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TWINKLE, TWINKLE, LITTLE STAR

A Lecture by

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Twinkle, twinkle, little star

One of the most fundamental questions which can be asked is "Where do I come from?" The elements which make up the majority of the living things (96% of the human body) are hydrogen(H), carbon(C), nitrogen(N) and oxygen(O), four of the five most abundant in the cosmos, and mankind's story is in fact their history. However, because these elements are so prolific and have an unsurpassed ability to form compounds, both organic and inorganic, the tale they can tell is ultimately that of the Earth, its construction, resources, environment, and relationship to its neighbours around the Sun, and in turn that body's connection to other stars.

This series of lectures aims to unravel the infinitely complicated pathway, with all its twists and turns, followed by the four fundamental elements which constitute life, from the "Big Bang", believed to have begun the Universe, to the latest joining together of a few atoms by biosynthesis.

I am going to begin at the beginning, well about fifteen seconds after the beginning anyway. To use the obvious analogies, before the Big Bang, the moment of conception, everything was energy. Then during a pregnancy of 15 secs, mass and energy were totally inconvertible according to Einstein's relativity equation $E=mc^2$. After about fifteen seconds the products of life's initial explosion had cooled sufficiently for protons ($p+$), a main building block of all matter, to become stable. The proton, the positively charged nucleus of hydrogen, is the starting point of our journey; it will take another 300,000 years for a negatively charged electron (e^-) to become permanently attached in orbit, like a little planet round a star, to give rise to a true atom of hydrogen which is electronically neutral. Under the high energy, high temperature conditions (3×10^9K) prevailing after 15 seconds, uncharged neutrons (n), the other fundamental building block of the elements, are present in about equal numbers compared to protons, although neutron abundance diminishes rapidly later.

Initially only protons and neutrons need concern us since they combine to form the nucleus of another hydrogen isotope, deuterium(d) which becomes stable after about 100 seconds. Until now we have been in the realm of the particle physicist as obstetrician, from the moment deuterium was produced as an isotope geochemist my interest is aroused.

Before continuing we must define the term isotope. The simplest pair of isotopes are protium and deuterium which are both forms of hydrogen; they have exactly the same chemical properties which are dictated by the number of protons (and their charge) but differ on the basis of mass. The deuterium has the extra neutron which plays no part in chemical properties but determines physical characteristics. A good analogy is imagine two identical twins: give them both the same clothes etc. and a suitcase they still appear and react identically. But, if one has inside his suitcase a weight very nearly the same as himself then, in any physical contest, running, jumping etc., the overburdened twin is bound to lose. Such is the situations with isotopes, they may also be considered as identical twins; the amount by which the heavy isotopic twin is handicapped decreases from hydrogen which is the worse case (100%); with carbon, the penalty is less, but nevertheless important, 1 over 12 or 8.33% additional mass. Fortunately we have a way, mass spectrometry, of always being able to tell which twin is which and we can work out the rate at which they do things very precisely. This is exceedingly informative in tracing the history of H,C,N and O.

To return to the manufacture of the first elements, these are mostly produced by a proton-proton chain reaction. The next element in the periodic sequence helium, mostly what is called the helium isotope 4, but also some helium -3 can now be rapidly produced. In the proton-proton chain protons are converted to neutrons, deuterium, and helium as follows:

$$\begin{array}{lcl} p + p & \rightarrow & d + e^{+} + \nu \\ d + p & \rightarrow & {}^{3}He + \gamma \\ {}^{3}He + {}^{3}He & \rightarrow & {}^{4}He + 2p \end{array}$$

In the 300,000 year aftermath of the Big Bang, the so called $\alpha\beta\gamma$ theory predicts the Universe's compliment of hydrogen to be 76% and helium to be 24%; within these percentages deuterium and helium-3 are formed at the level of 0.006 and 0.001% respectively. From here on hydrogen will never be made again. All the hydrogen currently in the Universe is left over from the Big Bang.

As with any explosion, the debris was thrown far and wide and soon became too diffuse or cool to react simply as a result of the initial process. In fact the Universe is still expanding but it has cooled from 10^{32} to 2.6K (just a little above absolute zero). One might think that because of this expansion nothing else could happen but it is one of the quirks of Nature that the Universe is inhomogeneous. A billion years after the Big Bang clouds of the initially produced gas began to coalesce together and collapse under a new force called gravity. As they contracted into a smaller and smaller volume they heated up and eventually the proton-proton reaction switched on again but now in a controlled way, hydrogen was systematically converted to helium-4, the deuterium and helium -3 made on route being destroyed immediately. The energy produced serves to heat the star and gives off the light essential for our lives. One particular form of life on which we depend, photosynthesis of course cannot do without it.

