The Cosmological Constant: an Example of the Extraordinary Fine-tuning of the Universe

Alex MOK

宇宙常數：宇宙的非凡微調的例子

莫榮基

[ABSTRACT] This article explores the cosmological constant problem and its anthropic interpretation.

Introduction

The 2011 Nobel Prize in Physics was awarded to three scientists for "the discovery of the accelerating expansion of the Universe through observations of distant supernovae".[1] The discovery of the increasing rate of cosmic expansion is arguably the greatest milestone in observational cosmology since the 1920s, when American astronomer Edwin Hubble first revealed evidence for the expansion of the universe. The most accepted explanation for the

---

[1] The American astrophysicist Saul Perlmutter received half the prize, with the other half shared between Brian P. Schmidt and Adam G. Riess. "The Nobel Prize in Physics 2011," *Nobelprize.org*, 28 May 2012, <http://www.nobelprize.org/nobel_prizes/physics/laureates/2011/> [2012/05/28].

observed acceleration of cosmic expansion is the non-zero value of the cosmological constant. The idea of the cosmological constant was first proposed by Albert Einstein in 1917, as a modification of his field equations to describe a static universe. Einstein later discarded this idea when it was observed that the universe was actually expanding. However, theoretical predictions for the value of the cosmological constant are substantially larger—by a factor of 10^{120} —than the observed value obtained from measurements by NASA’s Wilkinson Microwave Anisotropy Probe (WMAP). In this article, we will investigate this so-called cosmological constant problem and its implications.

We will begin our discussion with the picture of our universe which has emerged from modern observational cosmology. After introducing the basic cosmology ideas of the Big Bang, we will discuss fine-tuning of the universe for the existence of life. Finally, we will examine the value of the cosmological constant and its significance for a habitable universe.

Our Position in the Universe[2]

Our universe is immensely large, and as stated above, it is expanding at an ever-increasing rate. Therefore, vast scales such as the light-year are used to describe astronomical systems and distances. One light-year (ly) is the distance that light travels in empty space in one year,[3] equivalent to 9.461×10^{12} km. On average,

---

[2] To see illustrations of our position in the universe, the reader may start with “Earth’s location in the universe,” Wikipedia, 19 May 2012, <http://en.wikipedia.org/wiki/Earth%27s_location_in_the_universe> [2012/05/28].

[3] The speed of light in empty space (c) is 3.00×10^{5} km/s. For example, the average distance between the sun and the earth is about 0.0000158 ly (500 light-seconds or 8.3 light-minutes); the distance between the sun and the farthest planet Neptune is about 0.000475 ly (250 light-minutes or 4.2 light-hours).

our moon is about 1.26 light-seconds (equivalent to 380,000 km) away from the surface of the Earth. The nearest star system, Alpha Centauri, is about 4.3 light-years away from the Sun, which is 100 million times greater than the distance between the Earth and the moon. If the distance between Hong Kong and Shanghai were to represent the distance between the Sun and Alpha Centauri, then the Sun would be the size of a golf ball, providing an example of the truly great amount of space between the stars.

The Solar System is about 27,000 light-years from the centre of our home galaxy, the Milky Way, which contains approximately 200 billion other stars and is likely to contain the same number of planets.[4] The Milky Way is a barred spiral galaxy with a disk diameter of about 100,000 light-years and average thickness of 1,000 light-years. The Milky Way is a member of the Local Group, a gravitationally bound system of more than forty galaxies, including the well-known Andromeda Galaxy at a distance of 2.6 million light-years away from Earth. In turn, the Local Group and about one hundred other galaxy groups and clusters[5] are members of the Local Supercluster,[6] which has a diameter of approximately 110 million light-years. Astronomers estimate that there are millions of superclusters containing more than 200 billion galaxies in the observable universe, which hypothetically is a sphere centred on Earth with a radius of about 46 billion light-years. According to the theory of cosmic inflation, the observable universe represents only a very small region of the entire universe. Cosmologists estimate that

---

[4] A. Cassan, et al.,“One or more bound planets per Milky Way star from microlensing observations” in Nature (London: Nature Publishing Group, Jan. 2012, Vol. 481 Issue 7380), pp. 167–169.

[5] Galaxy clusters are larger than galaxy groups, and may contain thousands of galaxies.

