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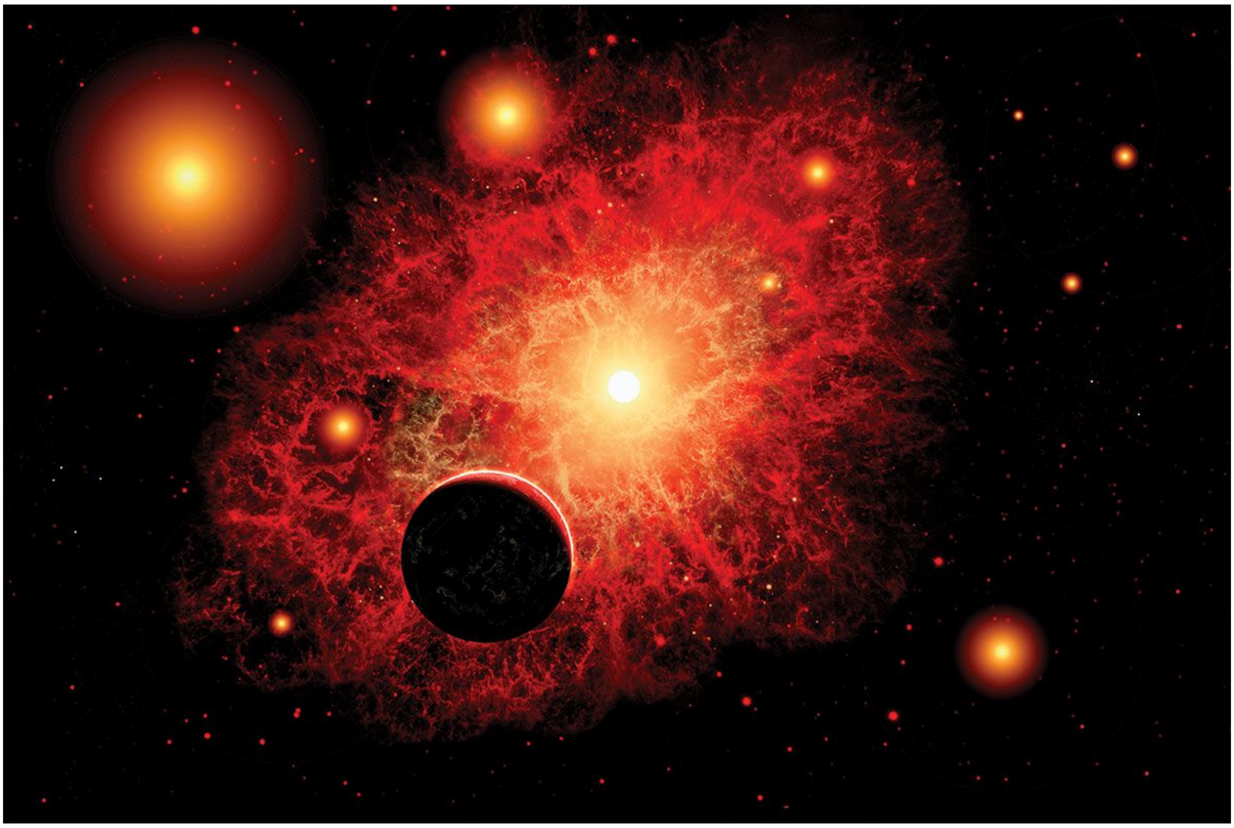
Life's subatomic secret: How we're cracking the Hoyle state

The cryptic carbon nucleus that gives rise to the heavy elements, and to life as we know it, is finally coming into focus



Red giant stars conjure carbon
MARK STEVENSON/STOCK TREK IMAGES/GETTY

By **Marcus Chown**

YOU are made of carbon. So are your pets and all your houseplants. Every living thing on Earth owes its existence to carbon atoms' ability to join up with other elements in a bewildering number of ways and form complex molecules. But the abundance of this element in our universe depends on a seemingly miraculous coincidence – an excited state of the carbon nucleus that our best models say shouldn't exist, but clearly does.

The nature of this weird form of carbon has baffled us for more than 60 years, much to the distress of nuclear physicists. Its existence is so essential in the sequence of reactions making life possible that our failure to explain it is deeply embarrassing. “We need this state to exist for us to be here and yet it is extremely unusual in nuclear physics terms,” says David Jenkins at the University of York, UK. “Cracking this problem has become a matter of pride.” And yet the more we learn, the more confusing things seem to become.

The story starts 13.8 billion years ago, when everything erupted out of nothing – or at least the ingredients for everything did. Actually, the only elements forged in the big bang were the very lightest: hydrogen, helium and a smattering of others. All the heavy stuff, starting with carbon, was forged later inside stars.

The first step in carbon manufacture is to fuse nuclei of the lightest element, hydrogen, to make the second-lightest, helium. The next step ought to be for two helium-4 nuclei – each containing two protons and two neutrons – to fuse to make beryllium-8. This would then grab another helium to make carbon-12. Except there is a snag. Beryllium-8 is highly unstable, meaning it decays in the blink of an eye – too quickly to produce the amount of carbon that exists in the universe.

The other possibility is that three helium-4 nuclei come together simultaneously inside bloated, dying stars known as red giants, where all the hydrogen has burned off to leave an extremely dense and hot core of helium. But this process is so rare that even over the aeons since the big bang, it couldn’t have produced enough carbon.

