Personalities and Pride

Understanding the Origins of Elements


Fred Hoyle

One mid-winter day in 1953, Fred Hoyle charged into the Kellogg Radiation Laboratory at Caltech. In the lab's particle accelerator, a team of nuclear physicists, led by Willy Fowler, bombarded atomic nuclei and discussed the results. As Hoyle entered the lab, they immediately recognized him as the visiting astronomer from Cambridge University in England. He wore thick glasses and slicked back his salt-and-pepper hair. Asking if he could get some accelerator time, Hoyle proposed to do something that no physicist had yet accomplished. If successful, what he proposed doing might lead to understanding how the larger elements originated in the universe. Hoyle maintained he could provide evidence for his claim if only he was given some accelerator time. The Caltech team, not wanting to be pushed around by a visiting *astronomer*, told Hoyle he had no business there. But Hoyle didn't go away. Instead, he became a pain in everyone's side until he got accelerator time. Within a few months, Hoyle had some evidence to support his claim. Yet, this evidence was just the beginning.

The pursuit to understand the origin of matter interested two camps of cosmologists. The first camp included those who supported the idea that the universe is expanding from an initial hot dense state. The second camp supported the idea that the universe is in a Steady-State. Let's start with the views of Fred Hoyle. While Hoyle wasn't big news in America, back in Britain he made quite the stir. A British astronomer and physicist of great renown, he was perhaps best known for his lively public speeches on the philosophy of science. Most people recognized him as the man who ridiculed over BBC radio any notion of an explosion at the beginning of the universe, derisively calling it the 'Big Bang.' Ironically, the name Hoyle used to mock the 'other' theory stuck and we still use 'Big Bang' terminology today. Such a beginning, he said, required an operator to start it, and then something to create that operator, and something to create that, and so on. For Hoyle, something could not come from nothing.

Hoyle advocated his own theory of the universe. Called the Steady-State, he developed this theory in 1948 with mathematician Hermann Bondi and astrophysicist Thomas Gold. In brief, the Steady-State proposes that the universe appears the same everywhere eternally. This eliminates the need for a beginning. The Big Bang, in comparison, expanded and became less dense over time.

Hoyle found the Big Bang distasteful because nothing *guaranteed* the uniformity of physics in a universe where density changed. Just how could the fundamental assumption that the laws of physics here were the same in some far, distant corner of the universe be maintained? The Steady-State universe, being uniform everywhere in time and space, solved this problem.

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> **Science, much like other ways of knowing, makes certain assumptions from which it works. While we cannot be absolutely certain that natural processes are uniform throughout the universe, that assumption has been fundamental to understanding the natural world.**

Nucleosynthesis had long been on Hoyle's mind, and the Steady-State theory gave him room to approach the origin of matter in a new fashion. The Steady-State theory accepted the universe's observed expansion. Yet, instead of making all matter at the beginning in one 'big bang' that would cause the continuous expansion, Hoyle proposed that the universe continually created matter that resulted in the observed expansion. This mechanism tosses the first law of thermodynamics – the conservation of mass/energy – out the window. Hoyle mathematically worked out a “creation field” as a fundamental feature of the universe. Although vague on the exact details of how the field worked, Hoyle asserted that every billion years or so production of about 3 atomic nuclei per square foot was needed. These new nuclei then formed new stars and galaxies while the old ones just kept expanding forever onward. This idea worked, but Hoyle admitted no way existed that would be sensitive enough to detect the creation of such a small amount of matter over such a long time.

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> **Science ideas must have conceivable evidence that would support or refute them. Hoyle notes the lack of *problems* in detection, not the *impossibility* for evidence to one day be obtained.**

1) Notice that both the steady-state and the big bang must account for the observed expansion of the universe, yet the two ideas are markedly different. How does this difference in explanation illustrate that data does not “tell” scientists what to think?

