John Gribben

way, how the heavy elements are built up inside stars. The first step is the combination of hydrogen nuclei (single protons) into nuclei of helium-4, which each contain two protons and two neutrons. This is the process going on inside the Sun and other main sequence stars. The 4 in helium-4 simply denotes the total number of nucleons (that is, protons plus neutrons) in each nucleus of the element, and is very important.

Helium-4, as it happens, is a very stable nucleus, and behaves in many ways like a single particle – which is why it is often called the alpha particle. This stability makes nuclei that contain a whole number of helium-4 nuclei (a whole number of alpha particles) particularly stable and common in the Universe. They include carbon-12 and oxygen-16, which can be regarded as being made up of three and four alpha particles, respectively. Once carbon-12 is present inside a star, then under suitable conditions of temperature and pressure it is relatively easy to add an extra helium-4 nucleus to make oxygen-16, and so on in fours all the way up the nuclear fusion ladder to iron-56.

In-between elements (like nitrogen-14) are made when lighter neighbours (in this case carbon-12) latch onto the odd proton or two from the surrounding superdense plasma, or when radioactive forms of some nuclei decay, spitting out the odd proton or positron (the positively charged counterpart of an electron) and readjusting their nuclear composition. Still heavier elements, beyond iron-56, are made in supernova explosions, which come in to the story of the life of a galaxy, told in the next chapter.

But there is a snag. The exception to the rule that nuclei made up from alpha particles are particularly stable breaks down drastically in one crucial place – on the very first rung up the ladder of nuclear fusion. The nucleus composed of two alpha particles put together is beryllium-8; and beryllium-8 is so unstable that any nucleus of beryllium-8 that happens to form when two helium-4 nuclei collide in the plasma maelstrom inside a star blasts itself apart within 10^{-19} a second. The only way to make carbon-12 (and therefore the only way to make anything heavier than carbon-12) seemed to be if a third alpha particle arrived on the

scene during that tiny split second in which a beryllium-8 nucleus existed. But under such circumstances kinetic energy provided by the impact of a third alpha particle would itself simply blow the beryllium-8 nucleus apart.

In 1954, Hoyle saw that there was only one way round the difficulty. It hinges on a property known as resonance. Atomic nuclei, including those of carbon-12, can exist in more than one state. The different states are known as energy levels, and you can think of them as like the different notes corresponding to a single plucked guitar string. The string can vibrate at its fundamental wavelength, one wave filling the length of the string, or it can produce overtone vibrations, harmonics in which the wavelength is one-half, or one-third, or some other integer fraction of the length of the string, so that there are always a whole number of waves filling the length of the string.

If you shout at a guitar, the strings will move a little in response to the waves in the air corresponding to the noise – but only a little, because the wavelengths of the sound you make do not correspond to natural wavelengths for the guitar strings. But if you play a note on another instrument at a wavelength that corresponds exactly to one of the harmonics of the guitar strings, the string will vibrate in sympathy, as if the guitar is playing itself.

Nuclei 'resonate' in an analogous way. If the right amount of energy is put into a carbon-12 nucleus, it will absorb the energy and move into an excited state for a while, before radiating the energy away again and falling back to its lowest energy level, known as the ground state. Hoyle said that the only way in which carbon-12 could be formed from a collision between highly unstable beryllium-8 and an alpha particle, during the split second that the beryllium-8 nucleus exists, would be if carbon-12 had a suitable excited state corresponding to the energy of one beryllium-8 nucleus and one alpha particle put together.

It is as if the 'shout' of an alpha particle hitting a beryllium-8 nucleus just happens to be in tune with a carbon-12 'harmonic note'. If so, then instead of the collision blowing everything apart, the combined nuclei would slip smoothly into the guise of an excited carbon-12 nucleus. That carbon-12 nucleus could then radiate away its excess energy, and settle down into its ground state.

In 1954, the idea seemed outrageous. In order to make carbon (and all the heavier elements), the laws of physics would have to be precisely fine-tuned for this resonance to occur. Hardly anyone took the idea seriously, and the researchers who did, under Hoyle's nagging, set out to measure the resonances of carbon-12 in the laboratory, did so more in the hope of shutting him up than in expectation of proving him right. But to their surprise, they found exactly what Hoyle had predicted. The coincidence is so remarkable that it is worth putting some numbers in. The energies involved are measured in mega-electronvolts (MeV), but that doesn't matter – just look at the numbers themselves.

The energy of a beryllium-8 nucleus plus a helium-4 nucleus is 7.3667 MeV; the energy of an excited carbon-12 nucleus is 7.6549 MeV. The difference between the two is just under 4 per cent, and the extra 0.3 MeV or so required to make the match perfect is just the sort of energy of motion that will be carried into the collision by the alpha particle. Instead of blasting the beryllium-8 apart, the energy carried by the alpha particle is just enough to carry the combination over the top and make excited carbon-12: 'just right' to make the carbon nuclei that go into the atoms in Baby Bear's porridge.

The power of the coincidence is brought home when you consider what would have happened if the balance had just tilted the other way, with the beryllium-8/alpha particle combination having an energy even just 1 per cent more than the excited state of carbon-12. Then there would be no resonance. The incoming alpha particle would indeed blast the beryllium-8 apart, and there would be no carbon (or any heavier elements) in the Universe. And all for the sake of a swing of just 5 per cent on the excited carbon-12 energy level.

This is not the end of the story. Other nuclei can also have excited states. Oxygen-16, for example, has an energy level at

7.1187 MeV, but the combined energy of a carbon-12 nucleus and an alpha particle is 7.1616 MeV. This is just too high (by a mere 0.6 per cent) for a combination of carbon-12 and helium-4 to yield a perfect match with oxygen-16. In this case the kinetic energy of the incoming alpha particle, adding to the total, makes the discrepancy even worse.

There is no problem about making oxygen-16 slowly inside stars, because carbon-12 (unlike beryllium-8) is stable and stays around to get involved in many collisions. For a proportion of carbon-12 nuclei, nuclear reactions resulting from these collisions eventually do the trick, without recourse to resonance. But plenty of carbon is left over at the end of the life of the star, ready to form part of the mix going into the next generation of stars and planets. If, however, the oxygen-16 energy level lay just above the combined carbon-12/alpha particle level (which would happen if the excited oxygen energy level were just 1 per cent higher), then it would resonate, and all the carbon-12 inside a star would quickly be converted into oxygen-16. There would be no carbon available to take part in all those interesting reactions that are the basis of life as we know it on Earth.

So there are two remarkable coincidences which allow life-forms like us to exist – a double Goldilocks effect – at work inside stars. The first makes it possible for carbon to form at all; the second prevents all the carbon turning into oxygen, but allows enough oxygen to be made to carry the process of nucleosynthesis on up the chain to iron-56. The fact that we exist, with bodies based on carbon chemistry and breathing oxygen from the air, tells us in very precise terms what some of the properties of nuclear particles must be. Could such coincidences arise by accident? Were they 'built in' to the structure of the Universe by a designer? Or have they evolved through natural selection?

Hoyle's own view was that if the Universe is infinite then there might be regions of the Universe in which different laws of physics operate. In some regions (most!) the coincidences that allow carbon and oxygen to form inside stars would not exist,