So how did we end up with so much of the stuff? That remained a mystery until 1953, when astronomer Fred Hoyle made an audacious prediction. He said that there must be an excited state of the carbon nucleus – a particular configuration of the protons and neutrons – with precisely 7.65 megaelectronvolts (MeV) of energy above the minimum, or ground state.

In an excited state, the particles at the heart of an atom jiggle around more vigorously than they do normally. The laws of quantum theory permit only a limited set of stable energy states. At most energies, the nucleus falls apart.

Why, then, did Hoyle make such a precise prediction for the energy of his proposed state? The answer is that 7.65 MeV represents the combined energy of three helium-4 nuclei whizzing about at 100 million degrees, the temperature at the heart of a red giant. This, Hoyle realised, would create a “resonant” reaction: rather than ricocheting off one another because they have too much energy to make carbon-12, the three helium nuclei become much more likely to fuse in a two-step process and store the excess energy in the jiggling of protons and neutrons. After that, the excited nucleus can decay into everyday carbon-12.

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Our best theory of reality says things only become real when we look at them. Understanding how the universe came to be requires a better explanation

Observations from collider experiments soon proved Hoyle right. It was an astonishing triumph, and remains the only successful prediction based on an anthropic argument ahead of experiment – that is, "I exist, therefore it must exist."

For Hoyle, it was also evidence that our universe must have been fine-tuned for life. If the energy of the Hoyle state, as it is now known, was slightly above or below that of the three helium-4 nuclei, there would be no carbon-based life. The fact that it happened to occur exactly where we need it to exist suggests an exceedingly fortunate coincidence. Either that or it's evidence that our universe is one of many in a multiverse, where all other possibilities also occur.

Then again, theorists have recently pointed out that in stars in alternative universes with different versions of the laws of physics, beryllium-8 could be stable. That suggests it may be easier to make carbon elsewhere.

Back in our own universe, the problem that persists more than 60 years on from the discovery of the Hoyle state is that we still don't know what it looks like. How are the protons and neutrons, collectively known as nucleons, arranged to retain stability at this particular energy?

Perhaps nuclear physicists shouldn't feel too sheepish about their slow progress. The hard truth is that calculating what all the protons and neutrons inside a nucleus are doing at any one time is a devilishly complex task. Using rough models of how nucleons interact under the forces that bind them – the strong nuclear force and the electromagnetic force – physicists can accurately describe the structures of many nuclei. But the Hoyle state does not arise from any of these models.

One way to crack the problem is with brute force: to take what we know about the strong and electromagnetic forces to calculate how the particles inside the carbon-12 nucleus arrange themselves in the Hoyle state.

For a long time, that seemed impossible. With carbon-12 containing 12 nucleons, each containing three fundamental particles called quarks, there were too many interactions to consider. We just didn't have the computing power to solve that many equations.

But in 2011, thanks to the number-crunching might of a supercomputer called JUGENE and a neat mathematical trick that allows us to ignore the quarks, a team led by Evgeny Epelbaum at the University of Bochum in Germany finally made what appeared to be a breakthrough. Every split second, JUGENE summed up the forces exerted on each nucleon by its 11 companions, adjusting each one in response, and repeating the process over and over again. It took weeks but Epelbaum and his colleagues were able to

Gigantic computers are helping towards achieving accurate predictions
THOMAS IMO/ALMAY STOCK PHOTO

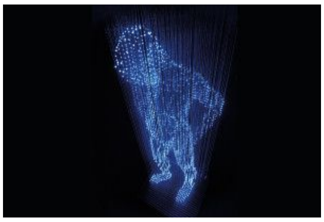
show that the 12 nucleons adopt a semi-stable state at roughly 7.65 MeV, the Hoyle state.

A couple of years later, they used a similar technique to calculate the structure of the Hoyle state. They found that rather than 12 nucleons buzzing about independently, it takes the form of a cluster of three helium nuclei – each containing two protons and two neutrons, and often referred to as alpha particles – arranged in a boomerang shape.

Quantum shift

Job done? Not a bit of it. For starters, the semi-stable state of carbon-12 simulated by JUGENE was a few per cent off the precise amount of energy contained in the Hoyle state. That means there is still a little way to go to predict it from first principles with perfect accuracy. More confusingly, when it comes to its internal structure, recent experimental work suggests other possibilities.

In 2014, a team led by Martin Freer at the University of Birmingham, UK, fired a beam of alpha particles at a carbon target to produce carbon-12 nuclei that spin so fast that they throw off alpha particles. By measuring the properties of this shrapnel, the team was able to reconstruct the energy levels of carbon-12, and came up with a different conclusion: that the alpha particles in the Hoyle state are arranged in the shape of an equilateral triangle.



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The Extreme Light Infrastructure facility, under construction in Bucharest, Romania, should help to settle the matter. It will scatter laser light off accelerated electrons to create high-energy gamma rays whose energy can be tuned with exquisite precision. The plan is to zap the carbon nucleus, then note at what energies it falls apart and what it falls apart into. "Basically, the idea is to confirm the Hoyle state by destroying it," says Jenkins.

Already there are fresh hints of oddness. Last month, Ulf Meissner at the University of Bonn in Germany and his colleagues showed that certain light nuclei exist near a quantum phase transition, the quantum equivalent of the threshold at which ice melts or water boils. It is the first demonstration that nuclei can switch between two phases: one a strange gas-like state of matter, in which the constituent particles hardly interact, and the other more like a liquid, in which they do.

This raises the possibility that the Hoyle state might exist on this boundary, making it even weirder than anyone suspected.

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