Hoyle now had to wrestle with how larger elements are built up in a universe that constantly, but slowly, creates hydrogen. Hoyle knew this question also existed for the Big Bang supporters, but felt the question was more difficult for them – how did all this matter come from nothing? Clearly Hoyle was aware of the competing idea, and the difficulties the proponents of that view must overcome. Many individuals in both camps were working to explain the creation of larger elements within the confines of their theories – Steady-State and Big Bang. Not only were the groups of scientists working to understand how the elements came to be, but also seeking vindication for the theoretical framework they supported.

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In science, like other endeavors, the framework used affects thinking. While both the Steady-State and the Big Bang camps were wrestling with the origin of larger elements, each group approached the problem with markedly different thinking setting the stage for different possible answers.

George Gamow proposed the first Big Bang model of nucleosynthesis (the process of combining smaller particles to create larger atomic nuclei). Gamow was a Russian immigrant who had moved to America in the 1930s. He stood as one of the giants of experimental physics and theoretical cosmology. A man of great personality, a lively sense of humor penetrated everything he did. He proposed a model in which the universe began in a hot dense state, and that *all* elements were built up via neutron-capture.

Here's a quick run-down of the nuclear physics involved. There are three components of an atom: the positively charged proton, the negatively charged electron, and the neutrally charged neutron. The atomic nucleus is composed of protons and neutrons while electrons 'orbit' at set levels. Now, without getting too specific, protons can be made into neutrons through the capture of an electron, and neutrons can be made into protons (and emit an electron) through a process known as beta-decay. Gamow, being an adherent of the Big Bang, thought that at the very beginning there must have been a primordial lump of neutrons that would decay into the first hydrogen nuclei (protons).

George Gamow

In part, Gamow's idea was inspired by the early theorizing of Abbé (Father) Georges LeMâitre, the 'father' of the Big Bang theory. LeMâitre proposed that the universe began as a “primeval atom” which contained all matter that underwent super-radiation to produce the matter we see today. Gamow's version was very similar – after the formation of the original hydrogen atoms via neutron decay, the heavier atoms built up by capturing one neutron at a time. Of course, all of this had to happen at an unimaginably fast rate, because the universe was quickly expanding.

Two major problems faced Gamow's neutron-capture method. The first was that it didn't explain the abundances of heavier elements. If elements were built by capturing neutrons one by one, it would seem logical that the lightest elements would be most prolific. However, iron (atomic number 26) is very common, gold (atomic number 79) is rare, and lead (atomic number 82) is as common as molybdenum (atomic number 42). A model of adding neutrons one by one couldn't sufficiently explain these different abundances.

The second problem was even more serious – no stable isotopes exist at the masses of 5 and 8. Adding a neutron to the stable isotopes helium-4 or lithium-7 produced 'unviable' byproducts that decayed almost instantly. Lithium-5 and beryllium-5 decay into other elements within 10^{-20} seconds. The same stands for beryllium-8 and boron-8. If no isotopes existed at these low masses, how could the heavier elements have been created by neutron capture? The problem could be likened to climbing stairs one at a time with the fifth and eighth step missing. Building elements through neutron capture simply couldn't work past helium. The theory, however, did accurately explain the abundances of hydrogen and helium.

Many scientists at that time shied away from pursuing the specifics of matter creation because it seemed like playing in God's toy box. This isn't to say they were afraid of commenting on questions that might undermine fundamental assumptions of reality. Rather, they stayed away from such pursuits because they felt ill-equipped with their scientific theories to talk about such issues. Astronomers and cosmologists, however, could hardly avoid talking about such issues. These philosophical questions were new territories for astronomers and might have seemed better left to theologians. Yet, a Catholic priest had developed the first conception of the Big Bang and, conversely, the Steady-State had been envisioned by at least one vocal atheist. Scientists' intellectual tools, however, didn't give them useful clues as to the origin of matter. General Relativity said nothing about an initial bang or creating matter. It simply predicted that a universe with matter would expand. Some models of Quantum Mechanics proposed 'virtual' particles at the time, but they didn't account for any creation of *real* matter. Determining the secrets of nucleosynthesis would require the creativity of both Big Bang and Steady-State scholars.

