Features - Cover Story

Crucible of creation; What really happened in the first few minutes after the big bang? One element could hold the answer, says Matthew Chalmers

Matthew Chalmers
2378 words
5 July 2008
New Scientist
28-31
volume 199; issue 2663
English

POP out the battery in your cellphone and it will contain something that has likely been around for almost 13.7 billion years - lithium. Along with other light elements, including hydrogen and helium, much of the lithium in the universe is thought to have been produced in a primordial fusion factory that powered up when the universe was barely a second old. In little more than 5 minutes, it produced the raw ingredients for all the ordinary matter in the universe, which billions of years later would clump into galaxies and stars.

This early forging of light nuclei is known as big bang nucleosynthesis (BBN) and, for the most part, our theoretical understanding of it is spot on. In fact, the amounts of hydrogen and helium tally so well with predictions that cosmologists claim this is the best evidence we have for the big bang.

Yet there is a problem: the abundance of lithium is way off the mark. Most of the lithium in the universe is in the form of lithium-7, though there is another isotope around, the lighter lithium-6. When astronomers measure the amount of lithium-7 in the very early universe, the result they get is only a fraction of what conventional cosmic history prescribes. Worse, when they look at lithium-6 they find 1000 times as much of it than there should be.

The mismatch is cause for concern. "If the lithium discrepancy persists and there are no answers from astrophysics, then there is something wrong," says Gary Steigman of Ohio State University in Columbus.

As observations have improved, the lithium problem has got so bad that some researchers are saying it is time for an overhaul of cosmic proportions. They want to retell the story of our origins by introducing exotic new particles into the first few minutes after the big bang. Their ideas have far-reaching consequences for our understanding of fundamental particles, the forces between them and even the very earliest moments in the cosmos.

Of course this isn't the first time that our understanding of the big bang has been challenged. Others have pointed to gravitational anomalies, ancient stars in ultra-distant galaxies and quirks in the cosmic microwave background - the dying glow of the big bang - as evidence that all is not well. What makes the lithium problem so serious is that cosmologists consider measurements of the abundance of light elements to be one of the most reliable ways of inferring what conditions were like a few seconds after the big bang.

The idea behind big bang nucleosynthesis was first set out in 1948 by George Gamow, Ralph

Alpher and Robert Herman. Their version of the theory described how nuclei could be built via a chain of reactions, beginning with the neutrons and protons that emerged from the cosmic gloop of fundamental particles present after the birth of the universe. Once protons and neutrons had paired up to make deuterium nuclei, the nuclei of heavier elements could be built simply by having the deuterium capture more neutrons, some of which would then undergo beta decay to become protons.

Gamow suggested that all the elements could be made in this way, but it turned out that he was wrong. According to the contemporary version of the BBN theory, only the four lightest elements were cooked up in the big bang itself. The amount of hydrogen in the universe was sealed within the first second of the birth of the universe.

By the end of the first 5 minutes, a quarter of the ordinary matter in the universe had been converted into helium-4 nuclei, plus tiny traces of the heavy hydrogen isotopes deuterium and tritium . As this happened, some helium-4 reacted with helium-3 nuclei to produce beryllium-7, which decayed into lithium-7. Other helium-4 nuclei collided with tritium nuclei to produce lithium-7 directly. As for the heavier elements in the periodic table, they were forged inside stars billions of years after the big bang and then ejected into the void by supernovae.

They may not have got every detail right, but remarkably Gamow, Alpher and Herman predicted the existence of the cosmic microwave background nearly 20 years ahead of its discovery. They realised that the universe had to be extremely dense and hot for the nuclear reactions to take place at the required rates. To ensure this was the case, they assumed that for every proton or neutron present during the first few seconds, there were around a billion photons jostling around. These photons are still present today, stretched to microwave wavelengths as the universe expanded.

