How a consideration of the fundamental physical forces and what is known about the structure and history of the universe reveal that the universe is "fine-tuned" for the existence of life.

Abstract

This document presents a series of examples, discoveries and phenomena that reveal how the Universe is "fine-tuned" for the existence of life. 6 different physical constants where identified to be key, including the cosmological constant, λ, strength of binding of atomic nuclei, ε, number of spatial dimensions, D, ratio of current and critical density in the Universe, Ω, the ratio of electrostatic and gravitational force, N, and the size of the entropy irregularity, Q.

1. Introduction

Since 1930s, with the discoveries of particles providing a closer look at their own structure, physicists have been making remarkable contributions into the fundamental structure of matter; including the realisation that everything in the universe is made from a few building blocks, the fundamental particles, which later would be found out to be governed by four fundamental forces[1]:

- Weak force acting between subatomic particles and responsible for the radioactive decay of atoms.
- Electromagnetic force involves the electric force acting between charged particles and the magnetic force acting only between moving charged particles.
- Strong force acts between subatomic particles present in the nucleus of atoms.
- Gravitational force acts between all masses, attracting any two objects with mass.

As observed from the descriptions, each force has a different strength of impact e.g. some may act on particles and other on planets or stars. The different ratios between these strengths influence on the existence of life in the Universe.

2. Gravity and electrostatic forces

One of the physical constants that contribute to the Universe to be fine-tuned is the ratio of the strength of the electrostatic force over the strength of the gravitational force, referred to as N.

Considering the respective equations for the gravitational force (1) and for the electrostatic force (2), two given protons would attract each other gravitationally and repeal each other electrostatically.

$$\boldsymbol{F_{gravitational} = G\frac{m_1 m_2}{R^2}} \quad \textbf{(1)} \qquad\qquad \boldsymbol{F_{electrostatic} = k\frac{e_1 e_2}{R^2}} \quad \textbf{(2)}$$

Where G is Newton's gravitational constant, m refers to the mass of a body, k refers to the Coulomb constant, e to the charge of the particle and R the respective distances.

The mentioned ratio of the strengths of these forces, N, is of the order of 10^{36} and is fine-tuned for the existence of life.

To prove how this ratio is fine-tuned, a different ratio can be considered to observe the consequences of this change. Should N be around 10^{30} instead, gravity would become stronger overcoming the electrical forces and reducing the number of atoms needed to form stars and planets by a factor of 10^9.

As a result, on one hand, gravity would crush all but the smallest animals and, on the other hand, stars would be smaller as they require less atoms what would burn hydrogen, H, sooner and they would be short lived, hence not providing enough time for evolution of life to take place.

Only weaker gravity would contribute to the evolution and formation of complex structures.

3. Early moments of the Universe

It is considered that soon after the "big bang" the universe was formed by hydrogen, H, and helium, He. These two elements formed the first stars which would then generate other elements through fusion up to Fe and heavier elements once the star starts to consume energy and undergoes events such supernovas.

Approximately, 73% of the mass of the visible universe is known to be H while He makes up around 25% and only 2% represents all elements with A (atomic mass number) above 4.[2]

The mass of the ^{4}He nucleus (consisting of 2 protons and 2 neutrons) is 99.3% of the mass of 4 H nuclei, meaning that the fraction ε (the strength of binding of atomic nuclei) equals 0.007, which is the mass converted into energy during this reaction as described by Einstein's equation (3):

$$\boldsymbol{E = mc^2} \qquad (3)$$

and this value of ε is fine-tuned for the existence of life in the universe.

Should ε be **smaller**, e.g. equal to 0.006, then H would be a less efficient fuel making stars have shorter lifetimes. Considering the mechanism used to form He from 4 H atoms:

$$H + H + H + H \Rightarrow He$$

If H is less efficient, it would form a higher amount of deuterium, ^{2}D, instead ($H + H \Rightarrow {}^2D$) which is unstable and in conclusion no formation of stars could take place.

Should ε be **larger**, e.g. equal to 0.008, the Coulomb repulsion could not maintain two protons separated so they would bind to each other, hence there would be no H in the universe meaning no formation of stars.