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Notice that some scientists did not want to engage in questions regarding the creation of matter. Yet, Hoyle and Gamow continued to search for a naturalistic explanation (an explanation that does not make reference to the supernatural). Consider why science works to explain natural phenomena, like the origin of elements, through natural processes. The approach to explain natural phenomena through natural means is referred to as *methodological naturalism*. Methodological naturalism does not claim supernatural entities do not exist. That claim falls under *metaphysical naturalism, and* need not be adopted when doing science.

As one might predict, Hoyle and Gamow weren't the best of friends. Throughout the 1940s, Fred Hoyle had almost a scatterbrained interest in everything: studying the interior makeup of red giant stars, working on radar during World War II, and formulating his Steady-State theory. Beginning as a mathematician (as many British astronomers did), he jumped into any field that interested him, including a long run as a science fiction writer. Gamow, meanwhile, had always been a theoretical physicist working with particles. Standing 6'3" and weighing 230lbs, he had survived an oppressive Russian regime and managed to escape to America, where he would also become a writer. By the 1960s, their spats boiled over into their books. In 1965, after the Big Bang had trumped the Steady-State, Gamow published *Mr. Tompkins in Paperback*, which featured a Hoyle character that appeared from nothing and launched into song, "And still new galaxies condense/From nothing as they did before/(LeMâitre and Gamow no offense!)/All was, will be for evermore/Stay, O Cosmos, stay the same!/We the Steady State proclaim!"

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Some people view scientists as cold, calculating, uninteresting individuals. Notice the sense of pride and use of sarcasm both Hoyle and Gamow demonstrate. Scientist's emotions enter their work, just like in other professions. Contrary to popular belief, scientists are not simply interested in furthering knowledge, but also in being the one who lays claim to important ideas.

Hoyle's pursuit of nucleosynthesis began by critiquing Gamow's Big Bang-based system. One of the most appealing qualities of the Steady-State was that it removed a time-scale problem present in the Big Bang. In 1950, Big Bang scholars estimated the age of the universe to be 2 billion years old. Geologists, however, used radiometric dating of rocks to conclude that the earth was at least 4 billion years old. How could it be that the earth was older than the universe? Furthermore, geologists argued that from their earthly evidence, elements must have come from a common stellar origin. It had long been concluded that stars fused hydrogen into helium, but the time required to reach the observed abundances (73% hydrogen to 25% helium) was 10^{11} years, or 100 billion years. Hoyle knew the weak points of the Big Bang model were the time-scale problem and the gap problems for isotopes with masses of 5 and 8.

2) Scientists often look to other disciplines or research areas for data/conclusions that might support their ideas. Why might scientists hope to find coherence among ideas/data from different scientific disciplines?

As early as 1946, Hoyle had worked out a chain of element production. Being fresh out of studying red giants, he knew that different stars have different abundances of elements. Therefore, Hoyle reasoned, elements cannot have a common origin at the beginning of the universe. Some elements must have a more recent origin. He developed a system similar to Gamow's, except he speculated that heavier elements could be created by the step-by-step addition of helium nuclei instead of neutrons. This system didn't exist much outside of Hoyle's notebook for the next few years as he busied himself shoring up the Steady-State theory, speaking publicly, and teaching classes that Cambridge University kept piling on him as penance for his frequent absences.

Then, in 1953, Hoyle decided to go to Caltech and make use of their new particle accelerator at the Kellogg Research Laboratory. Announcing he had calculated the energy level of carbon-12, he hadn't yet realized the implication this would have on Gamow's mass-gap problem. He thought heavier elements could be made inside the pressurized interior of stars by adding alpha particles (helium nuclei – 2 protons, 2 neutrons, 0 electrons, mass 4) to elements. However, he ran into the same problem of Gamow's neutron-capture: the isotopes at mass 8 decayed almost instantly. If isotopes at mass 8 didn't last long enough to interact with an alpha particle, then carbon-12 simply couldn't exist. But carbon did exist in significant abundance. The unstable beryllium-8 nucleus had a half-life of 10^{-18} seconds before decaying into two alpha particles. However unlikely, beryllium-8 *must have interacted* with another alpha particle to produce carbon-12, for the mere fact that carbon existed. Hoyle had done the necessary calculations to find the energy states required to pull off this near miracle of physics, and needed the power of Caltech's accelerator to verify his results.

