Big Bang Nucleosynthesis

Chris Williams
Student 1607421
HET 614

17th September 2004

Introduction

The origin of the stuff from which the Universe is made has been of interest for many centuries. In recent scientific history several possible scenarios for the origin of the 92 natural elements, consistent with Hubble's observation of an expanding Universe, have been proposed. A steady-state theory in which the Universe is eternal, elementary matter is spontaneously created everywhere to maintain a uniform density, and stars convert this to the elements we see, was championed by Hoyle. An alternate theory, supported by Gamow, postulated that all elementary matter was created in a single primordial explosion, the so-called *Big Bang*, and that the current state has evolved from there. Observational evidence has since discounted Hoyle's model by detecting artifacts of the Big Bang.

A key element of both these Universal models is a process called nucleosynthesis. The specifics of this process were of relevance to discounting Hoyle's model. This essay addresses nucleosynthesis, its role in the Universe, and the constraints placed on the conditions of the Big Bang in order to match observational evidence.

Atoms and Nuclei

All the material around us is built from atoms. Each atom, or element, has a structure consisting of a nucleus surrounded by a cloud of electrons (negative particles). The nucleus consists of positively charged protons and electrically neutral particles called neutrons (collectively called nucleons). The number of protons in the nucleus determines the type of element the atom represents. For example, Hydrogen atoms contain a single proton, Helium contains two, and Carbon contains six. The number of protons in a nucleus is called the atomic number (A). The protons within a nucleus may be accompanied by a number of neutrons, particles which have no electric charge and roughly the same mass as a proton. The protons and neutrons combined provide the bulk of the atom's mass; the sum of proton and neutron counts is called the atomic mass (Z). A shorthand is used to indicate the atomic number and mass of atoms, ${}^{Z}_{A}\mathrm{El}$, e.g. ${}^{1}_{1}\mathrm{H}$ for the Hydrogen atom or ${}^{4}_{2}\mathrm{He}$ for the Helium nucleus. Atoms with the same atomic number but varying neutron counts are called isotopes of the atom or element. For example, Hydrogen comes in isotopes with zero (${}^{1}_{1}\mathrm{H}$), one (${}^{2}_{1}\mathrm{H}$), or two (${}^{3}_{1}\mathrm{H}$) neutrons, with Z of one, two, or three as a result. The heavier Hydrogen isotopes are named Deuterium and Tritium, but typically an isotope is known only by its atomic mass number, for example Carbon-12 and Carbon-14 of Carbon-dating fame.

Nucleosynthesis

Nucleosynthesis is the process by which the defining structure of atoms, the nucleus, is constructed from smaller building blocks, protons and neutrons. There are two main processes by which an atom's nucleus may convert from one element to another: fusion, and neutron capture followed by decay.

In their large 1957 paper, Burbidge, Burbidge, Fowler, and Hoyle ([2], hereafter BBFH) outlined in substantial detail the processes of nucleosynthesis in the environments expected at the core of stars. Conditions in stellar cores are extreme by everyday standards, with our Sun harbouring a $15,000,000°\mathrm{C}$ core temperature and a pressure in the order of 10^8 atmospheres. Under such conditions protons have sufficient energy (motion) to overcome the repulsion, induced by the electrical charges of other protons, and fuse together. The resulting nucleus increases its atomic number by one and becomes a heavier element. For example, the capture of a proton by a Deuterium nucleus, with one proton and one neutron, gives a Helium isotope. Capture can also occur between more complex nuclei, e.g. between two Helium nuclei forming a Beryllium nucleus, but this requires more energy to overcome repulsion. At various stages in the lives of particularly heavy stars conditions can support fusion of nuclei as heavy as Silicon (${}^{28}_{14}\mathrm{Si}$) to form Iron isotopes (${}^{X}_{26}\mathrm{Fe}$).

BBFH also outlined another mechanism that could modify the nucleus of atoms in the end stages of stellar lifetimes, particularly in the catastrophic explosion of heavy stars (supernovæ). The process of neutron capture allows formation of a heavier isotope of the same element by adding a neutron e.g. a ${}^{3}_{2}\mathrm{He}$ nucleus may capture a neutron to become the most common form of Helium (${}^{4}_{2}\mathrm{He}$). Neutron capture does not have to overcome electrical repulsion and can occur with lower energy. Neutrons have only a short life span outside of a nucleus, which limits likelihood of capture, therefore supplies of free neutrons in quantity are required order to build up nuclei.

Our world is, for the large part, populated by long-term stable elements, and it is clear that nature favours certain arrangements of protons and neutrons over others. Isotopes that are not stable, such as all the radium isotopes, are termed radioactive and are subject to decay until they reach a stable configuration. Many possible configurations created by fusion or neutron capture are unstable over relatively short periods and eject a particle or change in other ways. A typical decay might eject two neutrons and two protons, a Helium nucleus or α-particle, to become an isotope of a lighter element. Another form of decay that affects the nucleus is when a neutron decays by emitting an electron and anti-neutrino to become a proton (β^- decay). β^- decay increases the nucleus' atomic number by one and changes the arrangement of nucleons, maybe to a more stable state. In environments where neutron capture is occurring more slowly than β^- decay the capture process is called the s-process (slow–), and can build nuclei as heavy as Lead ($^{208}_{82}$Pb) and Bismuth ($^{209}_{83}$Bi). When neutron capture rates exceed β^- decay rates, the process is called the r-process (rapid–), and may result in nuclei heavier than the s-process, e.g. Uranium ($^{238}_{92}$U).