Our sun may be bigger than these early stars but it works in a similar way; it is called a main sequence star. The energy it gives out is produced by the conversion of hydrogen to helium. Even though the sun has been "burning" (using hydrogen as a fuel) for 4.5 billion years it has only converted a few percent of its hydrogen to helium. The sun also contains 2% of heavier elements. These were not made *in situ* but are from other stars which existed before our solar system was formed. If the sun continues its lifetime for another 5 billion years then some carbon will be made from three helium atoms joining together, but most heavy elements are made in stars more massive than the sun.

The larger the cloud of hydrogen giving a protostar, the more it can contract under gravity and the hotter its core can get. A vital process for us is the carbon-nitrogen-oxygen cycle which switches on after carbon is formed from three helium atoms. The CNO cycle is a catalytic mechanism for converting hydrogen to helium according to the sequence:

$$\begin{array}{lcl} {}^{12}C + N & \rightarrow & {}^{13}C + \gamma \\ {}^{13}N & \rightarrow & {}^{13}C + e^{+} + \nu \\ {}^{13}C + H & \rightarrow & {}^{14}N + \gamma \\ {}^{14}N + H & \rightarrow & {}^{15}O + \gamma \\ {}^{15}O & \rightarrow & {}^{15}N + e^{+} + \nu \\ {}^{15}N + H & \rightarrow & {}^{12}C + {}^{4}He \end{array}$$

If collision occurs with helium nuclei instead of protons then other oxygen isotopes can be made e.g.:

$$\begin{array}{lcl} {}^{13}C + {}^{4}He & \rightarrow & {}^{17}O + \gamma \\ {}^{14}N + {}^{4}He & \rightarrow & {}^{18}F + \gamma \rightarrow {}^{18}O + e^{+} + \nu \end{array}$$

The most productive collisions regarding helium are the sequential adding of units 4 so that

$$\begin{array}{lcl} {}^{12}C + {}^{4}He & \rightarrow & {}^{16}O + \gamma \\ {}^{16}O + {}^{4}He & \rightarrow & {}^{20}Ne + \gamma \\ {}^{20}Ne + {}^{4}He & \rightarrow & {}^{24}Mg + \gamma \\ {}^{24}Mg + {}^{4}He & \rightarrow & {}^{28}Si + \gamma \end{array}$$

Since the star is still contracting under gravity and is getting hotter and hotter and carbon can combine directly first carbon burning switches on and then silicon burning:

$$\begin{array}{lcl} {}^{12}C + {}^{12}C & \rightarrow & {}^{24}Mg + \gamma \end{array}$$

$$^{28}\mathrm{Si} + {}^{28}\mathrm{Si} \quad \rightarrow \quad {}^{56}\mathrm{Ni} + \gamma + \rightarrow {}^{56}\mathrm{Fe} + 2e^{+} + 2\,\nu$$

The star is now out of control and explodes to become a supernova. Several different types of supernova exist but they need not concern us here, neither will the ways in which elements heavier than iron are made, other than to say that they are produced by adding neutrons sequentially rather than building from positive species such as a p or ^{4}He. Small stars like the sun have very long lifetimes; large stars age exponentially. It took something like 5 billion years before stars became big enough to become supernovae so elements heavier than iron, many of which have little to do with life, are comparative newcomers in our story.

Given that supernovae are another cause of very big bangs in the Universe, they spread their products of dust and gas far and wide. Of course they must have contributed to the formation of our solar system, hence the 2% heavier elements in the sun and indeed the rocks of our planet. It is therefore interesting to ask "can any material relateable to a pre-existing star actually be found now to study supernova stardust directly?".

Twenty years ago if you asked anyone this question most scientists would have answered "no - the cloud of gas and dust which made the solar system would have been so well mixed and heated up that all memory of previous existences would have been erased". A small group of people, particularly Donald Clayton, were not so sure - given that the Universe was heterogeneous, even after the Big Bang, they were wise to council caution. There is now very good evidence, to be considered later in this lecture series, that the solar system was very badly mixed.