3) Many people wrongly think that scientists follow a rigid step-by-step "scientific method". Hoyle is making statements about the required carbon-12 energy state being found within stars solely because he dislikes the Big Bang. Furthermore, Hoyle is creating explanations for the origin of carbon-12 using calculations, his prior knowledge, and his imagination. How does Hoyle's strategies illustrate that scientists are often not objective and do not follow a prescribed step-by-step scientific method?

Eventually Hoyle convinced one of the researchers, Ward Whaling, to put in a good word and he got his accelerator time. They used a small accelerator for particle collisions and moved a spectrometer from the larger accelerator. The scene, as described by biographer Simon Mitton:

> [Whaling's] vivid recollection is of moving the spectrometer, which weighed many tons on account of the huge magnet it contained, down a narrow hallway 4 feet wide, and round two corners. They rested a large steel plate on several hundred tennis balls, slid the multi-ton instrument onto this platform, and set the whole in motion. A pack of graduate students feverishly fed the squashed tennis balls from the back to the front as the procession proceeded!

To get carbon-12 to an excited energy state, they bombarded nitrogen-14 with deuterons (hydrogen with 2 neutrons), making alpha particles and excited carbon-12. This was no small task. By the time it finished three months later, Hoyle was back in Cambridge. The energy states were indeed as predicted by Hoyle.

Hoyle's process of adding alpha particles worked up to iron, but then stopped abruptly. Elements below iron were produced by nuclear reactions that *released* energy. Elements above iron required the *input* of energy. As elements got larger with more protons and neutrons crammed into the nucleus, the reactions required more and more energy to overcome the electrical resistance. One possibility of making elements heavier than iron would be to fire neutrons at nearly the speed of light into a heavy nucleus. The problem with this mechanism was twofold: 1) Hoyle was unsure if stellar interiors could be hot enough to accelerate particles to near light speed, and 2) 'free' neutrons (not bound to a nucleus) had only ten minutes before they decayed. In 1953, there was no known evidence for stars to have a seemingly unlimited supply of free neutrons flinging around at the speed of light for the mere sake of creating elements. Now there was another problem to be overcome, and the solution would mark the great triumph of nucleosynthesis.

Impressed by Hoyle's work, Willy Fowler had taken a sabbatical leave from Caltech to work in Cambridge. There he happened to attend a lecture on elemental abundances by a husband and wife team, Geoffrey and Margaret Burbidge. That night's lecture focused on the star Gamma Geminorum, which had a spectrum revealing the presence of earth-like elements. Feeling that the two would be interested in the question of how elements were created, Fowler invited them to meet Hoyle. They then became a group of four studying nucleosynthesis.

Soon after the meeting, a fortuitous paper appeared on Hoyle's desk. Submitted by Alistair Cameron to the *Astrophysical Journal*, it was on the docket for rejection, but the journal's editor decided to send it to Hoyle – the red giant expert – to get his opinion. Cameron had proposed that a generous supply of neutrons existed in red giants. He noticed that red giants had technetium (atomic number 43) in their spectrum. Yet, none of the 27 isotopes of technetium are stable. However, a star that emitted a steady stream of neutrons would constantly produce technetium. This would explain the appearance of technetium in the spectrum. Hoyle calculated that a red giant with a helium shell and an interior of carbon-13 would produce bountiful neutrons. These neutrons might then be "seeding" iron nuclei one-by-one (just as Gamow had suggested) to produce the heavier elements.

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It turns out that both Hoyle and Gamow's ideas were necessary in explaining the origin of the elements. Hoyle's alpha particle addition explained heavy elements through iron, and Gamow's neutron addition explained elements heavier than iron. While the two seemed to be working against one another, each was working to understand the natural world to which all science ideas are ultimately held accountable.

