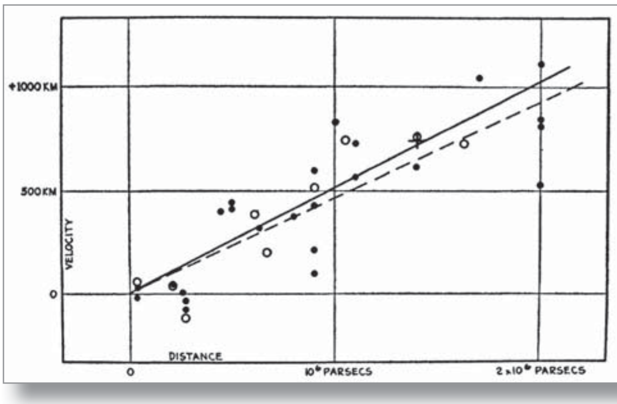
2011, the International Year of Chemistry, seems like a perfect occasion to consider where chemicals came from. Astronomers have known for decades that the Universe is full of the same matter we see around us here on Earth. We are, however, made mainly of elements that only make up a tiny fraction of the known matter in the Universe.

Hydrogen and helium are thought to make up 98% of the Universe's baryonic matter (atoms containing protons and neutrons). These two elements, and a trace of lithium and beryllium, were created in the first few minutes of the Universe. Stars have been generating the other heavier elements since then and made most of the mass within you. Your body is more than 60% oxygen by mass and it takes stars the size of the Sun or larger to live out their lives and die to create that oxygen. Before we look too deeply into this let's see what theories our understanding rests on.

It all started with the Big Bang

Well actually we don't know how it all started and we probably never will. The Big Bang theory doesn't say anything about what happened before or at the moment of the creation of the Universe. It only describes what happened once the Universe existed. The name itself, "The Big Bang" was actually invented to make fun of the theory by its opponents and is responsible for a significant misconception. The beginning of the Universe was not an explosion or a bang. An explosion expands rapidly from some region of space into space, but space did not exist! So what we commonly call "The Big Bang" (the creation of the Universe) was actually the creation of space and time containing a vast amount of energy in a very small volume. Once this "Big Bang" occurred we have a good idea of what happened thanks to the Big Bang theory and the Standard Model of Particle Physics.

The Big Bang theory is based on the General Theory of Relativity and the Cosmological Principle. General Relativity is a mathematical theory that describes gravity as a warping of space-time caused by matter. It predicts that matter bends space-time and this bent space-time tells matter how to move. This theory has been extensively tested and still remains unchallenged as our theory of gravity. The cosmological principle basically states that on average over large distances the Universe is the same everywhere (the universe is homogeneous and isotropic). The predictions by the Big Bang theory have been and continue to be tested and there is a growing body of supporting experimental evidence.

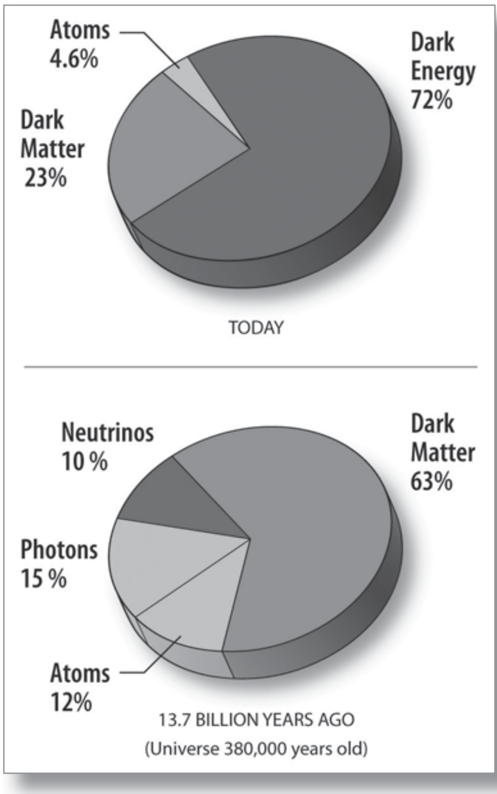


The evidence

In 1929 Edwin Hubble announced that he had discovered the velocity-distance relation (see graph on left). This showed that the further away a galaxy was the faster it appeared to be receding from the Earth. In his 1929 book *The Realm of the Nebulae Hubble* indicated that this relation can be considered an "observational basis for theories of an expanding Universe".

