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REVIEW ARTICLE ONBIG BANGNUCLEOSYNTHESIS AND FORMATION OF ELEMENTS IN STARS

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ABSTRACT

Baryons, especially protons and neutrons, the main constituents of observable matter, were first formed from energy in the early stages of the development of the universe after the Big Bang (according to the Big Bang theory), and hydrogen and helium atoms were created. Later, new and heavier atomic nuclei were formed inside stars from the existing elements by nuclear reactions. The present article focusses on the processes involved in both Big Bang nucleosynthesis and stellar nucleosynthesis.

INTRODUCTION

The present review article focusses on broad description of processes occurring in the universe after the Big Bang, which is the beginning of the universe according to one of the most accepted theories in this field, and reactions occurring inside stars leading to the synthesis of various elements from hydrogen which was the first and only element in the early universe.

Emergence of matter from energy after the big bang

Currently, the Big Bang Theory provides the most complete description of the beginning of the Universe. The idea of an expanding Universe was predicted by Einstein's General Theory of Relativity (1916), and was confirmed later by observations, with the implication that if galaxies are getting further apart as time passes, then they must have been closer together in the past, and there was a time when all the matter in the Universe must have been piled up in a dense fireball. Combination of theory and observation has established that the Universe began about 13.7 billion years ago with the sudden burgeoning of a microscopic bubble of nearly infinite density in space-time. This early universe was formed entirely of intense electromagnetic radiation.

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This energy immediately began to form particle-antiparticle pairs, and the particles and antiparticles immediately began to annihilate one another to make energy again. As Universe expanded rapidly (by a process called 'inflation' by American physicist Alan Guth, which increased the volume of the universe by a factor of 10^{60} within the first 10^{-23} second), it cooled its energy density decreased, so more massive particles could not be made. Eventually the energy density would have fallen so much that it became impossible to make even electrons. If the particle-antiparticle interactions were perfectly symmetric, the young Universe would have contained equal number of particles and antiparticles, and each particle would have interacted with its antiparticle counterpart and been annihilated. By the time the Universe was a few hundred thousand years old, all the matter would have turned back into radiation, but now at a temperature far too low for any pair formation. But the fact that matter still exists in the Universe suggests that under the conditions that existed in the early Universe, the particle-antiparticle interactions were not completely symmetric.

Russian physicist Andrei Sakharov first suggested the violation of this symmetry, called CP symmetry, in the 1960s to explain the existence of matter. CP symmetry states that if every particle in an interaction among quantum particles be replaced by the corresponding antiparticle and the whole interaction be reflected in a mirror, then the mirror image world will behave in the same way as the real world. He said there must be processes operating at energy densities of the early Universe which violated CP symmetry involving strong interaction to produce a tiny bit more baryons than antibaryons (CP violations have been confirmed experimentally). His idea also suggests that the Universe must be cooling (which means it is expanding), otherwise the reverse processes would have turned matter back into energy.

electron-positron pairs, and the remaining ones gradually annihilated one another, leaving behind the trace of electrons derived from the violation of CP symmetry, which exactly balanced the number of protons. No longer bathed in a sea of energetic electrons and positrons, protons and neutrons were eft alone.

