# Carbon, the Anthropic Principle, and Multiple Universes (1)

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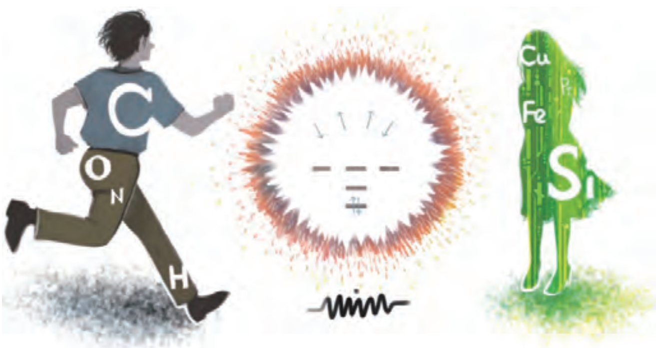
"I've been thinking about the other day… about you going to see Catherine, and that she has a body, and how bothered I was about the ways you and I are different. But then I started to think about the ways that we're the same. Like, we're all made of matter. And I don't know. It makes me feel like we're both under the same blanket. You know, it's soft and fuzzy. And everything under it is the same age. We're all 13 billion years old."
"Aw, that's sweet." — from the movie *Her* (2013)

Samantha is an artificial intelligence system that falls in love with a human man. It isn't easy. Unable to feel or give a warm embrace, Samantha puzzles over what to do. One day, after learning about physics from an AI system book club, she has an epiphany. She realizes that she isn't simply an "intelligence." It's an important fact: just like human beings, what allows her to exist is matter. Imagine that—snuggling with a lover the same age as her, underneath the soft and fuzzy blanket of matter formed from stars over the course of over 13 billion years!




The male protagonist dully shrugs off her words. Samantha's realization is too general, too abstract for a human being who longs for warm and fragrant breath. Rather than any kind of enjoyment, it calls to mind the cold image of someone simply embracing the rigid case of a computer, inhaling the hot breeze of a CPU fan mixed with the smell of metal and plastic. Machine and human intelligence might both come about through matter, but we can sense a huge difference in *how* they exist. Within the tiny human body is the accretion of all sorts of instincts and diseases experienced by the different organisms that have emerged over a long 4 billion years, all for the sake of survival and evolution. Shaped as it is in this way, human identity could never be the same as AI, which is produced through machines made of silicon, iron, copper, platinum, and other heavy elements.

Life is a miracle. Human intelligence and self-awareness are miracles as well, ones that are even more difficult to believe. But the word "miracle" often simply refers to something with exceedingly low odds of occurring naturally. The conditions needed for a very low-probability miracle to occur are an enormous range of different possibilities. For example, let's say that you have a very particular set of values, and the chances of your meeting someone you truly connect with are one-in-100,000. In that case, it would be a miracle beyond any expectation of ever happening for you to fatefully fall in love with someone who happened to talk to you on the street. Still, there's no reason to despair. There is a very simple way of turning that miracle into a certainty: just go up and talk to 100,000 different people. So long as you don't stop the experiment, it will happen for you eventually—it's just a matter of time. If you met one person a day, you would need 275 years to reach the 100,000 total. That number drops to 27.5 years if you're a gregarious type who enjoys meeting people and can go up and start a conversation with ten people a day. On the other hand, it really is a miracle that has no chance of ever happening if you're someone who hates gatherings and likes to spend time alone. Expecting that one of those people brushing by you on the street without talking will turn out to be the right match for you is about as likely as expecting chunks of scrap iron picked up by a typhoon to smash together and form an airplane.

That is why we can't really expect to ever find a lifeform based in iron and copper. The ways that heavy metals bond are just too limited. Rigidness of order leads to death. The conditions for life to occur are flexibility and diversity—stable, but allowing us to respond swiftly to changes in the environment. It's no accident that the self-replicating molecule that emerged on Earth about four billion years ago was a carbon-based organic molecule. Consisting of six protons, six neutrons, and six electrons, carbon had properties that allowed it to react easily with other molecules, and almost no restrictions on how it could bond molecularly. Carbon is also one of the most abundant elements on the planet. This translated into the potential for the kind of fast and varied chemical experiments that turn a miracle into an inevitability. Special environments like hydrothermal vents—which continue being found even day on the ocean floor—might have provided the conditions for experiments in synthesizing molecules of complex forms on the early earth. Most of those experiments would have ended in failure, but once a stable form of complex organic molecule had been successfully achieved, the subsequent process would have been able to gather momentum. Part of that process could have led eventually to the emergence of life. It's the same reason that allowed the miracles of intelligence and self-awareness: the possibilities for mutation in organic life forms are almost unlimited, and those possibilities have been manifested nonstop over the past 4 billion years with changes in the earth's environment and the mechanism of natural selection. And all of this thanks to carbon.