Hubble's observations actually supported earlier theoretical predictions of an expanding Universe using the theory of General Relativity. The basic idea that the Universe is expanding and galaxies are moving away from each other leads to an inevitable inference. At some time in the past the galaxies were much closer together. If all that matter was very close together the Universe must have been much hotter in the past. The Big Bang theory was beginning to take shape.

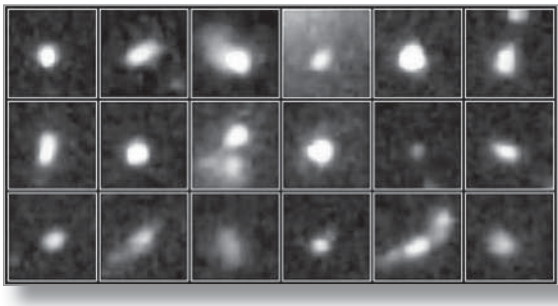
Contemplating the Origin of Matter in the International Year of Chemistry (continued)



An unexpected finding in recent years was the discovery that the expansion of the Universe is accelerating due to an unknown quantity we call Dark Energy. This coupled with the discovery of Cold Dark Matter (matter we cannot detect using electromagnetic radiation) has led to significant refinements in our model of the Universe (now called the Standard Model of Cosmology). The discovery of the acceleration of the expansion of the Universe has led to Professor Brian Schmidt from the ANU sharing the 2011 Nobel Prize for Physics. The charts (left) illustrate our current understanding of the composition of the Universe according to the Standard model of Cosmology.

In the 1950s the Big Bang theory received another boost from the emergence of radio astronomy. Surveys of large numbers of faint radio sources led astronomers to conclude that galaxies had evolved over time. This was the nail in the coffin of any theory that proposed a static and unchanging Universe. There was a time in the past within the Universe when galaxies were much more active. More of them emitted significant amounts of radio waves, much more than we see in the Universe today. This supported the idea that the Universe began some finite time ago and has been evolving ever since.

Observations by the Hubble space telescope in more recent years have added more support to this idea that galaxies evolve over time. An enormous number of small blue galaxies can be seen in the much younger Universe (see image on right). A population of these galaxies cannot be seen in the Universe today and this indicates again that galaxies have evolved.



In 1946 George Gamow suggested that nuclear fusion must have taken place in the early Universe if it was at much higher temperatures. Later theoretical work predicted that the energetic early Universe should have led to approximately 25% of the matter in the Universe being helium and the remainder hydrogen. Spectroscopic studies in the 1960's and 70's showed that stars and galaxies were comprised of approximately 24% helium. A further prediction was that the universe should contain a trace of an isotope of hydrogen (deuterium). This was confirmed by spectroscopy in 1973 when traces of deuterium were detected in the tenuous matter between stars (the interstellar medium or ISM). These predictions from our understanding of nuclear physics led more support to the Big Bang theory following their observational confirmation.

Probably one of the most compelling pieces of observational evidence for the Big Bang theory was the detection of the Cosmic Microwave Background Radiation (CMBR) 2.7K blackbody spectrum. George Gamow predicted in 1948 that electromagnetic radiation left over from the time when neutral atoms formed should fill the Universe. In 1964 radio astronomers Penzias and Wilson discovered this microwave radiation coming from the sky in every direction. For this achievement they won the 1978 Nobel Prize for Physics and cemented the Big Bang theory as our explanation of the evolution of the Universe. The study of the CMBR spectrum has yielded two more Nobel prizes in Physics since then.

There are numerous complexities related to the Big Bang theory but basically it predicts the Universe is expanding. This implies it began at some time in the past (approximately 13.7 billion years ago) containing a lot of energy in a small volume. The Standard Model of Particle Physics (which is founded on quantum mechanics) allows us to make predictions regarding the formation of matter in the hot and dense early Universe. Let's take a look now at the birth and evolution of matter.

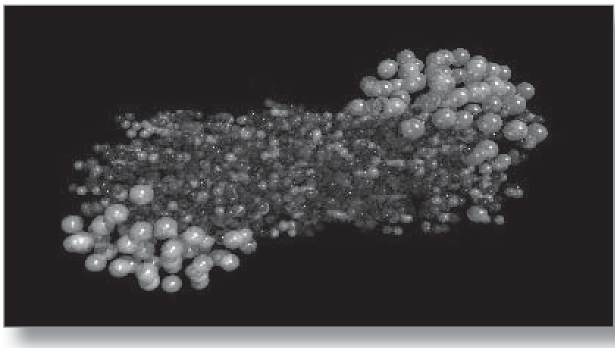
From Energy Comes Matter

When the Universe was born it contained an immense amount of energy in a very small volume. Some of this energy was converted into the matter that you are made of and some still fills the Universe today as the CMBR. The conversion of energy to mass is described by the Special theory of Relativity. The relationship between energy (E) and mass (m) is contained in Einstein's most famous equation $E = mc^2$. This tells us that mass and energy are interchangeable and are related by the constant c^2 (where c is the speed of light). Direct evidence for this relationship has been observed for decades in particle accelerators. So it is clear that matter can come from energy but exactly how that happens is a more mysterious story altogether.