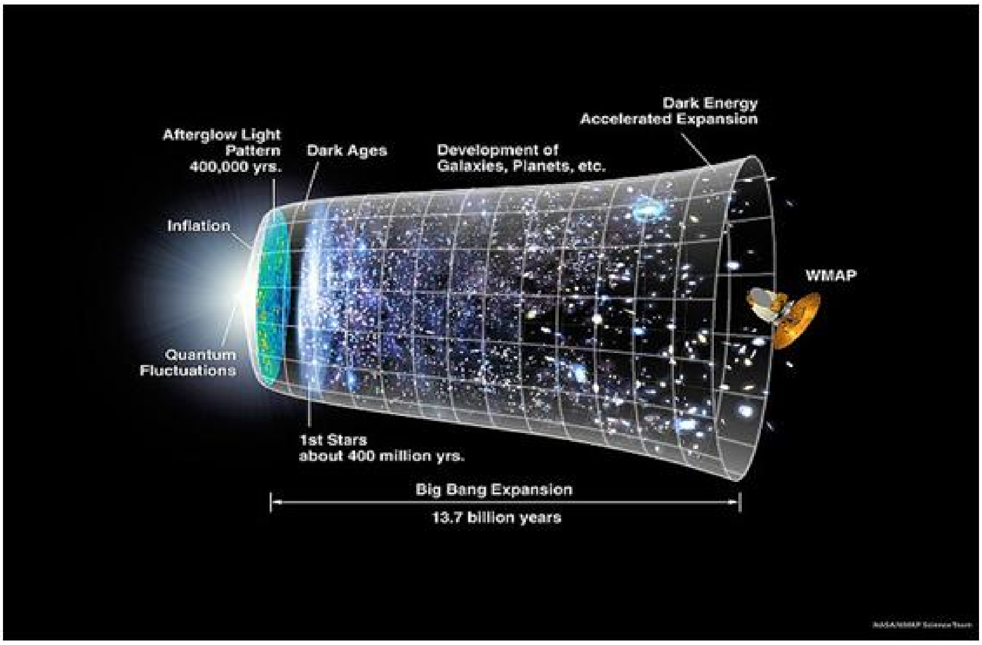


DIAGRAM SHOWING THE MAIN PHASES IN THE EVOLUTION OF THE UNIVERSE: Big Bang 13.7 billion years ago, quickly followed by inflation, then a slower expansion that began accelerating 4 billion years ago.

Credit: NASA/WMAP

Threshold temperature for pair production of protons and neutrons is about 10^{13} K, and the temperature of the Universe had fallen to about 10^{12} K by the time it had reached nuclear density (4×10^{17} kg/cu m), about 10^{-4}s after Big Bang. Lighter particles like electrons, positrons (antiparticle of electron) and neutrinos were made from the available energy. Thus, in this stage, the Universe of nuclear density consisted mainly of photons and electron-positron pairs, laced with about one proton or neutron for every billion photons. At temperatures above 10^{10} K, numbers of neutrons and protons were roughly equal due to the following reactions involving neutrinos:

${}_{0}n^{1} + v_{e} \rightarrow {}_{+1}p^{1} + {}_{-1}e^{0}$
${}_{+1}p^{1} + {}_{-1}e^{0} \rightarrow {}_{0}n^{1} + v_{e}$(neutrino)

Above 10^{10} K, both reactions proceed with equal ease, but as temperature dropped below 10^{10} K, when the Universe was just above a second old, the fact that the mass of a neutron (1.675×10^{-27} kg or 939.56 MeV/c^2) is a little more than that of a proton (1.6725×10^{-27} kg or 938.27 MeV/c^2) became important. With increasingly lesser energy available, it became difficult to make up the mass difference when an electron hit a proton, so the backward reaction (the second reaction mentioned above) became less effective. About a second after the beginning, neutron-proton ratio had dropped to 1:3. The neutron might have disappeared entirely, but below 10^{10} K the influence of neutrinos became less effective. By 13.8 seconds after the beginning, when temperature had fallen to 3×10^{9} K, 17% of the baryons were still in the form of neutrons. At this temperature there was no longer enough energy to make

A lone proton is very stable and long-lived, but a lone neutron is unstable and decays as:

${}_{0}n^{1} \rightarrow {}_{+1}p^{1} + {}_{-1}e^{0} + \bar{\upsilon}_{e}$ (antineutrino)

with a half-life of 10.3 minutes. But long before the Universe was 10.3 minutes old, the surviving neutrons were locked up in the atomic nuclei where they are stable. Apart from proton which is the nucleus of hydrogen atom, the simplest atomic nucleus was deuterium (${}_{1}H^{2}$) consisting of a proton and a neutron bound together by strong force, formed when the Universe was about 100 seconds old. The process of Big Bang nucleosynthesis continued as temperature fell, when deuterons interacted with neutrons, protons and other deuterons to make heavier nuclei –