[6] Superclusters are large groups of smaller galaxy groups and clusters. The Local Supercluster is also known as the Virgo Supercluster.

the entire universe may be at least a hundred trillion billion times larger than the observable universe.[7]

On the large scale of about 300 million light-years, the universe appears to be relatively homogeneous (same at every point) and isotropic (same in all directions). In modern cosmology, the assumption that the universe is homogeneous and isotropic is termed the cosmological principle. This is the ultimate statement of the Copernican principle, or the mediocrity principle, as it implies that the universe has no boundary and no centre. Based on the cosmological principle, the observation of darkness in the night sky infers that our universe is not static and should have a finite age.[8]

Our Time in the Universe

Though our universe is remarkably ancient, it is not infinitely old. In contemporary cosmology, the Big Bang is the standard cosmological model[9] that describes the evolution of the cosmos from its early history to the present observable universe. In the Big Bang model, the universe began about 13.7 billion years ago[10] with a gargantuan explosion, from which all matter, energy, space and time came into being. In this scenario, the universe has been expanding and its temperature has been falling ever since that extremely hot

---

[7] Alan H. Guth, *The Inflationary Universe: the Quest for a New Theory of Cosmic Origins* (New York: Perseus Publishing Group, 1997), p. 186.

[8] If the universe were homogenous, isotropic, infinite and unchanging, then everywhere in the universe would be as luminous as the surface of a star, so the whole night sky should be bright. This is called the Olbers' paradox.

[9] The 2006 Nobel Prize in Physics was awarded jointly to two American scientists, John C. Mather and George F. Smoot, for their work that offered increased support for the Big Bang theory of the universe.

[10] The best current estimation of the age of the universe is 13.75 ± 0.11 billion years, based on the WMAP project's seven-year data release in 2010.

primordial explosion.[11] One of the consequences of this cooling process was the formation of matter out of the hot radiation. Some of this matter later assembled into galaxies, stars, planets, and even life and consciousness which we observe today, in compliance with the laws of nature.[12] Modern cosmology shows that our own existence is intimately linked to the history of the cosmos as well as the underlying physical laws and physical constants governing all of the interactions in the universe.

Throughout history, humanity has looked to the sky with awe and sought to understand our lives within the context of the universe. Modern astronomical discoveries constantly reinforce this fact, as new findings have profound existential significance. If we condense the entire history of the universe into just 24 hours, then the Big Bang occurred at 00:00. The first galaxies and stars were born at 00:20.[13] Our solar system was formed out of the solar nebula at 16:00.[14] The most primitive life on earth appeared at 17:30[15] and later evolved into the diversity of life that we observe today.[16] Dinosaurs came on to the evolutionary stage at 23:36 and became

---

[11] Modern cosmology can only describe the evolution of the universe from 10^{-43} s after the beginning, when the temperature of the universe was 10^{32} ºC.

[12] For a more comprehensive description of modern cosmology and the anthropic principle, see Robert John Russell, Nancey Murphy, and C. J. Isham (editors), *Quantum Cosmology and the Laws of Physics* (Vatican City State: Vatican Observatory, 1996) and John D. Barrow and Frank J. Tipler, *The Anthropic Cosmological Principle* (Oxford: Oxford University Press, 1986).

[13] The first galaxies and stars formed about 200 million years after the Big Bang. "First galaxies were born much earlier than expected," *Science Daily*, 12 April 2011, <http://www.sciencedaily.com/releases/2011/04/110412101330.htm> [2012/05/28].

[14] The solar system formed approximately 4.6 billion years ago; Earth was born about the same time.

[15] The earliest living organisms were prokaryotes which appeared about 3.8 billion years ago.

[16] Discoveries from paleontology indicate that more than 99% of all species which developed have become extinct during evolutionary history.

extinct at 23:53.[17] *Homo sapiens* were latecomers, and appeared only one second ago at 23:59:59,[18] following *Homo erectus* which originated in Africa at 23:59:47.[19] Molecular biology and fossil discoveries have demonstrated that human beings and modern African apes share approximately 99% of their DNA, indicating that both species are descended from common ancestors[20] who existed before 23:59:15. Early human civilizations began at 23:59:59.9 and the industrial revolution occurred at 23:59:59.998. Although human beings appeared only a blink of an eye ago on the cosmic stage, we are indisputably part of nature and, more significantly, have a long cosmic and biological evolutionary history.[21]

The Big Bang Cosmology

The Big Bang is the most comprehensive and accurate explanation[22] for multifarious modern astronomical discoveries, including the red-shift of distant galaxies, background microwave radiation and the abundance of the elements. According to the Big Bang theory, the universe was originally in an extremely hot and dense state that expanded at great speed against the force of gravity. This expansion caused the universe to cool and resulted in the

---

[17] Dinosaurs first appeared on Earth 230 million years ago and died out due to an asteroid impact which caused a mass extinction 65 million years ago.