A carbon-based human being and a heavy element-based machine—the huge divide between the two arises ultimately from the properties of the matter that constitutes them. As recently as the early 1950s, the origins of carbon were a mystery that had physicists and astronomers scratching their heads. What kinds of stars could this element—so crucial to human identity—have been made in, and through what form of nuclear reaction?

The process of creating heavy elements from light ones is cumulative. For instance, two hydrogen atoms (with a mass number of 1) react with each other to form deuterium, which has a mass number of 2; deuterium then reacts again with hydrogen to form $^{3}$He, a helium isotope with a mass number of 3. $^{3}$He reacts with a different $^{3}$He to form $^{4}$He, an isobar of helium with a mass number of 4. The problem is what comes after that. There are no atoms on the planet with mass number of 5 or 8. Nuclear physicists have found through various different experiments that atoms with mass numbers of 5 or 8 cannot exist in stable states. An atom with a mass number of 8 could combine with helium (mass number 4) to form carbon (mass number 12)—but the instability of atoms with a mass number of 8 poses a huge obstacle to its formation. The stepping stone between helium and carbon does not exist.

For example, two helium atoms could combine to produce beryllium, with a mass number of 8.

$$^{4}\mathrm{He} + {}^{4}\mathrm{He} \rightarrow {}^{8}\mathrm{Be} \tag{1}$$

Beryllium would then combine again with helium to produce carbon.

$$^{8}\mathrm{Be} + {}^{4}\mathrm{He} \rightarrow {}^{12}\mathrm{C} \tag{2}$$

The term "triple alpha reaction" is often used to describe these reactions (1 and 2) where three helium atoms combine in sequence to form carbon. The name comes from the old practice of referring to helium atoms as "alpha particles."

But $^{8}$Be is an exceedingly unstable atom that will decay into helium in the short space of one six-hundred-quadrillionth of a second ($6 \times 10^{-17}$ s).

$$^{8}\mathrm{Be} \rightarrow {}^{4}\mathrm{He} + {}^{4}\mathrm{He} \tag{3}$$

For carbon to be produced, the beryllium has to combine with helium before this decay takes place, and the chances of that happening are exceedingly small. Given the environment inside of a star, it is more likely that when reaction (1) occurs, reaction (3) will happen before (2) has a chance to.

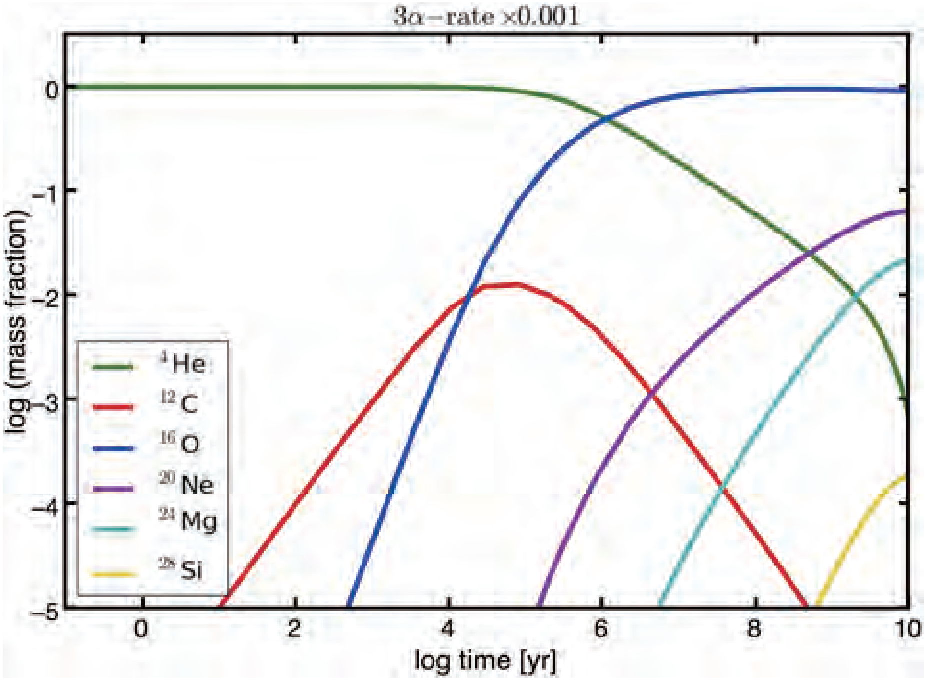



**Fig. 1:** The horizontal axis represents time, while the vertical axis shows mass fractions for different elements in log units. This shows how helium synthesis would occur if the rate of the triple alpha reaction were a thousand times lower than we know it to be. The calculation presumes a temperature of 2,000,000,000 ($2 \times 10^8$) K and a density of 1,000 g/cm$^3$. At first, only helium was present (green), but the triple alpha reaction (reactions 1 and 2 from the main text) result in minute quantities of carbon being formed (red). The carbon thus created combines again with helium to make oxygen (blue). Once the equilibrium point is reached, most of the final atoms formed as a result of the nuclear reactions of helium are oxygen atoms.