Unfortunately, the process would again be too slow to explain the observed abundances. A seeded iron nucleus might wait another 100,000 years before receiving a jolt energetic enough to transmute it to the next stage. For some elements this was fine, but many others had shorter half-lives. Hoyle turned to established knowledge of atomic "cross-sections," or their physical likelihood to capture a neutron. Elements with small cross-sections would be less likely to capture a neutron and those with large cross sections would be more likely. As a result, the elements with large cross-sections would be rarer, because they were more likely to capture a neutron and transmute. Calling it the s-process (for "slow"), the team had made progress to understanding the abundance of the heavier elements.

But the s-process couldn't explain everything. There must have been a faster way, and they called it the r-process (for "rapid"). They thought that perhaps supernovae might be strong enough to make neutron-capture take off at a rapid rate. But they could only locate inadequate data from a 1937 supernova. However, the United States military had just tested its first hydrogen bomb. As part of its ongoing Atoms for Peace program, the military released scientific studies on the bomb's mushroom cloud. Here, in the military's data printouts, Hoyle and his team noticed crucial data. While the bomb's explosion was certainly much weaker than a supernova, in a single blast it had created elements heavier than iron and even trace amounts of elements beyond uranium. The r-process, in which iron nuclei were intensely bombarded with neutrons in a supernova-like event, explained the production of elements left out by the s-process.

Armed with the triple-alpha process, the s-process, and the r-process, the team published a seminal paper in 1957. They named it alphabetically, the B^2FH paper. Weighing in at 108 pages (a monster for a journal article), it has since been cited over 1300 times in scientific literature and set the stage for further research on nucleosynthesis. Of course the group didn't have all the answers, but the ideas seemed to explain major processes concerning the origins of the elements.

Gamow, meanwhile, had turned his interests toward biology and the study of amino acids. He continued writing popular books and articles on cosmology. Having said his part very early in the game, he sat back and watched as others took up the project.

4) Many people think science is done by lone scientists who take up and solve important mysteries. However, this historical episode demonstrates that scientific knowledge is the result of many individuals working together, against each other, and using past ideas to cumulatively work toward more accurate ideas. How might science be different if scientists did not work together, debate each other, and use ideas that are already accepted?

One major question remained into the 1960s. Was helium primordial or stellar? Work throughout the 1950s conflicted on the abundance levels of helium in the universe. Estimates fluctuated from near 15% to 30% by mass. In 1964, Hoyle teamed up with a Cambridge colleague, Roger Tayler, and they realized that current stellar processes couldn't explain the observed amount of helium. A temperature of 10^{10}K was required, possible only in the early stages of a Big Bang universe. They concluded that, "Either the Universe has had at least one high-temperature, high-density phase, or massive objects must play (or have played) a larger part in astrophysical evolution than has hitherto been supposed." Obviously Hoyle supported the latter in the form of super-massive red giants, but most scientists took this evidence to be the clincher for a hot Big Bang.

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Many people wrongly think that scientific theories eventually develop into scientific laws. However, laws and theories are different, yet related, kinds of assertions about the natural world, and one never becomes the other. Laws are statements of invariable relationships, and theories explain those relationships. While the Big Bang has become the accepted scientific explanation concerning the origin of the universe and the elements, the idea is still considered a *theory* as it always will be. The Big Bang explains why the universe is expanding, why we observe the elemental abundances we do, and other phenomena. The theory, no matter how much evidence is gained, will not become a scientific law. The Big Bang is considered to be a well-established theory because of its great explanatory power.

Nucleosynthesis stood out from other scientific work in many ways. The idea successfully furthered scientists' understanding of how the universe worked on large and small scales, helped discriminate between the Big Bang and its competitor the Steady-State model, and furthered knowledge concerning the microphysics of stellar interiors. Furthermore, the development of nucleosynthesis highlights how science requires both theory and observation. This episode also demonstrates how science might make use of ideas from competing theories. While this story focuses on events occurring in the early to mid 1950s, work concerning nucleosynthesis extended from 1946 to 1964, spanning continents and involving many of the most eminent physicists of the time.

Personalities and Pride: Understanding the Origins of Elements written by Blair Williams, Jerrid W. Kruse, Michael P. Clough, Matthew Stanley, & Charles Kerton

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