[18] Modern humans appeared about 200,000 years ago.

[19] *Homo erectus* originated about two million years ago.

[20] For example, the chimpanzee-human last common ancestor (CHLCA) lived more than 7 million years ago.

[21] For a chronology of human evolution, see “Timeline of human evolution,” *Wikipedia*, 25 May 2012, <http://en.wikipedia.org/wiki/Timeline_of_human_evolution> [2012/05/28].

[22] It should be emphasized that scientists can never observe the Big Bang itself. It is only a scientific model for explaining what we can observe today. In the philosophy of science, it is called an inference to the best explanation, also known as abduction.

present diluted state which continues to expand, though at a lower speed due to the effect of gravity. By assuming that the universe is homogeneous and isotropic, the dynamics of the entire universe can be described by Einstein's theory of general relativity, in which gravity can be expressed as a geometrical property of space and time. The theory of general relativity can be summarized by the famous quote of John Wheeler[23] who stated that "matter tells spacetime how to curve, and curved spacetime tells matter how to move."

The spacetime geometry of a homogeneous and isotropic universe[24] is described by the Friedmann-Lemaître-Robertson-Walker (FLRW) metric,[25] which can be written in terms of the spherical coordinate system (r, θ, φ) as:[26]

$$c^2 d\tau^2 = c^2 dt^2 - R^2(t)\left[\frac{dr^2}{1-kr^2} + r^2 d\theta^2 + r^2 \sin^2\theta d\varphi^2\right] \quad (1)$$

where c is the speed of light in empty space and $d\tau$ is the proper time.[27] The time-dependent function $R(t)$ is the cosmic scale factor, which represents the relative expansion of the universe. The

---

[23] John Archibald Wheeler (9 July, 1911–13 April, 2008) was an American theoretical physicist who made significant contributions to general relativity, as well as quantum mechanics.

[24] The FLRW cosmological model is the standard model of modern cosmology. For a basic introduction to general relativity with application to cosmology, see Edwin F. Taylor and John A. Wheeler, *Exploring Black Holes: Introduction to General Relativity* (San Francisco: Addison Wesley Longman, 2000).

[25] A metric is a mathematical function that defines the separation between two events in 4-dimensional spacetime (curved spaces). It is similar to the famous Pythagorean formula (also called the Euclidean metric), which gives the distance between two points in 2-dimensional or 3-dimensional (flat) space.

[26] The reader can simply skip the equations if he/she is not familiar with mathematical expressions.

[27] Proper time is the time interval between two events as measured by a clock passing through both events.

constant *k* in Equation (1) can only have the values $+1, 0, -1,$ giving three different kinds of spatial curvatures corresponding to a closed, flat or open universe. Einstein's field equations relate the evolution of the scale factor $R(t)$ to the pressure and energy of the matter in the universe. From Einstein's field equations, we can obtain two independent equations for the FLRW metric:

$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{R^2} \tag{2}$$

and

$$\frac{\ddot{R}}{R} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right) \tag{3}$$

where a dot (·) indicates a time derivative and *G* is the gravitational constant. In the derivation of these equations, it is assumed that the matter of the universe is in the form of a perfect fluid of mass-energy density ρ and pressure *p*. As the density and pressure of the perfect fluid are always positive, Equation (3) implies that the second time derivative of the scale factor, $\ddot{R}(t)$, is negative. This means that the universe must be either expanding or contracting, and the expansion rate of the universe must be decreasing[28] because of the mutual gravitational attraction of matter in the universe. In other words, Einstein's field equations actually predict that the universe cannot be static. Equations (2) and (3) are usually called the Friedmann equations.[29] They describe the expansion of a

---

[28] If the universe is contracting, its contraction rate must be increasing.

