Uzbek Journal of Physics

Vol. 12(№4-6) 2010 PP.262-268

COSMOLOGY AND THE ORIGIN OF NUCLEI

Jayant V. Narlikar

Inter-University Centre for Astronomy and Astrophysics, Pune, India

The problem of explaining the origin of all the chemical elements found in the universe is a central problem in astrophysics. In the 1940s Fred Hoyle suggested that they were cooked inside stars, starting with nucleosynthesis of neutrons and protons. In the same decade George Gamow argued that in a hot big bang universe in the first few minutes, the ambient conditions were suitable for formation of nuclei. This paper will review the progress of both these ideas and show that a reasonable compromise between these ideas can be found today.

Let me begin by asking the question: "What do we know about the origin of nuclei in the universe?" The chemist may argue that it is his subject that will provide the answer. The physicist will overrule him, saying that the topic belongs to nuclear physics. But in the end, it will be the astronomer who will win the debate by stating that the location of origin of nuclei lies in the vast universe studied in astronomy.

In this talk I will review the current ideas on how the atomic nuclei were formed in the universe. To begin with let me say that there were two important developments in the 1940s, one initiated by George Gamow and the other by Fred Hoyle. George Gamow argued that the expanding universe was much denser and hotter in the past and that in the first few moments, say within three minutes of its origin, the universe was so hot that it acted like a thermonuclear reactor and synthesized all nuclei by joining protons to neutrons. Fred Hoyle used the stars as the basic reactors, each star possessing a core hot enough to carry out thermonuclear fusion of nuclei. I will elaborate on both these approaches beginning with the stellar approach.

I. WHY DO STARS SHINE?

Perhaps, one of the earliest questions that man may have ever asked about nature is: "What makes the Sun shine?" The Sun had to have a source of energy. Using the inverse square law of illumination to estimate the output of energy from the Sun from the amount received here at a distance of nearly 150 million kilometers, we get the answer as 4×10^{33} ergs per second. Assuming that the Sun has been around for approximately 5 billion years, which is the estimated age of the Solar System, and its luminosity has been more or less constant over this period, the total energy so far emitted by the Sun comes out to be approximately 6×10^{50} ergs. What energy reservoir does the Sun draw upon?

Two leading physicists of the 19th century, Lord Kelvin and Baron von Helmholtz, had independently worked out that if the Sun was to derive its energy from a slow gravitational contraction, then the energy so available would keep the Sun shining at its present rate for 20 million years. By the beginning of the 20th century it became clear that this reservoir was grossly inadequate. In other words, the gravitational energy reservoir of the Sun was only about 0.4 % of the required value just estimated.

It was this inadequacy of the reservoir known to classical physics that posed a challenge to the astrophysicists in the beginning of this century. In the early 1920s, the Cambridge mathematician and astronomer Arthur Stanley Eddington had worked out the internal structure of the Sun, based on a hot gas-cum-radiation model that supported the solar sphere in equilibrium through an exact balance between its self-gravity and internal pressures. Using the laws of statistical mechanics, Eddington estimated the central temperature of the Sun to be more than 10 million degrees.

In the Eddington model, the surface temperature of a star may be a few thousand degrees (that of the Sun is about 5700 K), and therefore a temperature gradient is set up within the star leading to flow of heat from the central core to the outer regions. In the Sun, the flow of heat is predominantly through radiation in the inner parts and through convection in the outer parts. However, to sustain the model, a source of energy was required at the centre, to supply the heat flowing outwards and to maintain the central temperature at the high value deduced from the model.

It was at this stage that Eddington made the bold conjecture that this temperature was high enough to cause a fusion reaction to take place a reaction in which the four nuclei of hydrogen would combine to form one nucleus of helium. In this process, because of the binding energy of helium, Eddington could estimate that there was a mass deficit in this reaction that would be made up by the release of energy as per the celebrated Einstein equation $E = Mc^2$. This, according to him, was the energy that gives the Sun its luminosity.