${}_{0}n^{1} + {}_{1}H^{2} \rightarrow {}_{1}H^{3}$ (tritium)
${}_{1}H^{3} + {}_{1}H^{1} \rightarrow {}_{2}He^{4}$ (helium-4)
${}_{1}H^{1} + {}_{1}H^{2} \rightarrow {}_{2}He^{3}$ (helium-3)

As He-4 is very stable, most of the available neutrons were locked up in the He-4 nuclei, although traces of deuterium, tritium, He-3 and lithium-7 (${}_{3}Li^{7}$) were left over. However no heavier elements were synthesized because the temperature of the Universe fell below 6000 K, so nuclei could not be fused in more complex ways. By this time the impact of photons became too weak to break the bonds of electromagnetic forces holding nuclei and electrons together; and all the nuclei and electrons got locked up in electrically neutral atoms. With no more free electrons to obstruct them, photons were able to stream through space largely uninterrupted, Universe became transparent to radiation, and matter dominated over radiation for the first time. This was 380,000 years after the Big Bang. The flash of primordial light that was reflected from the free electrons just before they combined with protons is the cosmic microwave background glow (detected in 1971). After more than 13 billion years of expansion, this light has cooled down with maximum intensity at radio wavelengths (7cm).

Nucleosynthesis inside stars

Stars are the most abundant large structures in the Universe. They are formed from interstellar clouds of dust and gas (mainly hydrogen) in space. The low temperature (about 20 K) and high densities of these clouds allow the force of gravitation to overcome thermal pressure, and gravitational collapse of these clouds starts. As the cloud collapses, it begins to rotate at progressively greater speed, forming a roughly spherical protostar with a protostellar disc spinning around it. Its core is not yet hot enough for hydrogen nuclei to fuse. As the protostar rotates, it generates a strong magnetic field which in turn generates a protostellar 'wind' – an outward flow of gases and particles into space. This wind clears away the dust around the protostar and it comes out of the cloud. Progressive contraction of the protostar releases energy that heats up the dust and gases, which start to glow, emitting weak infrared light. As temperature of the gases increases, the cloud starts emitting visible light – it is now a young star.

As the interior of the collapsing sphere gets hotter and denser, the gas molecules break up into atoms, then atoms lose their electrons and become ions. At this stage the cloud transforms into electrically charged hot plasma composed of equal number of freely moving positively charged ions and negatively charged electrons. Finally when the core reaches a temperature of 15×106 K, the hydrogen nuclei begin to fuse and produce helium by the proton-proton chain –

${}_1H^1 + {}_1H^1 \rightarrow {}_1H^2 + {}_{+1}e^0$ (positron) + ν (neutrino)

${}_1H^2 + {}_1H^1 \rightarrow {}_2He^3 + \gamma$ (photon)