What is so impressive about the BBN theory is that it says the abundances of light elements depend on just one fundamental parameter, the baryon-to-photon ratio. This is a measure of the number of photons per proton or neutron and it holds the key to whether the universe will expand forever or collapse under its own weight. It also provides strong evidence that most of the material in the universe is in the form of mysterious, invisible dark matter.

Until recently the baryon-to-photo ratio has been difficult to measure precisely, however. So for nearly 40 years we have used the BBN theory to work out the baryon-to-photon ratio from measurements of the very early abundance of deuterium, in particular. We can infer the primeval elemental abundances by fixing our sights on the most ancient stars and galaxies, which are untainted by heavier elements.

To look for deuterium, for instance, researchers study dust clouds that lie between us and old galaxies called quasars. A dark line at a certain wavelength in the galaxy's spectrum shows that deuterium atoms in the intervening dust cloud have absorbed some of the quasar's light, and just how dark the line is indicates how much deuterium is present.

The third element

In the last few years, however, these methods of determining the baryon-to-photon ratio have been superseded by more accurate measurements of tiny temperature ripples in the cosmic microwave background. This has allowed us to make some crucial cross-checks of the BBN theory. By plugging the baryon-to-photon ratio from the microwave background into the theory, we can work out what the very early abundances of light elements should be and then compare them with existing measurements. "This is a very big deal," says Jim Peebles of Princeton University, who in 1965 was one of the first people to predict the abundances of light elements.

Measurements of the temperature ripples, captured with unprecedented accuracy since 2003 by NASA's Wilkinson Microwave Anisotropy Probe (WMAP), have revealed a startling problem with the amount of lithium predicted by the BBN theory. When the latest WMAP results are plugged in, the theory says that for every million hydrogen atoms, there should have been roughly 80,000 helium-4 atoms, 10 deuterium and helium-3 atoms, and 10-4 lithium-7 atoms in the very early universe.

According to Steigman, the observed and predicted deuterium abundances are now in "virtually perfect agreement". For helium, the situation is less clear-cut, though there is still broad agreement. The same cannot be said of lithium. Observations of the very oldest stars in the galaxy reveal that there is only a third the amount of lithium-7 predicted by the BBN theory.

Not everyone is panicking over this discrepancy. After all, lithium can also be produced inside stars and in collisions between cosmic rays and interstellar gas. Like many astrophysicists, Andreas Korn of Uppsala University in Sweden suspects that we may solve the lithium problem with a better understanding of stars, rather than the big bang. In 2006 his team studied the chemical composition of 18 ancient stars at different stages of evolution using the Very Large Telescope (VLT) at Cerro Paranal in Chile.

Their work led them to conclude that lithium does not survive the mixing that is thought to take place close to a star's surface, from which nuclei diffuse into the hotter interior and later return via convection (Nature , vol 442, p 657). The amount of lithium eaten up as these ancient stars burn is just enough to explain the observed shortfall. The team is preparing to make more detailed measurements at the VLT and the Keck telescope in Hawaii this year to be sure.

In the meantime, however, the lithium problem has potentially got much worse. Two years ago, Martin Asplund, now at the Max Planck Institute for Astrophysics in Garching, Germany, and his colleagues detected unusually large quantities of lithium-6 in 24 ancient stars (The Astrophysical Journal , vol 644, p 229). This turned one problem with lithium into two.

Theory says that the BBN fusion factory can produce lithium-6 - but not in anything like the amount Asplund observed, which exceeds the predicted quantity by a factor of 1000. Verifying or refuting the lithium-6 measurements has become a matter of some urgency, since the slight shortfall in lithium-7 and enormous excess of lithium-6 could be a sign that exotic new particles were present in the early universe. But working out the abundance of lithium-6 is extraordinarily difficult. Asplund and four others took almost five years to analyse their results, partly because the spectral signature of lithium-6 is superimposed on that of the more common lithium-7, which is 20 times more intense. In fact, the measurements are so tricky that some researchers don't think there is a lithium-6 problem at all. "The best explanation of the lithium-6 problem is that the true abundance of lithium-6 is presently unknown," says Robert Cayrel of the Paris Observatory in France, who along with several colleagues has recently called into question Asplund's results by undertaking a more thorough spectral analysis of a single star (www.arxiv.org/abs/0708.3819 [http://www.arxiv.org/abs/0708.3819]). The various lithium-6 observations are unlikely to be reconciled soon.