This prediction was, however, resisted by the atomic physicists of his time. They argued that to bring the positively charged hydrogen nuclei together, the Coulomb barrier has to be overcome and this would require the nuclei to approach each other with energy far greater than the thermal energy at the solar centre. In other words, hot though the centre was, it was not hot enough. At this objection, Eddington retorted: "We do not argue with the critic who urges that the stars are not hot enough for the process, we tell him to go and find a hotter place."

Polemics apart, here was a controversy at the threshold of the frontier between physics and astronomy. Astronomers needed the reaction to work so that their problem of solar energy source would be resolved. The atomic physicists were unconvinced, partly because their knowledge of the nuclear force, in the 1920s was rudimentary. In the end, the issue was resolved in the following decade. In 1938, Hans Bethe published a paper giving the complete solar model including the power generation by nuclear fusion. For, by then the nature of the nuclear force was much better understood. Its attractive nature and strength exceeding the Coulomb interaction over a short range allowed the hydrogen nuclei at Eddington's calculated central temperatures to come together and get fused.

II. THE ORIGIN OF CARBON

I next move on towards another important issue highlighted by another basic question: "What will happen to the Sun after it has exhausted its hydrogen fuel?"

The example of the Sun just discussed shows that the solar reactor can make helium out of hydrogen. Indeed, as we found in the case of the Sun, the production of helium ion the central core of a hydrogen star will go on till all hydrogen within a certain radius is converted to helium. Beyond that radius, the ambient temperature would have fallen below threshold for fusion, and thus the star would have hydrogen in the outer envelope.

Will the process of stellar radiation come to an end, now that the fuel at the centre is exhausted? In short, will the star cease to shine?

There are two reasons why one would not consider the story to have ended here. Think of making nuclei heavier than helium, by further fusion. Can we make the whole gamut of nuclei in stars by a ladder like procedure in which we slowly mount the atomic mass ladder by nuclear fusion? Secondly, the astronomers can readily identify the stars which are currently producing helium from hydrogen. The luminosity of a star can be calculated and related to its mass by following up on the Bethe model. Stars showing this mass-luminosity relation are called the *Main Sequence Stars*. These, however, do not exhaust the whole range of stars observed in the sky. There are others, which do not conform to this relation. In particular, there are the *red giant stars*, which are reddish but far more luminous and larger in size than the main sequence stars. How can the structure of these stars be understood?

Theoretical nuclear physics held out long term hope and short-term difficulties. The hope was that as one progressed towards larger and larger nuclei, the trend was towards greater binding energy, until one hit the iron group of elements, that is the Fe^{56}, Co^{56} and Ni^{56} group. This promised further reservoir of energy for the star, beyond the main sequence, provided it managed to ascend the ladder through fusion reactions. Perhaps these other stars were those in which such reactions were taking place. The short-term problems were to find a sequence of nuclear reactions, which would take the fusion process beyond He^4. The addition of hydrogen to helium would produce a nucleus of mass 5 while two helium nuclei would produce one of mass 8. The trouble was that both these nuclei are unstable. Thus it is like trying to climb a ladder in which the next two rungs are weak and break whenever one steps on them!

In the early 1950s the situation had reached a stalemate; the stellar evolution beyond the main sequence remained stuck on how to continue the nuclear ladder. There was a suggestion by Ed. Saltpeter that instead of a two-body reaction, perhaps the route lay via a *three-body interaction,* in which three helium nuclei combine to produce C^{12}. But a three-body encounter is very rare and the chance of this process delivering any energy as well as the carbon nuclei was very very rare.

It was at this stage that another breakthrough emerged through an interaction between an astrophysicist and a group of nuclear physicists. Fred Hoyle, the astrophysicist, had long felt that the nucleosynthesis process must go on beyond the making of He^4 for the simple reason that we human beings exist! To explain this cryptic remark further, think of us as made of chemical elements, which include carbon. Unless carbon was produced in the universe somehow, we could not exist. So some way had to be found to make C^{12} in stars. And Hoyle found a way that circumvented the problem of low probability of a three-body collision.