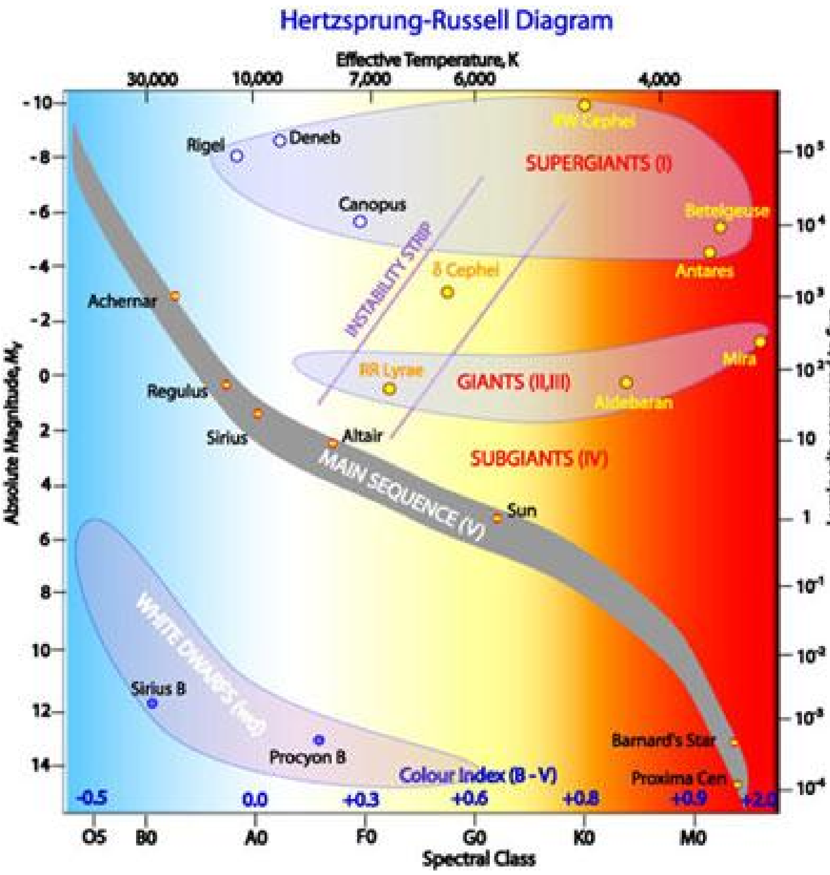
${}_2He^3 + {}_2He^3 \rightarrow {}_2He^4 + {}_1H^1 + {}_1H^1 + E$ (energy)

The mass of a helium nucleus is 0.7% less than that of 4 protons; this 'lost' mass, rather the lost 'rest energy', is transformed into energy as suggested by Einstein's mass-energy equivalence relation E=mc2.

This energy liberated in the interior of the young star creates a pressure that counterbalances gravitation, so the star ceases to collapse and stabilizes to a main sequence star.

Different Types of Stars and Associated Thermonuclear Reactions

All the characteristics of a star (surface temperature, intrinsic luminosity, diameter, lifetime and lifecycle) are determined by its mass. Greater the mass of a star, greater is the effect of gravity and higher the pressure and temperature in the core of the star.



HERTZSPRUNG-RUSSELL DIAGRAM for main sequence stars, in which LUMINOSITY is plotted against SURFACE TEMPERATURE in kelvin. Luminosity of the Sun is 1 and its surface temperature is about 6000 K. The red giants and supergiants and the white dwarfs have moved out of the main sequence

Hence, more intense is the thermonuclear fusion, which gives rise to a number of elements, and which, in turn, raises its surface temperature and luminosity. Therefore, the temperature and luminosity of a star can provide us with information about reactions occurring inside it.

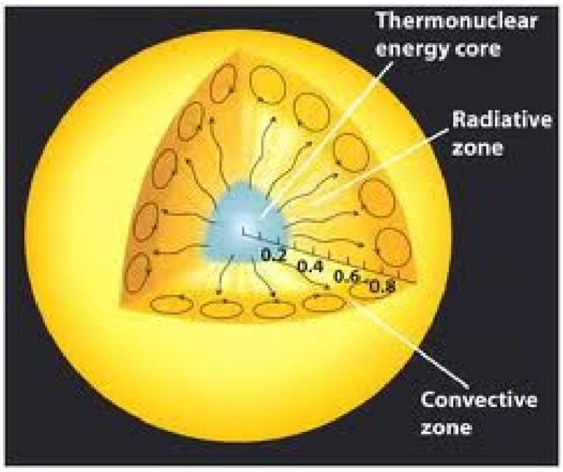
The following diagram classifies stars depending on their luminosity and surface temperature. Taking the mass of the Sun (2×10^{30} Kg) as reference, there can be 3 types of main sequence stars depending on mass –

Stars of very low mass (more than 0.075 to less than 0.8 solar mass)

In such stars, called red dwarfs, heat from fusion of hydrogen nuclei into helium in the core diffuses mainly by convection, that is, by the movement of gases that are heated by coming in contact with the core and as a result, becoming less dense, rising up to the surface where they cool down, then plunging again towards the core to repeat the cycle. These movements continuously supply hydrogen to the core, sustaining the nuclear fusion taking place there. When all the hydrogen is consumed, the star is transformed into a ball of inert helium gas. The main reaction is the proton-proton chain –

