The Universe Fine-Tuned for Life

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Einstein once said,"What really interests me is whether God had any choice in the creation of the world. This is a fundamental question." Compared to this question, all other questions seem trivial. Yes, God would have had many choices if He had wanted to create a barren universe. However, in order to create a universe where life is possible, with the same set of natural laws as ours, it seems that He had only limited choices. According to recent findings, the values of physical constants should have been fine-tuned to make the emergence of life in the universe possible. This was first noticed by Brandon Carter,[1] and the notion was recently popularized in several books.[2,3]

There are many physical constants such as the speed of light c, the gravitational constant G, Planck's constant h, and Boltzmann's constant k. The electron mass, proton mass, and constants determining the magnitudes of electromagnetic interaction, strong interaction, and weak interaction are also regarded as fundamental constants. We do not know why these fundamental constants have the actual values they do. We simply measure them to find their values. For example, we know that the speed of light, which is the maximum speed in the universe, is 300,000 kilometers per second (about 186,000 miles per second). But we do not know why the speed of light should have this particular value.

To explain the theory of relativity and quantum theory to the public, George Gamow wrote a popular book entitled *Mr. Tompkins in Wonderland.*[4] To make the relativistic and quantum effects noticeable in daily activities in *Wonderland*, Gamow set the value of c much smaller than its actual value and the values of G and h much larger than their actual values. For example, a bicyclist in *Wonderland* can see city blocks becoming shorter as he speeds up because his speeds are relativistic (comparable to c). In *Wonderland*, hunters have difficulty shooting game animals because their positions are fuzzy due to quantum uncertainty.

In *Wonderland*, the values of c, G, and h are different from their actual values by enormously large factors. If the value of any one of these physical constants had been set even slightly differently in the beginning of our universe, however, it would be a totally different place. Life could not have emerged in such a universe. In some cases, even if life had emerged, it would not be possible for intelligent life forms to emerge. I explain briefly only simple cases, because most of the arguments for this are highly technical. (To readers who are deeply interested in this subject, I recommend *The Accidental Universe.*)

A brief explanation about the requirements for the life on earth is necessary. All living things on earth are carbon-based. That is, carbon atoms that have four chemical bonding hooks act as chain links to make complex molecules. All living creatures depend directly or indirectly on photosynthesis. Ecosystems teeming with life were recently found on the deep ocean floors where no sunlight can penetrate; these organisms get energy from sulfur compounds emitted from hydrothermal vents. However, scientists conjecture that they feed on the carcasses of great whales on ocean floors (which indirectly depend on photosynthesis for life) while migrating along the sea floor from one thermal vent to another.[5]

Visible light is necessary for photosynthesis. Each photon of infrared light has too low an energy for photosynthesis. On the other hand, each photon of ultraviolet light has too high an energy and is harmful to life. Life forms on other planets may utilize different chemical reactions than photosynthesis on earth, but the energy levels of chemical reactions of complex molecules are similar, being determined by the magnitude of electromagnetic interaction. Therefore, we also expect that life forms on other planets are sustained by visible light.

Can stars other than the sun support life? The intensity of light emitted by a given object depends on its wavelength or frequency. How the intensity changes as a function of frequency is called the *spectrum* of light. The spectrum of light emitted by a star is determined by its surface temperature, which is, in turn, influenced by the energy generation rate in the stellar core and by the surface area. The energy generation rate and the surface area are, in turn, determined by many physical constants such as the magnitudes of strong interaction, gravitational interaction, and electromagnetic interaction, and by the electron mass, the proton mass, and the speed of light.

We can divide main-sequence stars into two classes: blue giants and red dwarfs. Blue giants are massive stars, and energy generated in the core of a blue giant is transported by propagation of light through the stellar interior. Because blue giants emit copious ultraviolet light, they are not suitable for supporting life. Red dwarfs are low-mass stars, and energy generated in the core of a red dwarf is transported mainly by convection. (In a heated pot, energy is transported from the bottom to the top by the convection of water.) Red dwarfs emit mainly infrared light, whose energy is too feeble to support life. In terms of their characteristics, sun-like stars fall between red dwarfs and blue giants: both convection and radiation play roles in transporting energy in such stars, and they emit most of their energy in the visible band, which supports photosynthesis. Because most stars happen to be situated near the boundary between the blue-giant regime and the red-dwarf regime, a slight change in the value of one of the above-mentioned physical constants one way or the other would push all stars to become blue giants or to become red dwarfs. In order to have sun-like stars in the universe which can sustain life, the values of these fundamental constants must be fine-tuned.