Another possibility, of course, is that even if reaction (3) happens much more rapidly than reaction (2), there is an equilibrium state between the two that results in the formation of minute quantities of carbon. With a high enough temperature, for instance, there may be an equilibrium point at which reaction (2) could happen once for every million times that reactions (1) and (3) take place.

An even bigger issue is what happens next: however it is formed, the carbon vanishes when it combines again with helium to form oxygen.

$$^{12}\mathrm{C} + {}^{4}\mathrm{He} \rightarrow {}^{16}\mathrm{O} \qquad (4)$$

For example, figure 1 shows a scenario where reaction (2) is very inefficient compared to reaction (3).

Initially, small amounts of carbon are formed through reactions (1) and (2), but this carbon then disappears completely, transformed into oxygen through reaction (4). This means carbon cannot exist in the universe—and we human beings cannot live and breathe as we do!

It was incomprehensible, at least in terms of the understanding of nuclear physics as recently as the early 1950s. Big Bang theory proponent George Gamow (1904–1968) argued in a 1948 paper written with his student Ralph Alpher (1921–2007) that all of the atoms existing in the universe were formed at the moment of the Big Bang. Their research successfully explained that the mass fraction of hydrogen and helium in the universe was around 1/4. But the paper also overlooked the extreme instability of atoms with mass numbers of 5 and 8—an omission that drew intense criticism. The parts that explained the origins of atoms heavier than helium were less than convincing.

Fred Hoyle (1915–2001) of the University of Cambridge opposed the Big Bang theory, advocating the steady state model instead. The origins of heavy elements under the steady state model as Hoyle conceived it lay not in the Big Bang, but in nucleosynthesis within stars. Hoyle delved deeply into the question, and his achievements laid the groundwork for the stellar evolution model. His steady state model would end up losing ground to the Big Bang theory after the 1964 discovery of cosmic mi-

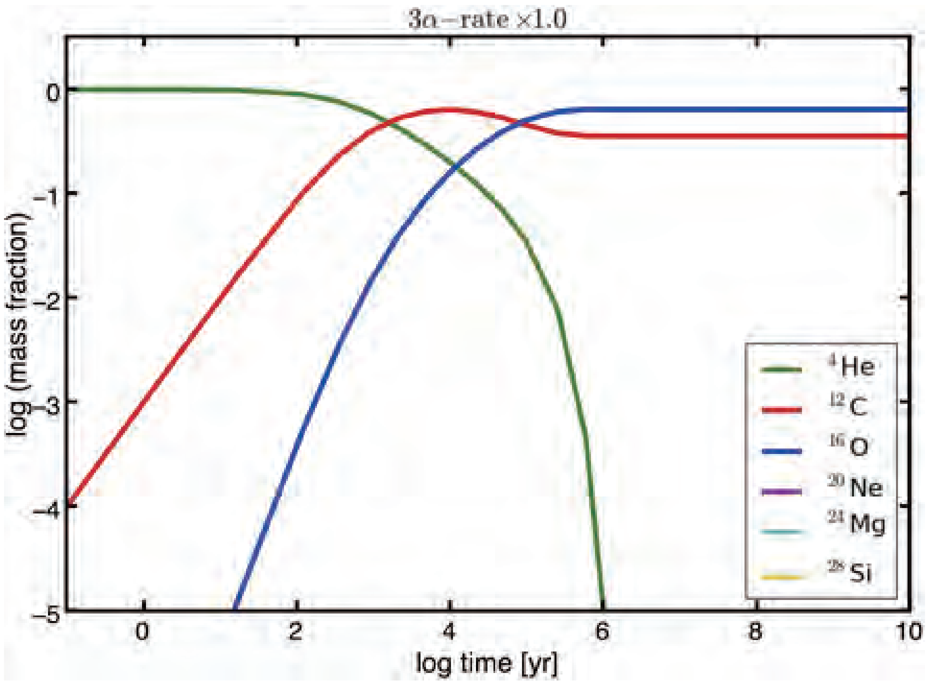



**Fig. 2:** This figure is similar to figure 1, but the rate of the triple alpha reaction is calculated according to values as we currently understand them. In other words, the triple alpha reaction rate is 1,000 times faster than in figure 1. The helium initially present (in green) is rapidly synthesized into carbon (red) through the triple alpha reaction, and a portion of the carbon combines with helium through reaction (4) to produce oxygen.

crowave background radiation—but it was not a total victory for Gamow. When it came to explaining the origins of elements heavier than helium, Gamow was wrong and Hoyle was right.