${}_1H^1 + {}_1H^1 \rightarrow {}_1H^2 + {}_{+1}e^0$ (positron) + ν (neutrino)
${}_1H^2 + {}_1H^1 \rightarrow {}_2He^3 + \gamma$ (photon)
${}_2He^3 + {}_2He^3 \rightarrow {}_2He^4 + {}_1H^1 + {}_1H^1$ + E (energy)

Such stars are by far the most common type of star at least in the Milky Way galaxy. Proxima Centauri, the nearest star to the sun, is a red dwarf.



Convection and radiation zones in a medium mass main sequence star

Stars of intermediate mass (0.8 to less than 8 solar masses)

Life of such a star can be divided into the following phases –

i) **Main sequence**: Such stars spend billions of years fusing hydrogen into helium via the proton-proton chain –

${}_1H^1 + {}_1H^1 \rightarrow {}_1H^2 + {}_{+1}e^0$ (positron) + ν (neutrino)
${}_1H^2 + {}_1H^1 \rightarrow {}_2He^3 + \gamma$ (light)
${}_2He^3 + {}_2He^3 \rightarrow {}_2He^4 + {}_1H^1 + {}_1H^1$ + E (energy)

Energy released in this fusion in the core flows by radiation to the outer regions. There is usually a convection zone in the outer layer whose activity determines whether the star will have some activity like a sunspot cycle.

Over its lifetime the star consumes its core hydrogen and converts it into helium. The core shrinks and heats up gradually and the star gradually becomes more luminous. Eventually nuclear fusion exhausts all the core hydrogen.

ii) **Red giant**: When hydrogen fusion can no longer happen in the core, gravity begins to collapse the core. This raises the temperature of the core, which allows hydrogen fusion to proceed in a spherical shell surrounding it. Energy released in this process forces the outer layers of the stellar atmosphere to expand - the star becomes a red giant, with surface temperatures 5000 K or lower, and luminosity increases by a factor of 1000-10000. For a star of mass like the Sun, this expansion takes a billion years and the star's radius increases 100 times. Eventually, when the core becomes denser and reaches a temperature of 10^8 K, He-4 nuclei begin to fuse into carbon nuclei by the triple alpha process –

${}_2He^4 + {}_2He^4 \rightarrow {}_4Be^8$ – 0.092 MeV
${}_4Be^8 + {}_2He^4 \rightarrow {}_6C^{12} + 2\gamma$ (+7.367 MeV)

As a side reaction, some oxygen is also produced by the reaction –

${}_6C^{12} + {}_2He^4 \rightarrow {}_8O^{16} + \gamma$ (+7.162 MeV)

He-4 fusion heats the core rapidly and a 'helium flash' takes place, causing the core to expand. This lowers core temperature and reduces the total energy output; then the outer layers contract and the star's temperature increases a bit. After about 100 million years, the star fuses all its core helium into C-12. Then a helium fusion shell forms around the core, and hydrogen fusion shell remains around that. Then the star again becomes a red giant and remains like that for a few million years with its outer layers continuing to expand. Well-known examples of red giants are Aldebaran in the constellation Taurus, Arcturus in the constellation Boötes and Gamma Crucis in the constellation Crux. These are some of the brightest stars in the night sky.

iv) **White dwarf**: Eventually the red giant becomes so large that gravity can no longer contain its outer layers and the star ejects these layers into space. The remaining carbon core is very hot and emits ultraviolet radiation that ionizes the gas in the expanding shell and makes it glow brightly. This glowing gas is called a planetary nebula. The carbon core initially has a temperature of about 10^5 K, at which fusion of carbon cannot take place, so nucleosynthesis stops. As a result there is no thermonuclear energy to support the outer layers against gravity, and after these layers are shed as planetary nebula, the carbon-oxygen remnant becomes a white dwarf with about 0.17-1.4 solar mass.