Hoyle's approach was through a *resonant nuclear reaction.* In such a reaction, the energy of the product nucleus matches the total energy of the participating nuclei. This makes the reaction proceed very fast, thus compensating for its low probability. In this case, however, the matching required the C^{12} nucleus to have a slightly higher energy than actually found. So Hoyle argued that *there must exist an excited state of this nucleus with the requisite energy*. He urged the nuclear physicists to look for such an excited state. In particular he approached the Caltech nuclear physicists Ward Whaling and Willy Fowler at the Kellogg Radiation Laboratory to make the search.

Years later, Willy Fowler recalled that their first reaction was very skeptical, since they, being hard core laboratory physicists, found Hoyle's astrophysical reasoning rather far fetched. Still they did performed the experiment and found an excited state of C^{12} exactly at the expected energy level.

In retrospect, I find this the finest example of anthropic reasoning: to expect a physical result to be valid purely because our existence as human beings is vitally linked with it. Had there been no such excited state, the process for making carbon in the universe would not be possible; *ergo,* the human beings should not exist!

The solution to the problem of nuclear fusion of helium into carbon opened out further avenues for the star to shine. For, the reaction is exothermic and the energy generated in it is available to the star for radiation. Only its internal structure will have undergone drastic changes so as to adjust to the new situation. Without getting into those details, I will simply state what those changes are. The core will have contracted and heated to at least ten times its original temperature when the nuclear reaction of helium to carbon takes place. The envelope on the other hand blows up under the pressures created by the new generation of heat. So much so, that the star grows in size more than a hundredfold. In the case of the Sun, the growth will be such as to make it swallow the Earth! This is when it will have attained the state of a *red giant star*.

Thus we see how the two problems received a simultaneous resolution: the nuclear fusion in stars could continue beyond helium and one could also understand the nature of red giants.

III. THE ORIGIN OF CHEMICAL ELEMENTS

Let me now turn to the fundamental issue of how chemical elements were formed in the universe in the first place. The clue given by the fusion of hydrogen followed by the fusion of helium opened the way to the making of heavier nuclei. The first systematic attack on the problem was by four scientists working together: Margaret Burbidge, an observational astronomer, Geoffrey Burbidge, a theoretical astrophysicist, William Fowler, a nuclear astrophysicist, and Fred Hoyle, another theoretician. They looked at the observational evidence for elements in the form of stellar spectra, the features of various stars, etc., theoretical issues of stellar interiors and the problems of nuclear structure having a bearing on the production of these nuclei in the stellar scenario. Their *magnum opus*, published in the Reviews of Modern Physics in 1957 came to be known as the B^2FH theory and is the basis for all subsequent work on stellar nucleosynthesis [1].

The details of this work are too intricate to describe here. But the general feature is as follows. Following the helium to carbon reaction, there are more leading to formation of oxygen, neon, magnesium, silicon, sulphur, etc., all nuclei with atomic masses increasing in units of 4, because they are formed by successive fusion of He^4. This process is known as the α-process, since the helium nucleus is often called the α-particle. At each stage, after the fuel for a reaction is exhausted, the force of gravitation gains a temporary ascendancy over the thermal and radiation pressures. The stellar core therefore shrinks and heats up, leading to the next fusion reaction. The envelope, on the other hand expands further. It has an onion like structure, with its 'skin' consisting of inner layers of progressively heavier nuclei.

The nuclear binding energy curve tells us that these reactions are all exothermic till the iron group is reached. Thereafter, any further fusion will not provide energy to the star, rather it will extract energy from it. So far as the star is concerned it has by now become gigantic and is also at the end of its state of equilibrium. Something drastic would now happen. The star would explode, ejecting its envelope into space, while its core collapses inward. Such a star is called a supernova and its core may end up as a neutron star or as a black hole.