For heavier elements, the value of ε determines the size of the most bound nucleus and the size of the lightest unstable nucleus which in our Universe correspond to ^{26}Fe and ^{92}U, see Fig. 1:

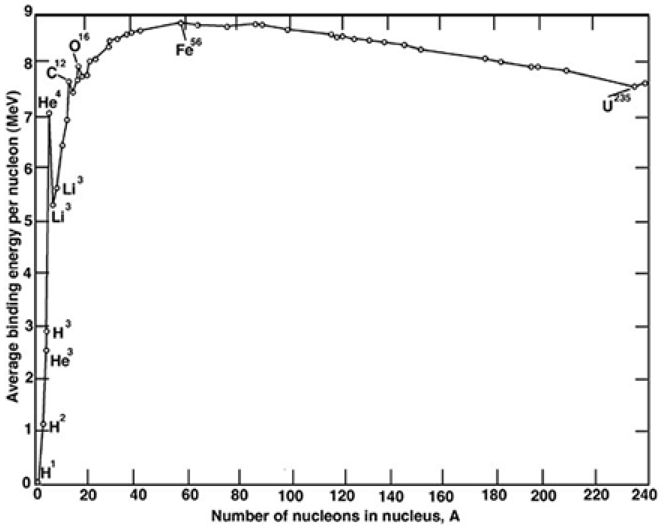

Figure 1: Shows the nuclear binding energy as a function of A. It highlights light elements, the most bound element, Fe56, and the lightest unstable nucleus, U238.

4. Origin and Future of the Universe

It is accepted that the **origin** of the Universe started from the "Big Bang", to this idea contributed the observations of the "Doppler" effect studying how the characteristic spectra of stars and galaxies are shifted towards the red end of the spectrum.

The Doppler effect is the change in frequency of a wave moving closer or further from an observer relatively to the wave source. This phenomenon was observed by the Hubble experiment in the 1920s which measured an increased red shift for distant objects, suggesting an increase in velocity and as a result implying the expansion of the Universe.

Nowadays, we can confirm that the Universe is expanding, but when Einstein introduced the theory of General Relativity in 1917, he proposed the collapse of the Universe (considered static back then) due to gravity and to account for it he introduced the cosmological constant λ.

Einstein predicted the expansion of the Universe considering λ to be a non-zero value, as a result, λ has to be a fine-tuned property or else, if it was too large, galaxies could have never formed.

While the Universe expands, its **future** can only be questioned, it is not yet known if it will expand forever or if gravity will eventually cause its collapse for example. To obtain a glimpse on the future of the Universe it is important to study the density of matter in it.

Approximately 5 atoms per cubic meter were identified as the critical density, any concentration above this parameter would suggest a collapse of the Universe while anything below, as it is our case with an approximate current density of 0.2 atoms per cubic meter, suggests a continuous expansion.

The ratio between these two densities, Ω (actual density/critical density) is another crucial characteristic supporting the fine-tuned structure of the Universe for the existence of life. If Ω is too small the Universe would expand so fast that there would be no time for stars to form and if Ω is too large the Universe would collapse rapidly.

Currently, the ratio Ω is approximately 1, and there is a small range of values around this one that would allow the formation of stars, and hence galaxies, necessary for the evolution of life.

5. Thermodynamics in the Universe

In the Universe, one encounters different and complex regions, some are very hot, others incredibly cold and others present complex events ranging from supernovas to cosmic rays.

From the 2^{nd} law of Thermodynamics: entropy always increases, it suggests that eventually the Universe will become uniform. The reason why this uniformity has not happened yet, 10 to 15 billion years after the creation of the Universe, may be explained by an essential lack of uniformity in the early stages after the Big Bang. Which is maintained as gravity acts more strongly in denser regions contributing to the formation of stars.

The size of this irregularity is represented by Q, the ratio between energy to disperse matter in Universe over the rest energy of matter in Universe, which determines the “texture”.

This is again, a key parameter which must be fine-tuned for the existence of live as it determines the formation of stars, galaxies and other spatial bodies.

The value of Q in our Universe is 10^{-5}, should this value be smaller, e.g. 10^{-6}, then gas would not condense into galaxies and no stars would form. On the other hand, if Q was higher, e.g. 10^{-4}, large amplitude waves would develop in the early Universe, regions bigger that galaxies would collapse into black holes and star-star interactions would disrupt any planetary systems.

6. A 3 Dimensional Universe

Ours is a Universe with 3 spatial dimensions, 3D, which allows for planets to adopt stable orbits from the combination of gravitational attraction and the centrifugal force.

This is the fine-tuned spatial dimension needed for the existence of life since a 2D Universe would have no space for life to develop and in a 4D Universe there would be no stable orbits.

7. Conclusion

As we can see from this document, there are a series of key properties that must be fine-tuned for the existence of life in the Universe. These are:

- The ratio of electrostatic and gravitational force, N, with a value of 1036.

- The strength of binding of atomic nuclei, ε, with a value of 0.007.

- The density of the Universe over the critical density, Ω, with a value of approximately 1.

- The cosmological constant, λ, with a non-zero value and not too large for galaxies to form.

- The ratio between energy to disperse matter over the rest energy of matter in Universe, Q, identified at 10^{-5}.

- And finally, the number of spatial dimensions, D, which in our Universe is 3.

REFERENCES

[1] The standard model. https://home.cern/science/physics/standard-model (accessed 27/05/2020)

[2] Origin Elements. https://www2.lbl.gov/abc/wallchart/chapters/10/0.html (accessed 27/05/2020)