Stars of high mass (more than 8 solar masses)

More massive a star, faster are the phases of its life and shorter is its lifetime. The life of such a star can be divided into the following main phases:

i) **Main sequence**: Depending on mass, such stars spend some hundred thousand to some millions of years fusing hydrogen into helium via the proton-proton chain. As the core temperatures are 17×10^6 K or higher, the major process of helium production is the catalytic CNO cycle that is triggered by the small amount of C-12 produced in the star –

$${}_{6}C^{12} + {}_{1}H^{1} \rightarrow {}_{7}N^{13} + \gamma \text{ (+1.95 MeV)}$$
$${}_{7}N^{13} \rightarrow {}_{6}C^{13} + {}_{+1}e^{0} + \nu_e + 1.20 \text{ MeV}$$
$${}_{6}C^{13} + {}_{1}H^{1} \rightarrow {}_{7}N^{14} + \gamma \text{ (+7.54 MeV)}$$
$${}_{7}N^{14} + {}_{1}H^{1} \rightarrow {}_{8}O^{15} + \gamma \text{ (+7.35 MeV)}$$
$${}_{8}O^{15} \rightarrow {}_{7}N^{15} + {}_{+1}e^{0} + \nu_e + 1.73 \text{ MeV}$$
$${}_{7}N^{15} + {}_{1}H^{1} \rightarrow {}_{6}C^{12} + {}_{2}He^{4} + 4.96 \text{ MeV}$$

Thus in this process, 4 protons fuse to form one He-4 nucleus but energy release is more than that in the proton-proton chain, so larger main sequence stars are brighter than smaller ones.
ii) **Supergiant**: When all the core hydrogen is consumed, the outer shell hydrogen takes part in the fusion by the proton-proton chain, and the star becomes a supergiant. When the outer shell hydrogen is consumed the star shrinks a little under gravity. This raises its core temperature to 10^8 K, and core He-4 nuclei begin to fuse to form C-12 by the triple alpha process –

$${}_{2}He^{4} + {}_{2}He^{4} \rightarrow {}_{4}Be^{8} - 0.092 \text{ MeV}$$
$${}_{4}Be^{8} + {}_{2}He^{4} \rightarrow {}_{6}C^{12} + 2\gamma \text{ (+7.367 MeV)}$$

When core He-4 is exhausted, helium fusion takes place in the outer shells and the star again enters the supergiant phase. When this phase almost ends, carbon fusion sets in to produce O-16 by the reaction –

$${}_{6}C^{12} + {}_{2}He^{4} \rightarrow {}_{8}O^{16} + \gamma \text{ (+7.16 MeV)}$$

This stabilizes the star as long as the concentration of C-12 is high; after that the processes of contraction, heating and triggering of a new stages of fusion repeats, each stage lasting for a shorter time than the previous one. By the addition of one alpha particle at each step, a large number of elements heavier than oxygen are produced –

$${}_{8}O^{16} + {}_{2}He^{4} \rightarrow {}_{10}Ne^{20} + \gamma \text{ (+4.73 MeV)}$$
$${}_{10}Ne^{20} + {}_{2}He^{4} \rightarrow {}_{12}Mg^{24} + \gamma \text{ (+9.32 MeV)}$$
$${}_{12}Mg^{24} + {}_{2}He^{4} \rightarrow {}_{14}Si^{28} + \gamma \text{ (+9.98 MeV)}$$