The key to tracking stardust was seeking "isotopic anomalies" - these can be defined as patterns in isotopic composition which cannot be related to a single common pattern. To use the identical twin analogy again, mass spectrometry can distinguish between the twins even if they are dressed alike and change their loads by differently packing the suitcase. If you suddenly start giving one twin two suitcases or dressing him/her with hobnail boots whilst the other is in running shoes, it sticks out like a sore thumb and becomes very easy to spot the differences. Isotopic anomalies are the equivalent of the extra suitcase.

The first isotopic anomalies were found for all the wrong reasons. The one which leads us to supernovae was a red herring concerning an attempt to find a very heavy (heavier than Uranium) radioactive element which might have existed a long time ago but which is now extinct. The key to this was looking for an anomaly in xenon, a chemically simple "noble" gas, which has a most complicated isotopic pattern involving 9 isotopes. When an anomaly for this element was found in a meteorite called Pueblito de Allende (much more about meteorites and their origins in later lectures) it became of interest to track down the mineral where the anomaly was and thus where the putative extinct radioactive element had been hidden. It soon became obvious that the host was a material which contained carbon and was insoluble in acids. Because it was carbonaceous, it became of great interest to someone like myself who specialises in the study of the light elements, carbon, nitrogen etc. We soon found that the carbon was associated with large amounts of isotopically anomalous nitrogen, and in fact the noble gases can be decoupled by careful stepped heating experiments; thus xenon is probably superfluous to the story. Perhaps the biggest surprise of all came after very careful work by Edward Anders to purify the mystery substance. The carbonaceous material was infact diamond. In retrospect, given the great stability of diamond (it is after all the hardest substance known and is "forever"), it should not have been such a surprise. Because of the Allende meteorites we have been able to add a magnification factor of 10^{25} to telescope observations.

It is now well accepted that many meteorites contain diamond stardust as very tiny crystals only a few thousand atoms or 2×10^{-9} metres across. The diamond can have very high contents of nitrogen up to 0.25%. Theory predicts beautifully how such material could be formed in a type II supernova explosion. A problem which originally confused people working in this area was that it was long believed that diamond could only be made at high temperatures (no problem in a star) and high pressures (very difficult in the diffuse out pourings from a stellar explosion). The solution comes from the fact that in recent times it has been discovered that tiny diamonds can be made from a plasma of ions. This process has now become the subject of a multi-million pound industry. A process which is being regularly used to create diamonds artificially in the laboratory was being employed by Nature may be 10 billion years ago.

Next time you hear the children's nursery rhyme, written by Jane Taylor in 1805, just remember how prophetic it turned out to be.

> Twinkle, twinkle little star,
> how I wonder what you are,
> up above the world so high,
> like a diamond in the sky.

Further reading

Barrie Jones, Chair, Open University Course Team S281, Book 1 The Stars and the Interstellar Medium, 1994

Stuart Clark. The Encyclopedia of Stars and Atoms. Andromeda Oxford 1994

John Gribbin. Companion to the Cosmos, Weidenfeld and Nicolson, London 1996.

Research Papers

C. T. Pillinger. Elemental Carbon as of Intersellar Dust, Phil Trans Roy Soc Lond A **343** 73-86 (1993).

S. S. Russell, J.W. Arden and C. T. Pillinger. Evidence for multiple sources of diamond from primitive chondrites. Science **254** 1188-1191 (1991)

D. D. Clayton, B. S. Meyer, C. I. Sanderson, S. S. Russell and C. T. Pillinger. Carbon and nitrogen isotopes in type II supernova diamonds. The Astrophysical Journal **447** 894-905 (1995).

10 to the power

Prefix	Power	Number	
atto-	-18	0.000 000 000 000 000 001	
femto-	-15	0.000 000 000 000 001	
pico-	-12	0.000 000 000 001	
nano-	-9	0.000 000 001	one-billionth
micro-	-6	0.000 001	one-millionth
milli-	-3	0.001	one-thousandth
centi-	-2	0.01	one-hundredth
deci-	-1	0.1	one-tenth
deka-	1	10	ten
hecto-	2	100	one hundred
kilo-	3	1 000	one thousand
mega-	6	1 000 000	one million
giga-	9	1 000 000 000	one billion
tera-	12	1 000 000 000 000	one trillion
peta-	15	1 000 000 000 000 000	
exa-	18	1 000 000 000 000 000 000	

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