[29] The Friedmann equations were first derived by the Russian cosmologist Alexander

homogenous and isotropic universe and are the most important equations in cosmology.[30]

In physical cosmology, the Hubble parameter is defined as:

$$H(t) \equiv \frac{\dot{R}}{R} \qquad (4)$$

At the present time t_0, $H_0 = H(t = t_0)$ is called the Hubble constant, which is related to the age of the universe. With the measured value of $H_0 = 73.8 \pm 2.4$ (km/s)/Mpc derived by the Hubble space telescope in 2011, the age of the universe[31] is given approximately by:

$$t_0 \approx 1 / H_0 = 13.3 \pm 0.5 \text{ billion years.} \qquad (5)$$

Putting Equation (4) into Equation (2) and setting $k = 0$ give:

$$\rho(k=0) = \rho_c = \frac{3H^2}{8\pi G} \qquad (6)$$

In Equation (6), ρ_c is known as the critical density which differentiates a universe that expands forever from one that re-collapses. For $H = H_0$,

$$\rho_c = 9.3 \times 10^{-27} \text{ kg/m}^3 \qquad (7)$$

This value seems very small for the critical density, and corresponds to about five hydrogen atoms in every thousand litres of space.

Friedmann in 1922.

[30] We will include the cosmological constant in these equations when we discuss the acceleration of cosmic expansion in the later sections.

[31] See Footnote 10.

However, if we express ρ_c in terms of the solar mass $\mathrm{M}_{\mathrm{Sun}}$ and megaparsecs[32] (Mpc), we obtain:

$$\rho_c \approx 10^{11}\ \mathrm{M}_{\mathrm{Sun}}/(\mathrm{Mpc})^3 \qquad (8)$$

Now ρ_c does not look so small. In fact, $10^{11}\ \mathrm{M}_{\mathrm{Sun}}$ is about the mass of a typical galaxy and a megaparsec is roughly the typical separation between galaxies. Therefore, our universe should not be far away from the critical density.

Let us define the ratio of the actual density of the universe to the critical density using:

$$\Omega \equiv \frac{\rho}{\rho_c} \qquad (9)$$

This is known as the cosmic density parameter. Using Equations (6) and (9), the Friedmann equation in Equation (2) can be written as:

$$\Omega - 1 = \frac{kc^2}{R^2H^2} \quad . \qquad (10)$$

This equation is particularly useful. It implies that if $\Omega = 1$, then $k = 0$; therefore $\Omega = 1$ for all time, even though both R and H are functions of time. However, if $\Omega \neq 1$ (and thus $k \neq 0$), then Equation (10) tells us how the density of the universe has evolved. Moreover, Equation (10) clearly connects the matter and energy density (Ω) of the universe with the geometry (k) of the universe, as described by general relativity. There are three possible cases:

(1) If the matter and energy density in the universe is greater than the critical energy, i.e. $\Omega > 1$, the average curvature must be positive ($k = +1$). The universe is closed; therefore it will eventually collapse into a point (the big crunch).

---

[32] One megaparsec (Mpc) is approximately 3,262,000 light-years. Astronomers commonly measure the distances between galaxies in megaparsecs.

(2) If $\Omega < 1$, the average curvature must be negative ($k = -1$). The universe is open and it will expand forever.

(3) If the matter and energy density in the universe is equal to the critical density, i.e. $\Omega = 1$, the geometry of the universe is flat ($k = 0$). The universe will also expand forever but will approach a zero expansion speed.

That is to say, the geometry (and hence the fate) of the universe is determined by the cosmic density. It should be noted that Ω cannot be much greater than 1, otherwise the universe would have collapsed before stars had time to evolve. Conversely, Ω cannot be much smaller than 1, as the universe would have expanded so quickly that matter would not have condensed into stars and galaxies. This is actually an example of the anthropic principle, which will be discussed in more detail in the next section. Current estimations of Ω from the WMAP project, combined with other astronomical observations, give $0.99 < \Omega < 1.01$. This suggests that the matter and energy density in the universe is almost equal to the critical energy, and we in fact live in a flat universe, or a nearly flat one.