Of course, there is a less drastic fate in store for a star which is not very massive, say, not more than six times the solar mass. Such a star will slowly eject its outer envelope in small puffs blowing a 'smoke ring'. This is seen as the ring shaped planetary nebula surrounding the star. The star thus sheds mass and usually ends up as a white dwarf. The radius of a white dwarf is about a hundredth of the radius of a main sequence star.

In either case, we have the chemical elements manufactured in the star thrown out into the interstellar space. What is the mass distribution of different elements thrown out of stars? How does it compare with the observed abundances of these elements in the universe? These questions can be answered by carrying out thermodynamic calculations in the pre-explosion phase of the star, when different nuclear reactions are in thermal equilibrium at a very high temperature of several billion degrees. Known as the *e*-process, this equilibrium calculation predicts abundances for different nuclei, with a peak at the iron group.

There are, however, other processes, which help build more massive nuclei, although they do not provide energy to the star. With a large number of free neutrons and protons, the process leads to addition of neutrons to existing nuclei, which subsequently decay to protons by beta decay. Known as the *s*-process (slow process), this will generate nuclei of higher atomic numbers, provided the process adding neutrons is *slower* than the beta-decay rate. If the process adding neutrons is faster then neutron-rich isotopes will form. This is the case known as the *r*-process (rapid process).

The agreement between theory and observations of abundances for most elements is very good indeed, thus justifying the stellar nucleosynthesis scenario.

IV. PRIMORDIAL NUCLEOSYNTHESIS

When describing the agreement between theory and observation I used the adjective 'most' to qualify the elements whose theoretical abundances match the observed ones. Are there divergences between theory and observation for a few elements? The answer is 'Yes', for a few light nuclei, including helium and deuterium. If we estimate the stellar hydrogen burning activity in the Galaxy, there is not enough of it to produce the observed helium. Whereas the observed quantity of helium is nearly 25 % by mass, the stellar contribution is only a tenth of it. This is a major discrepancy and warns us that something is missing in our overall picture. Likewise, the observed mass fraction of deuterium is only about 10^{-5}, but even that amount cannot be produced in stars. So where is the missing source of these light nuclei?

The answer may be found in the ideas of George Gamow, who in the mid-1940s argued that in the big bang universe, in the early moments soon after the creation of the universe, its temperature passed through several billion degrees. In the big bang theory the universe expands after creation and cools down as its density falls. Gamow [2] argued that during the first few minutes after creation the temperature and density were suitable to form *all* chemical nuclei through thermonuclear fusion of neutrons and protons.

However, Gamow's conclusions were not borne out by detailed studies and the interest in the primordial scenario gradually subsided.

It was revived, however, when it was found that the scenario can deliver the light nuclei, especially deuterium and helium in the right amounts. As we noticed earlier, this is precisely the region where the stellar scenario proves inadequate. The agreement between theory and observations, however, turns out to depend crucially on the coefficient of proportionality K in the nucleon density-temperature relationship

$$\rho = KT^3.$$

To get the right answer for the helium and deuterium nuclei, however, one needs to fine tune the value of K. This takes away some credit of the predictive power of the theory.

Gamow's younger colleagues Ralph Alpher and Robert Herman used the theory to make an important prediction, namely that the relic of the hot era today will be a cool radiation background with thermal spectrum and it will be distributed isotropically [3]. This prediction was borne out when, in 1965, an isotropic background of radiation with a thermodynamic temperature of around 3 K was found by Penzias and Wilson [4]. Further examination of the radiation in 1990 by the COBE satellite showed a very accurate thermal spectrum for this background [5]. Thus this background can be easily explained as the relic of the hot era in the early universe.