In 1953, Hoyle paid a visit to the California Institute of Technology. One of the professors there at the time was William Alfred Fowler (1911–1995), an experimental physicist who would go on to win the Nobel Prize in 1983 for his achievements in nuclear physics. Hoyle made a very bold proposal to the nuclear physicists at Caltech. Although it had never been confirmed experimentally or predicted by theories at the time, he argued that an excited energy level must exist within carbon—similar to the combined energy of helium and beryllium. In that case, reaction (2) could take place at a much faster rate than people believed at the time.

We can draw an analogy with human beings: sometimes we are calm, and other times we are excited or giddy. The big and small accidents that occur in life do not typically happen when we are calm; they happen when we are in an excited state and we encounter and experience resonance with someone else who is excited. Atomic nuclei can exist in a range of energy states. When atoms A and B combine to form atom C, and the combined energy of A and B is similar to the energy of C in its excited state, then the reaction can generate resonance that rapidly speeds up its rate.

A plausible hypothesis, but it isn't physics if the numbers don't add up. Hoyle made a simple calculation. The core temperature of main sequence stars like our sun is too low for a triple alpha reaction to occur. As the hydrogen at a star's core is fully consumed and transformed into helium, the helium nuclei contract due to gravity, and the temperature increases. A star at this stage becomes a red giant. Hoyle estimated the core temperature of a red giant to be around 140,000,000 K, and he believed that the triple alpha reaction took place there. He also took note of the observed ratio of carbon, oxygen, and neon in the universe, which is around 1/3:1:1. For this ratio to emerge as a result of nuclear reactions (1) to (4) and other subsequent nuclear reactions, he showed that the resonance energy level for carbon in its excited state had to be around 7.7 MeV from its baseline state.

The experimental physicists at Caltech immediate went to work testing Hoyle's predictions. The value they obtained from their accelerator experiment was 7.68

MeV—astonishingly close to what Hoyle had predicted! Later, more precise calculations put the value slightly lower at 7.65 MeV, but this was still not far off from Hoyle's estimate.

As with all achievements in science, Hoyle's did not come from a vacuum. The person who awakened him to the importance of the triple alpha reaction was the Austrian physicist Edwin Ernest Salpeter (1924–2008). In a paper published in 1952, Salpeter pointed out the carbon formation problem while positing the triple alpha reaction as an energy source for red giants. He too was well aware that the problem could be solved if there was a suitable resonance energy level in carbon, but he did not take it as far as Hoyle did. Later on he would recall, "According to my calculations, most of the helium would transform into oxygen and neon rather than carbon. But I wasn't bold enough to consider a resonance level that hadn't been discovered yet." The paths to important scientific discoveries often diverge at these small points of difference—and the boldness to forge the small differences is the product of a commitment to delving all the way.

The importance of this finding is something we can easily understand by comparing figure 1 with figure 2. Figure 2 shows the helium nuclear fusion reaction process predicted when carbon possesses a resonance energy level corresponding to 7.65 MeV. As expected, large amounts of carbon are formed through the triple alpha reaction. Some of the carbon turns into oxygen through reaction (4), but enough remains in the final equilibrium state to account for the amount of carbon existing in the universe. The origins of carbon were no longer a secret to humankind: carbon is created through triple alpha reactions in the core of a star that has reached its final stage of evolution, with a temperature in the hundreds of millions of kelvins.

The moment when carbon's resonance level was discovered was quite dramatic—one of the most fascinating scenes in scientific history. But if we look at it a different way, Hoyle's approach does not appear all that rigorous scientifically. The carbon resonance level was not something he arrived at deductively from a first principle. In other words, he did not say, "According to the laws of physics, an energy level corresponding to 7.7 MeV must exist." He established an answer ahead of time—that carbon was unquestionably formed within stars—and the 7.7 MeV value was something he came up with while trying to get that answer to fit. There are probably some people who sense a hint of the religious in this reasoning process. Here's an example of that:

- Human beings could not exist without X.
- We human beings do in fact exist.
- Therefore X is true.

For Hoyle, "X" was a carbon energy level corresponding to 7.7 MeV; for some religious believers, "X" is God. Superficial similarities like these are often seized upon in "creation science" and other pseudosciences to argue that science is rooted in subjective beliefs just like religion. Is that really the case? To be sure, there are serious flaws to this kind of argument, but the syllogism above is worth giving some thought to—for it ultimately leads us to the matter of the anthropic principle.

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