From Equations (2) and (10), we obtain:

$$(\Omega^{-1} - 1)\rho R^2 = -\frac{3kc^2}{8\pi G}. \qquad (11)$$

The right side of Equation (11) is a constant. Assuming that matter is non-relativistic,[33] we have $\rho \propto R^{-3}$ and therefore $\rho R^2 \propto R^{-1}$. Equation (11) then yields $(\Omega^{-1} - 1) \propto R$. This means that $(\Omega^{-1} - 1)$

---

[33] For radiation and relativistic matter, we then have $\rho \propto R^{-4}$.

increases rapidly with R and also with time; hence, Ω must be extremely close to 1 at the beginning.

Fine-tuning of the Universe

Living in the age of science, we are often reminded of the fine balance required for life to exist on our planet—the perfect blending of chemical elements and energy necessary to produce and maintain life as we know it. Yet, the requirements for the existence of life extend far beyond our atmosphere, and even our solar system. As revealed by modern cosmology, our presence is intimately linked to the fundamental parameters and laws of nature.

The more scientists discover about the conditions necessary for life to emerge, the more we see how narrow this window is. Any slight change in the laws of nature or to the values of the fundamental physical constants[34] would result in an absence of life in the universe. For example, if the gravitational constant were slightly larger, stars would burn up quickly and unevenly, thereby making the evolution of life on planets impossible; if it were smaller, no nuclear fusion could occur in stars and heavy elements would not be produced. In fact, the observed value of the gravitational constant is 'just right' for the occurrence of life. This fact, along with many other similar phenomena, has led to the promulgation of the so-called anthropic principle[35] : the view that the likelihood of the emergence

---

[34] There are about a dozen physical constants whose values have to be determined from experiments. For example, the gravitational constant (G) is equal to $6.67384(80)\times10^{-11}\,\mathrm{m^3kg^{-1}s^{-2}}$.

[35] As stated by Barrow and Tipler (Footnote 12), there are three primary versions of the anthropic principle: (1) Weak Anthropic Principle (WAP): "The observed values of all physical and cosmological quantities are not equally probable but they take on values restricted by the requirement that there exist sites where carbon-based life can evolve and by the requirements that the Universe be old enough for it to have already

of intelligent life hinges on the delicate balance of the natural laws and constants.

The discovery of the accelerating universe in 1998 immediately became a strong example of the anthropic principle, sparking much discussion among scientists and theologians. The widely accepted scientific explanation for the increasing speed of cosmic expansion is the presence of dark energy, which accounts for 73% of the total mass-energy of the universe,[36] based on feedback from the WMAP project. Dark energy is often defined as the negative equation-of-state energy that gives rise to a repulsive force of gravity. The simplest form of dark energy is the cosmological constant, which describes the constant energy density in empty space. According to the energy-time uncertainty principle in quantum mechanics, an empty space, or vacuum, is filled with virtual particles that can contribute some background energy in space, even when space is devoid of matter and radiation.[37] This quantum vacuum energy can give rise to a negative pressure that drives the accelerating universe.

The Value of the Cosmological Constant

Historically, the cosmological constant was first proposed by Albert Einstein, as a modification of his field equations to describe a

---

done so.” (2) Strong Anthropic Principle (SAP): “The Universe must have those properties which allow life to develop within it at some stage in its history.” (3) Final Anthropic Principle (FAP): “Intelligent information-processing must come into existence in the Universe, and, once it comes into existence, it will never die out.” Barrow and Tipler, *The Anthropic Cosmological Principle*, pp. 15–23.

[36] 73% of the mass-energy content of the universe is proposed to be dark energy, 23% is dark matter and only 4% is the ordinary matter that we can observe with our telescopes.

[37] The effects of vacuum energy have been observed in different experiments such as the Casimir effect and the Lamb shift.

static universe. As mentioned in the previous section, the Friedmann equations entail a changing universe. This result conflicted with the conviction of scientists in the early 20th century, including Einstein, who thought that our universe should be unchanging.[38] Therefore Einstein introduced the cosmological constant Λ in his field equations, so that their solutions might correspond to a static universe.[39] As a result, the Friedmann equations could be modified by adding a new constant term on the right-hand side as follows:

$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{R^2} + \frac{\Lambda c^2}{3} \tag{12}$$

and

$$\frac{\ddot{R}}{R} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right) + \frac{\Lambda c^2}{3}. \tag{13}$$

In light of Equations (12) and (13), we can define the vacuum-energy density ρ_Λ and vacuum-energy pressure p_Λ as:

$$\rho_\Lambda = \frac{\Lambda c^2}{8\pi G} > 0 \tag{14}$$

and

$$p_\Lambda = -\rho_\Lambda c^2 < 0. \tag{15}$$

It should be noted that the vacuum-energy density ρ_Λ is a positive constant; therefore, the total vacuum energy increases as the universe expands. Moreover, the corresponding vacuum-energy pressure ρ_Λ is negative, thus giving rise to gravitational repulsion.