Nuclei with masses divisible by 4 interact with particles from their surroundings, absorbing the odd proton and emitting the odd positron to produce F-19 and Na-23 are in modest quantities. By this time the core becomes so hot (3×10^8 K) and dense that a single Si-28 nucleus may photodisintegrate to release 7 He-4 nuclei. One or more of these alpha particles may be absorbed by a single Si-8 nucleus to form S-32, Cl-36, Ar-36, and even Ni-56 by capturing all 7 alpha particles, in a single step –

$${}_{14}Si^{28} + {}_{2}He^{4} \rightarrow {}_{16}S^{32} + \gamma$$
$${}_{14}Si^{28} + {}_{2}He^{4} \rightarrow {}_{17}Cl^{36} + {}_{+1}e^{0} + \nu_e$$
$${}_{16}S^{32} + {}_{2}He^{4} \rightarrow {}_{18}Ar^{36} + \gamma$$
$${}_{18}Ar^{36} + {}_{2}He^{4} \rightarrow {}_{20}Ca^{40} + \gamma$$
$${}_{20}Ca^{40} + {}_{2}He^{4} \rightarrow {}_{22}Ti^{44} + \gamma$$
$${}_{22}Ti^{44} + {}_{2}He^{4} \rightarrow {}_{24}Cr^{48} + \gamma$$
$${}_{24}Cr^{48} + {}_{2}He^{4} \rightarrow {}_{26}Fe^{52} + \gamma$$
$${}_{26}Fe^{52} + {}_{2}He^{4} \rightarrow {}_{28}Ni^{56} + \gamma$$

But Ni-56 is unstable, and quickly disintegrates to stable Fe-56 by the following way –

$${}_{28}Ni^{56} \rightarrow {}_{27}Co^{57} + {}_{+1}e^{0}$$
$${}_{27}Co^{57} \rightarrow {}_{26}Fe^{57} + {}_{+1}e^{0}$$

Fusion of lighter nuclei to form heavier ones stops here because formation of elements heavier than Fe consumes energy rather than release it. An old star may have a series of shells surrounding its iron core, with heavier elements near the core and lighter elements nearer the surface, with an outermost shell of non-burning hydrogen.

iii) **Supernova**: After formation of Fe-56, since energy is no longer produced in the core, the internal pressure drops, and the outer layers of the star collapse under gravity, compressing the core to the point where its protons and electrons are squeezed into close contact and their de Broglie waves overlap. The core, which exceeds Chandrasekhar limit (1.44 solar mass), responds with an explosive release of energy. This explosion, called supernova, sends a titanic shock wave throughout the collapsing star and blows off several solar masses of hot material which expands rapidly at 5000-20000 Km/s, brightening the supernova to about 5×10^9 times the brightness of the sun.

The shock wave squeezes and heats the ejected matter so much that nuclear fusion reactions are triggered and many elements heavier than Fe-56, like zinc (Zn), lead (Pb), tin (Sn), silver (Ag), gold (Au), mercury (Hg), uranium (U), etc. are formed. These debris are incorporated into the next generation of stars, planets, and in living organisms too. Indeed, the late American astronomer Carl Sagan rightly said “We are made of stardust”. The iron core left behind after the supernova explosion goes on contracting under gravity till electrons and protons are pushed closer together than quantum limit allows, and they combine to form neutrons with release of neutrinos –

$${}_{+1}p^{1} + {}_{-1}e^{0} \rightarrow {}_{0}n^{1} + \nu$$

The core finally stabilizes as a ball of neutrons of mass more than 1.44 to less than 3 solar masses, with average density of 3.7×10^{17}-5.9×10^{17} Kg/m^3. If the mass of the iron core exceeds 3 solar masses, then it collapses under its own gravitational force and forms a black hole.

Brown dwarfs: These are protostars with mass less than 0.075 solar mass. They never reach the 10^7 K temperature required for efficient fusion of hydrogen to helium. As a result such stars do not play any role in nucleosynthesis.

Conclusions

Thus, theories and observations have confirmed that all the elements that constitute matter, at least visible matter, have been formed by processes of nucleosynthesis – both Big Bang and stellar. Hydrogen, the lightest element, its isotopes, some amount of helium, both He-3 and He-4, and little amount of lithium (Li-7) were formed in Big Bang nucleosynthesis. All the heavier elements, including carbon, oxygen and nitrogen which are very important for growth and development of living organisms, all the metallic elements and also radioactive elements like uranium were formed by thermonuclear reactions inside stars. Stellar nucleosynthesis is still going on, and will continue as long as new stars are formed in the galaxies.

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