Very recently, Asplund's team observed 10 more stars using the Keck telescope, and so far the results indicate that many of these seem to contain an even greater abundance of lithium-6 than the first batch. The team is still analysing the results and expects to submit a paper later this year. "At least that is our hope," says Asplund.

Theoretical cosmologist Joseph Silk at the University of Oxford believes that novel particle physics may be required to solve the lithium problem. "Although we need to further understand lithium, I can't believe it's a stellar problem," he says.

Silk is one of many theorists who suspect that the presence of as yet unseen particles altered the abundances of the light elements during BBN itself, or perhaps even long afterwards. Most of these ideas are rooted in supersymmetry, an extension to the standard model of particle physics which posits that every known particle has a heavier partner.

Supersymmetry could solve both lithium problems at once. In 2004 Karsten Jedamzik at the University of Montpellier in France realised that if gravitinos, the supersymmetric partners of gravitons (the particles thought to carry gravity), were present during the first few minutes of the universe, they could decay and so inject neutrons and protons into the fray. Even a tiny number of extra neutrons would be sufficient to cause lithium-7 to form much earlier than it would according to the standard BBN theory, causing it to be destroyed because the temperature would be too high for the nuclei to remain stable. This would explain the shortfall of lithium-7.

The extra neutrons could also strike helium-4 nuclei to produce a proton, neutron and tritium. The tritium might then fuse with other helium-4 nuclei into lithium-6. What got Jedamzik really excited was that this simple chain of events can explain the magnitude of the lithium discrepancies (Physical Review D , vol 70, p 063524).

A couple of years later, Maxim Pospelov of the Perimeter Institute in Waterloo, Ontario, suggested that supersymmetric particles could act as a catalyst for a second round of nucleosynthesis. He showed that if negatively charged supersymmetric particles called staus - partners of the tau lepton - were present in the early universe, they would start to bind with positively charged beryllium-7 after the first 15 minutes. This bizarre bound state tends to capture protons to make a hybrid stau-boron-8 state that decays to two helium-4 nuclei instead of lithium-7.

The presence of staus doesn't just reduce the abundance of lithium-7; it also boosts the amount of lithium-6, Pospelov claims. Nearly 3 hours after the big bang, a fraction of helium-4 nuclei would bind with the staus to make a new state that can fuse tens of thousands of times more efficiently with deuterium to produce lithium-6 than conventional helium-4. Asplund says a particle physicist has even mentioned to him that the lithium-6 observations "may be the strongest empirical argument for supersymmetry that exists today".

But without hard and fast evidence for supersymmetry, such models have failed to win round the sceptics. "Mixing effects in stars are inevitable, while the particle physicists' solutions are currently sheer speculation," says Korn.

We may not be in the dark for much longer. "Arguing over whether the solution to the lithium problem lies in particle physics or astrophysics is moot," says Jonathan Feng of the University of California, Irvine. "We'll know the answer in a year."

All eyes are now on the Large Hadron Collider, which is nearing completion at the CERN particle physics laboratory near Geneva, Switzerland. One of its main targets is to find evidence of supersymmetry. Feng might be overly optimistic about progress on this front, given that gravitinos interact too weakly and staus are too heavy to be created directly in the LHC's collisions. But by the time astronomers have either confirmed or ruled out the crucial lithium-6 results, cosmic history may already have been rewritten in the lab.

Matthew Chalmers is a writer based in Bristol, UK

Document NEWSCI0020080703e4750000d