One form of Heisenberg's Uncertainty Principle from Quantum Mechanics indicates that there is a large uncertainty in the energy at any point in space if you consider a time interval short enough. Applying Heisenberg's Uncertainty Principle to Einstein's equation ($E = mc^2$) then leads to an expression that says over a small enough time there is a huge uncertainty in the amount of matter at any location in space. Our understanding of these ideas leads us to postulate that matter could be created from the vacuum of space. This might sound far-fetched but there is direct evidence that matter is created as virtual pairs of particles.

The 1955 Nobel Prize for physics was awarded for the discovery of the Lamb shift in the spectrum of hydrogen. This is taken as evidence for the energy fluctuations in all of space at the smallest scales. These fluctuations are thought to be responsible for spontaneous creation of virtual pairs of particles. These pairs are virtual because we cannot observe them directly without violating the uncertainty principle. These pairs consist of a particle and its antiparticle (e.g. an electron and a positron) and no sooner have they been created and they have met again and have annihilated. These virtual pairs can be converted into a real pair of particles by the collision of two gamma rays. When this pair annihilates they liberate two gamma ray photons. This all means that we believe fundamental particles (like electrons, quarks, and neutrinos) and photons of electromagnetic radiation could fill the early Universe and came from quantum fluctuations.

Through the observation of the CMBR a period in the early universe called inflation was proposed by Alan Guth and he is tipped to be a future recipient of the Nobel Prize for this achievement. This period of rapid expansion separated virtual pairs as they formed and they became real particles. When a particle and its antiparticle collide they annihilate and produce gamma rays. So once particles had formed a large number of gamma rays were introduced into the Universe. An equilibrium was established for a brief time between the formation and annihilation of matter.



The First Three Minutes

The LHC has recently confirmed the sort of conditions that were thought to exist at about 10^{-12}

Contemplating the Origin of Matter in the International Year of Chemistry (continued)

seconds after the "Big Bang". It is a new state of matter called a quark-gluon plasma. The image to the right shows a simulation of a collision between two lead atoms that formed a quark-gluon plasma (protons and neutrons in grey). This would have filled the Universe when it had a temperature exceeding about one trillion Kelvin.

In its infancy the Universe contained a plasma of fundamental particles (including quarks and electrons) and electromagnetic radiation. As the Universe expanded the radiation was redshifted to longer wavelengths. This decrease in the energy led to the Universe cooling over time. Between 10^{-6} and 1 second the temperature dropped enough for the strong nuclear force to bind sets of three quarks to form protons and neutrons. Protons and neutrons can also be produced by pair production if the energy of the two gamma rays is high enough. Therefore there were several processes at work creating these particles.

Eventually the photons in the Universe did not have sufficient energy to create certain particle pairs. When the Universe was about 0.0001 seconds old the temperature dropped below 10^{13} Kelvin the threshold for protons and neutrons. Most of the protons and neutrons were then destroyed through annihilation with their antiparticles. If it was not for an asymmetry in the production of these particles all of the matter would have been converted into radiation and we would not be here today. It is calculated that matter must have outnumbered antimatter by 1 in a billion and this led to a Universe containing matter today. The laws of physics must have been just right for our existence with this tiny excess of matter over antimatter. The symmetry breaking that is responsible for this excess is still not understood. Although some asymmetries in particle physics have been discovered this is a field still being actively investigated by particle physicists.

When the Universe was about one second old the Universe cooled below 6 billion Kelvin and electrons and positrons annihilated. This filled the Universe with more radiation and left behind the electrons that would give rise to Chemistry. For about another second neutrons were still being created by collisions of protons and electrons. But the number of neutrons and protons reached their final values after most of the electrons were annihilated. Even though free neutrons began to decay with a half-life of about 10.5 minutes the Universe was cool enough for the strong nuclear force to bind protons and neutrons into positive nuclei so most of them did not remain free. The major components of atoms were now constructed.