There is one additional constraint that this interpretation imposes on cosmology. In order that the deuterium abundance matches observations, the nucleon density ρ must not exceed a certain well defined limit. Present indications are that the universe has considerable amount of dark matter. If all of it were taken into consideration for ρ, that limit would be exceeded and there would be no deuterium formed. Thus to sustain the scenario, it becomes necessary to postulate that the dark matter is mostly *non-baryonic*.

V. THE QUASI-STEADY STATE COSMOLOGY

I now come to an alternative cosmology which was motivated by the Armenian astrophysicist Victor Ambartsunian. He had strongly argued that events like quasars, AGN, radio sources, gamma ray bursts, etc., show evidence for explosive activity in localized form, and they hold the key to the basic problem of origin of matter. In recent times Fred Hoyle, Geoffrey Burbidge and I have argued that these events are centres of creation of new matter, where there is exchange of energy between the matter and a cosmic scalar field of negative energy and stresses. A cosmological theory based on these creation centres as sources of matter and energy can be developed fully consistent with the law of conservation of matter and energy. For details see [6, 7].

In this cosmology, called the *Quasi-Steady State Cosmology*, the universe expands because of the outward 'push' given by the negative stresses generated by the scalar field, which arises from these creation events. These events may be called *minibangs*, to distinguish them from the 'big bang' of standard cosmology.

There are several unusual features of this new cosmology. I will briefly outline one which has a bearing on today's talk. The theory tells us that the created particle is the so-called *Planck particle*, which has the Planck mass energy of the order of 10^{19} GeV. This particle is short-lived and through a series of high energy processes, it decays into the baryon octet. All eight members of the octet are at relativistic energies and in thermodynamic equilibrium, with numerical equipartition. Of these 6 members are short-lived, and decay to protons, the stablest member of the octet. The remaining two, viz. The neutron and proton combine into helium nuclei. Thus two out of eight particles lead to helium nuclei while the rest go into hydrogen. In this way it is easy to see why the universe has 25 % of the matter in the form of helium and the rest in the form of hydrogen. The first paper on this cosmology [6] contains the details of this calculation.

VI. FUTURE OUTLOOK

To conclude, the problem of light nuclei still poses problems. B^{2}FH had worried about the problem of producing deuterium and other light nuclei in stars and not knowing the answer, had called the process the *x-process*. A stellar scenario for producing light nuclei is still to be found. In the absence of one, the process of primordial nucleosynthesis assumes greater significance. However, in that case one needs the hypothesis of nonbaryonic dark matter with density exceeding by 5–6 times the density of normal baryonic matter. The QSSC is offering an alternative scenario, which needs to be worked out further.

For ending this talk I can do no better than recall the apocryphal story when Rutherford at the Cavendish Labs in Cambridge ran into Eddington and asked the latter, how old he thought the universe was. Using the then available cosmological data, Eddington replied "About 2.000 million years". This large number would have impressed any person, scientist or otherwise. But not Rutherford! He produced a rock from his pocket and said: "I have just estimated the age of this rock to be 3.000 million years."

As the radiaoactive age determinations turned out to put significant constraints on the cosmological models, so I expect future inputs from nuclear science to provide useful constraints on our understanding of astronomy and cosmology. Equally strongly, I believe that astronomical inputs will help widen the horizons of nuclear science.

REFERENCES

1. E.M. Burbidge, G.R. Burbidge, W.A. Fowler, and F. Hoyle, Rev. Mod. Phys. **29**, 547 (1957).
2. G. Gamow, Phys. Rev. **70**, 572 (1946).
3. R.A. Alpher and R.C. Herman, Nature **162**, 774 (1948).
4. A.A. Penzias and R.W. Wilson, Astrophys. J. **142**, 419 (1965).
5. J.C. Mather *et al.*, Astrophys. J. **354**, L37 (1990).
6. F. Hoyle, G. Burbidge, and J.V. Narlikar, Astrophys. J. **410**, 437 (1993).
7. F. Hoyle, G. Burbidge, and J.V. Narlikar. A Different Approach to Cosmology (Cambridge, 2000).