Let us consider the consequences in a change of the magnitude of the strong force, as an example. If the magnitude of the strong interaction were slightly higher, the nuclear fusion rates inside stars would be higher than they are now. The star would expand because it would become hotter. The exact change in the stellar structure would have to be investigated by numerical simulations. Because of the increased fusion rate, however, the lifetimes of stars would decrease. Carbon, oxygen, and nitrogen are currently the most abundant chemical elements after hydrogen and helium. However, if the strong interaction were somewhat stronger than it is now, these elements would be less abundant because they would more easily fuse to form heavier elements in the stellar interior. Hence, heavy elements would be more abundant. With carbon less abundant, it is doubtful whether carbon-based life would arise in such a universe.

If the magnitude of strong interaction were greater by only two percent, two protons could combine to form a nucleus made of just two protons. This process, which is governed by strong interaction, would be much more rapid than the deuteron formation, which is governed by weak interaction. In this case, all hydrogen would have been converted to helium during the Big Bang nucleosynthesis. Without hydrogen, stars would shine by combining helium into carbon, and stellar life would be several million years instead of billions of years. Such stellar lifetimes are too short to allow the evolution of life, considering that it took about 800 million years for the earth to produce even the simplest organisms. However, this point is moot; because, without hydrogen, there would be no water, which is also a prerequistie to life.

There are ninety-two natural elements. What determines the number of natural elements? The magnitudes of strong interaction and electromagnetic interaction determine the nuclear structure, and their relative magnitudes determine the number of natural elements. Strong interaction, an attractive force operating between nucleons (protons and neutrons), is a short-range interaction and operates only in distances shorter than 10^{-13} centimeter (one ten-trillionth of one centimeter). On the other hand, electromagnetic interaction is a long-range interaction whose magnitude is inversely proportional to the square of the distance between two electric charges. Therefore, a proton in a heavy nucleus is pushed by electric forces of all other protons while it is pulled only by nearby nucleons in the nucleus. It follows that the electric repulsive force exerted on a proton increases as the number of nucleons in the nucleus increases; however, the attractive force due to strong interaction does not increase after the nucleon number exceeds a certain threshold.

Therefore, very heavy elements are loosely bound and some of them decay naturally. Such elements are called radioactive. If the magnitude of strong interaction were slightly weaker than it actually is, the number of stable elements would be smaller, and iron could be radioactive. Iron is a constituent of human blood cells. It is not clear whether other elements could substitute the function of iron in blood cells. Without heavy elements like calcium, however, big animals requiring bones to maintain their structure would not be able to emerge. If the magnitude of strong interaction were weak enough to make carbon, nitrogen, and oxygen radioactive, then, life would not be possible at all.

A more dramatic change would occur in the nucleosynthesis process if the magnitude of strong interaction were decreased by five percent: a proton and a neutron would not be able to combine to form a deuteron. Deuteron formation is the first step of nuclear synthesis; thus, without the first step, nucleosynthesis would not be possible at all. Without a stellar energy source and heavy chemical elements, no life would be possible.

Let us consider that the magnitude of weak interaction. When the iron core of a massive star exceeds 1.4 times the mass of the sun, it suddenly collapses, and neutrinos emitted from the core push out the stellar envelope to cause a supernova explosion. The neutrino reaction within the stellar envelope is governed by weak interaction. Therefore, if the magnitude of weak interaction were slightly less than it is now, supernova explosions would not be possible. Supernova explosions expel heavy elements synthesized deep inside massive stars into interstellar space. Therefore, without supernova explosions, planets like earth would not have heavy elements, some of which are essential to life. In addition to carbon, nitrogen, and oxygen, sulfur and phosphorus are such elements.[6] Iron in hemoglobin in our blood cells is necessary to carry oxygen; calcium is required for making bones. Therefore, unless the magnitude of the weak force is fine-tuned, life could not emerge in the universe.

If the gravitational constant were larger than its current value, stars would be more tightly bound, with their central temperatures increasing. The increase of the central pressure and the temperature of the sun would increase the nuclear energy generation rate. In order to radiate more energy at the surface, the temperature and/or the area of the surface should increase. However, the stronger gravity would tend to decrease the surface area. Therefore, the surface temperature of the sun would have to be higher than it is now, emitting the bulk of its energy in ultraviolet radiation. The solar-mass stars would be like blue giants, unsuitable for supporting life. With stronger gravity, some low-mass stars would emit most of their energy in visible light, suitable for supporting life. However, such stars would not stay in the main-sequence stage long enough to preside over the long evolutionary history of life.

Similarly, a slight change in the magnitude of the electric force, the speed of light, Planck's constant, or Boltzmann's constant would have dire consequences: the universe would not be able to produce life. A slight change in the mass of the electron would also be disastrous.[*]

Notes and References

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[*] This article is adapted from a section of the book entitled *The Creative Universe and the Creating God* being written by the author.