When the Universe was about three minutes old the photons in the Universe had lost enough energy to allow deuterium ions to exist in large enough numbers for a series of fusion reactions to produce helium ions. This led to one helium nuclei being produced for every ten hydrogen nuclei and this abundance is observed in the Universe today. Some lithium and beryllium nuclei were produced as well. After about 15 minutes the Universe had cooled sufficiently that fusion reactions could no longer occur. At this time the initial chemical composition of the Universe had been established.

There are of course enough nuclear equations that describe the reactions that occurred in the first three minutes to fill a whole text book. So the description above is only a basic outline of the steps that are thought to have led to the formation of elements. We have seen that it took only three minutes to make all the initial matter in the Universe from energy. The building blocks for Chemistry had been created and it was only matter of time.

Atoms and Chemistry at Last!

When the temperature of the Universe approached 3000K electrons could finally occupy orbitals around nuclei, radiation was emitted and the first atoms were formed. This was about 370,000 years after the "Big Bang" and the radiation in the Universe was finally free to travel without being constantly scattered by plasma. This radiation fills the Universe today as the CMBR as it has been redshifted by the expansion of the Universe from visible to microwave wavelengths.

Contemplating the Origin of Matter in the International Year of Chemistry (continued)

The first chemistry in the Universe was most likely the formation of H2 molecules. One of the proposed mechanisms is a two-step process catalysed by a proton:

$$H + H^+ \rightarrow H_2^+$$

$$H_2^+ + H \rightarrow H_2 + H^+$$

Only 2% of the matter in the Universe today is not hydrogen or helium. Most of this could not be created until stars were born. Sometime around 100 million years after the "Big Bang" the first stars were thought to have formed. These were likely very massive and had short lives. They produced all the elements up to iron on the periodic table through nuclear fusion. When they ended their lives in huge supernovae explosions they produced all the elements heavier than iron and spread them into the ISM.

Once the ISM contained heavier elements carbon and silicon for example could aggregate to form dust grains. These grains are incredibly significant as their surfaces acted as catalytic converters producing much more molecular hydrogen and a myriad of compounds. The surfaces of these grains brought atoms together and allowed them to react. Much like the surfaces we use in industrial processes today to manufacture chemicals using less energy. Dust also acted as a radiation shield. Blocking the ultraviolet light from stars, that would destroy many of the newly formed molecules and compounds.

Dust grains also develop ice mantles as substances like water and methane are deposited on their surfaces. These ice mantles allow even more complex molecules to arise, like methanol, and the variety of molecules in the Universe grows. Over 100 complex carbon compounds have been discovered in space using spectroscopy. Samples from space in the form of meteorites confirm these observations. Even large amounts of amino acids can be found in some meteorites. Indicating that the chemical building blocks of life existed in space before life began on Earth.

So Here You Are, a Product of the Big Bang and Chemistry

We've seen that particles came from energy in the early Universe. Quarks formed protons and neutrons. These formed nuclei thanks to the strong nuclear force. Electrons eventually occupied orbitals around nuclei and atoms were formed. Chemistry began with the exchange or sharing of electrons creating molecules and compounds.

Once stars began to shine the heavier elements began to form. Stars formed the elements up to iron and the explosive deaths of large stars formed the rest of the elements. Once dust grains could form they played an important role in producing molecules and compounds. Ice mantles on these dust grains expanded the variety of compounds. Eventually, enough elements had formed and concentrated on planets like Earth for at least one to harbour life.

Once you know that you are about 60 to 70 percent water and 60 percent oxygen by mass you can see your connection with the story of the formation of matter and the history of the Universe. Our part of the galaxy must have had a few generations of stars so far to form the abundances of elements it has today. The hydrogen in your water molecules was made in the first three minutes of the Universe. Your oxygen was created in the centre of star and the iron in your blood must have come from a star big enough to produce a supernovae. Regardless of the elements you are made of many of the particles in you were made in the first moments of the Universe. But it is only once they were combined through chemistry that they could eventually build something as complex and marvellous as you.

References

Figure 1 = Figure 9 p114 from Realm Of The Nebulae by E. Hubble 1936

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Figure 3. Accessed at

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http://www.lbl.gov/abc/wallchart/teachersguide/pdf/Chap10.pdf Nuclear Science—A Guide to the Nuclear Science Wall Chart; ©2003 Contemporary Physics Education Project (CPEP). Chapter 10 *Origin of the Elements*