Chains of the processes described could, on the face of it, allow the construction of any element from only Hydrogen given the correct environment. BBFH concluded that fusion processes could reasonably account for the abundances of naturally occurring elements as heavy as iron. Elements heavier than iron were created by the s– and r-processes in the violent explosion of massive stars. BBFH also admitted that hard evidence was needed to bolster the case. Unfortunately, the stellar processes alone could not account for the unexpectedly high observed Helium concentration, which leads to the other place that nucleosynthesis could occur.

Big Bang

Nucleosynthesis outside of stars is a pivotal part of the Big Bang model of Universal creation. In the Big Bang model our Universe was once contained within an infinitely dense point that exploded to form the space and time that we know. All of the energy and matter contained in our Universe was present in this original point so, shortly after the explosion, temperature and density would have been extreme and a candidate for processes of nucleosynthesis. In the moments following the initial explosion of the singularity, nucleons as we know them did not exist because they were dissociated into even smaller particles called quarks and gluons. To form neutrons and protons a mechanism was required to dramatically cool the Universe. The theory calls for a period of rapid inflation in order to produce the even distribution of matter we see, and this is also a cooling factor. As the expansion progressed and temperatures dropped, neutrons were able to form from the quark soup. Neutrons are not stable for long period outside of atomic nuclei due to β^- decay. However, until the temperature and density of the Universe dropped sufficiently, any neutron that decayed into a proton would quickly reabsorb an electron (inverse β process), leading to an equilibrium state.

Ultimately the Universe cooled sufficiently that the equilibrium was broken and protons became more common, and neutrons less so. The Universe now had the building blocks of nucleosynthesis.

In 1946, George Gamow [3] outlined reasoning supporting the formation of the basic elements in a short period following the initial event. Alpher, Bethe, and Gamow [1] expanded on this work to flesh out the consequences of this model on the abundance curve of the elements. Gamow *et al.* considered that the initial gamut of elements was determined between when conditions allowed free neutrons to exist ($T \approx 3 \times 10^{10}$ Kelvin) and was largely fixed by the time that Deuterium nuclei could form without immediately being disassembled ($T \approx 0.9 \times 10^{9}$ Kelvin). In this time period neutrons were decaying into protons, a process that would cease when there were no longer free neutrons to decay. Once Deuterium became stable Gamow determined that all the available neutrons would be rapidly absorbed into larger nuclei. At the point the process ceased, the ratio of protons to neutrons would be fixed; with expectations of about ten to one.

When Deuterium nuclei became stable conditions were such that fusion of nuclei was still possible. However, this remained so only until expansion once more removed temperature and diluted density. If expansion was slow enough conditions could remain suitable for fusion of Helium and Lithium, and heavier elements would follow. If expansion was faster then less Helium would form, and remaining Deuterium would decay back into Hydrogen. The only stable isotopes of mass of eight or less are ${}^{1}_{1}\mathrm{H}$, ${}^{4}_{2}\mathrm{He}$, and ${}^{7}_{3}\mathrm{Li}$, and it is these that we observe in the early Universe. While unstable isotopes ${}^{2}_{1}\mathrm{H}$, ${}^{3}_{1}\mathrm{H}$, ${}^{3}_{2}\mathrm{He}$, ${}^{5}_{2}\mathrm{He}$, ${}^{5}_{3}\mathrm{Li}$, ${}^{8}_{4}\mathrm{Be}$ could form, they would all decay on short timescales. The end point of the process is strongly linked to the expansion rate, which is given a lower limit by observed Helium to Hydrogen ratios.

The ratio of protons to neutrons and the dominance of stable Helium as a heavier nucleus leads directly to relative abundances of Hydrogen and Helium. Working with the 10:1 estimated ratio, each ${}^{4}_{2}\mathrm{He}$ nuclei must be matched by eighteen Hydrogen nuclei to maintain the ratio. In the example, the Helium nucleus is 18% of the mass. Current estimates of the primordial Helium abundance, based on distant, younger galaxies much closer to original abundances, are 23–24% (e.g. Izotov & Thuan [4]). This corresponds to a proton/neutron ratio of seven or eight to one. Universal expansion between the time that neutron-proton equilibrium broke and the formation of Deuterium must be within a narrow range to arrive at these ratios. The observed Helium abundance therefore constrains the conditions of the early Big Bang model.

Conclusion

Everything around us is made from atoms, and these atoms originated in the Big Bang. The processes of nucleosynthesis operated to build larger nuclei from protons and neutrons, but the process was limited by expansion. The precise ratio of material in the primordial Big Bang material constrains the conditions of the early Universe, particularly the rate of expansion. Only Hydrogen ($\approx 77\%$), Helium ($\approx 23\%$) and minute traces of Lithium are observed in regions close to this period. Stars have since taken the rudimentary building blocks from the Big Bang and produced the pantheon of elements we see now using largely the same processes that occurred briefly during the Big Bang. For this reason, we can truly be said to be made from the stuff of stars.

References

[1] R. A. Alpher, H. Bethe, and G. Gamow. The Origin of Chemical Elements. *Physical Review*, 73:803–804, April 1948.

[2] E. M. Burbidge, G. R. Burbidge, W. A. Fowler, and F. Hoyle. Synthesis of the Elements in Stars. *Reviews of Modern Physics*, 29:547–650, 1957.

[3] G. Gamow. Expanding Universe and the Origin of Elements. *Physical Review*, 70:572–573, October 1946.

[4] Y. I. Izotov and T. X. Thuan. The Primordial Abundance of 4He Revisited. *Astrophysical Journal*, 500:188–+, June 1998.