Hi this is Steve Nerlich from Cheap Astronomy www.cheapastro.com and this is *Supernovae - The nucleosynthesis story.*

This is the second of two podcasts on supernovae.

So, in the beginning there was the Big Bang - and for the first three minutes it was just too hot for anything to form. But after the first three minutes, the universe had expanded enough for protons to form from the piping hot quark-gluon soup that had existed only seconds before. And for the next seventeen minutes - while the entire universe was as dense as the core of the Sun - there was nucleosynthesis and, just like in the core of the Sun, single protons - which these days we call hydrogen nuclei fused to form what these days we call helium nuclei. And some of those helium nuclei even fused with more protons to form a tiny bit of lithium and even traces of the next element along the periodic table beryllium, which has four protons in its nucleus.

But after the first twenty minutes, that was that. The universe kept expanding, its density decreased, so that it cooled and soon no more nucleosynthesis could take place. It was still very dense and hot though. Indeed another 380,000 years had to pass before the universe had spread out enough for the photons of the cosmic microwave background to move freely out of the broiling plasma of the early universe.

But anyway, I'll hazard a guess you're currently moving along - or otherwise resting upon some mixture of compounds composed of elements which are higher up the periodic table than hydrogen, helium, lithium or beryllium.

About five hundred thousand years after the Big Bang, the tiny, newly born atoms of hydrogen, helium and those trace elements began to clump together, perhaps shepherded by some kind of dark matter scaffolding. And, as those baby atoms clumped and compressed together, they began to heat up.

This heating is largely because of electromagnetism. An atom in isolation is fairly stable - with an equal number of positively charged protons and negatively charged electrons. But start collecting those atoms together and the negatively charged electron shells of each atom repel each other - and as you continue to cram them together within an even smaller volume you end up with a mass of rapidly vibrating, indeed wildly oscillating, atoms - trying and failing to get the heck away from each other.

And if you wildly oscillate charged particles in space-time you generate waves of electromagnetic radiation - which in the infra-red part of the spectrum we often call heat.

Of course, as well as getting hotter, a dense cluster of massive particles also generates its own self gravity - which pulls in more and more atoms into an increasingly confined space - until those atoms are so densely packed and so wildly oscillating that the relationship between one nucleus and its electrons becomes a little meaningless and you end up with a dynamic soup of positively-charged nuclei and negatively-charged electrons, moving independently of each other in a state of matter called plasma - and since those charged particles are now oscillating in an even wilder manner again - higher energy-level electromagnetic radiation is produced - including, visible light. And so you get a universe full of bright stars.

As a result of gravitational compression, the deeper you go into these stars, the denser the material is - and within the core of the stars, it becomes so hot and dense that it's like things were three minutes after the Big Bang - and hydrogen undergoes fusion to form helium. And because (unlike the Big Bang) a star's core can just keep on getting hotter and denser, two helium nuclei can fuse to form carbon and three helium nuclei can fuse to form oxygen and if you fuse carbon with more hydrogen you can form nitrogen.

In mid-range stars that might form red giants, you can get even more nucleosynthesis by what's called the slow, or s, process - were a seed atom like iron collides with and captures an extra neutron - which then undergoes beta decay to form a proton - and with each such proton addition you get a new element with a higher atomic number (since atomic number is the number of protons in a nucleus). This s process is not really fusion - since, technically, nothing heavier than iron can undergo fusion, but this slow process is an important part of the story of how heavier elements get distributed across the universe - which they do when a red giant blows off its outer layers at the end of its life.

But OK - what about the supernovae? Isn't this what the podcast is supposed to be about? Well, if a star is massive enough it won't form a red giant, it will to go to supernova.

Within a massive star the core is hot and dense enough to undergo other types of fusion. These big stars firstly fuse all their hydrogen (over millions of years), then their helium and their carbon (which might take place over only thousands of years), then when those elements run out they will fuse neon, oxygen and silicon (which the star might burn through in just a day or two) - until there's iron being formed which can't undergo fusion itself, so it just starts building up as a solid core in the middle of the star. And if the star is big enough that this solid iron core reaches a mass of 1.4 solar masses - remember that's the Chandrasekhar limit - the core collapses inwards at nearly a quarter of the speed of light as the iron nuclei themselves collapse.

Immediately, the rest of the star collapses inwards to fill the space created by the core collapse, but that inner core 'bounces' back a bit as the heat produced in the initial collapse kind of makes it 'boil'. This bounce creates a shockwave – a bit like a thunderclap multiplied by many orders of magnitude, which is the beginning of the supernova explosion. The shock wave begins blowing out the surrounding layers of the star – although as soon as this material expands outwards, it also begins cooling. So, it's unclear if any nucleosynthesis happens at this point.

But the collapsed iron core isn't finished yet. A huge amount of energy and heat is created by the collapse. but after its initial' bounce', it settles into a new ground state of compressed neutrons – essentially a proto-neutron star. It is able to 'settle' due to the release of a huge burst of neutrinos, which carry heat away from the core.

It's this neutrino burst that drives the rest of the explosion. It catches up with, and slams into, the already blown-out ejecta of the progenitor star's outer layers, reheating this material and adding momentum to it. It is probably this neutrino impact event that is the site of rapid, or r, process nucleosynthesis.

Rather than the steady, step-wise fusion of elements over thousands of years seen in main sequence stars and the slow S process of red giants – seed elements in a supernova explosion have multiple neutrons jammed in to them in a matter of seconds, while at the same time being exposed to disintegrating gamma rays. This combination of forces can build up a wide range of light and heavy elements, anywhere from cobalt and gallium, up to uranium and even plutonium - which contains a whopping 94 protons.

It's thought that rapid r-process nucleosynthesis is probably over within a couple of seconds, but it could still take an hour or more before the supersonic explosion front bursts through the surface of the star, delivering some fresh contributions to the periodic table.

Thanks for listening. This is Steve Nerlich from Cheap Astronomy, www.cheapastro.com. Cheap Astronomy offers an educational website where we can do nucleosynthesis podcasts without ever mentioning that we are star dust. No ads, no profit, just good science. Bye.