---

[38] In fact, there was no scientific evidence for a static universe at that time.

[39] For a static universe, the scale factor would be a constant, i.e. $\dot{R}(t) = \ddot{R}(t) = 0$.

After Edwin Hubble discovered that the universe was actually expanding by measuring the red-shifts and the distances of the remote galaxies in the later 1920s, Einstein completely abandoned the idea of the cosmological constant. In an academic discussion with George Gamow,[40] Einstein remarked that the addition of the cosmological constant to his equations was the biggest blunder in his life. In fact, the static universe solution to the modified Friedmann equations is not stable. If the universe expands slightly, it will gain vacuum energy that causes it to expand further. Similarly, if the universe contracts a little, it will continue to contract until it collapses.[41]

Since the remarkable and unexpected discovery of the increasing rate of cosmic expansion, the idea of the cosmological constant has been revived with much attention.[42] In physical cosmology, the value of the cosmological constant is often expressed in terms of the ratio between the vacuum-energy density ρ_Λ and the cosmic critical density ρ_c as:

$$\Omega_\Lambda \equiv \frac{\rho_\Lambda}{\rho_c}. \qquad (16)$$

It should be noted that ρ_c actually changes with cosmological time, whereas ρ_Λ is a real constant independent of the age of the

---

[40] George Gamow (4 March 1904–19 August 1968) was a famous Russian-born physicist.

[41] In addition, the gravitational attractive force between matters will decrease as the universe expands and increase as the universe contracts. In physics terminology, the static universe is in an unstable equilibrium.

[42] Before 1998, cosmologists simply took the value of the cosmological constant to be exactly zero.

universe. Based on measurements from WMAP as well as other supporting evidence,[43] we have:

$$(\Omega_\Lambda)_{\text{observed}} = 0.73 \qquad (17)$$

for the present time.[44] In the flat universe ($\Omega = 1$), the present ratio of the matter density[45] to the critical density is then:

$$\Omega_M = 0.27 \,. \qquad (18)$$

The fact that Ω_Λ and Ω_M are of the same order of magnitude in the present epoch is an unsolved problem in cosmology,[46] which is usually termed the cosmic coincidence problem.

If we assume that dark energy is caused by the quantum vacuum energy fluctuation, we may roughly estimate the vacuum-energy density ρ_Λ using Planck units, which are based only on the properties of free space. By definition,

$$\rho_\Lambda = \frac{M_P}{l_P^3} \qquad (19)$$

where M_P is the Planck mass and l_P is the Planck length,[47] which leads to $\rho_\Lambda = 5.2 \times 10^{96}$ kg/m^3. Hence, using Equation (7), we obtain:

---

[43] John D. Barrow and Douglas J. Shaw, "The Value of the Cosmological Constant," in *General Relativity and Gravitation* (Berlin, Heidelberg: Springer, Oct. 2011, Vol. 43 Issue 10), pp. 2555–2560.

[44] The corresponding value of the cosmological constant (Λ) is $1.3 \times 10^{-52}\text{m}^{-2}$ (in SI units).

[45] The matter density includes both dark (non-baryonic) matter and ordinary (baryonic) matter.

[46] Note that $\Omega_\Lambda + \Omega_M = \Omega$. In the past $\Omega_M >> \Omega_\Lambda$, but in the future $\Omega_\Lambda >> \Omega_M$. Presently we have $\Omega_\Lambda \approx \Omega_M$.

[47] In Planck units, $M_P = \sqrt{\hbar c / G} = 2.18 \times 10^{-8}\text{kg}$ and

$$(\Omega_\Lambda)_{\text{theory}} \approx 10^{122} \qquad (20)$$

Our rough estimation for Ω_Λ is 122 orders of magnitude[48] greater than the observed value. A more sophisticated calculation,[49] based on quantum field theory, still gives $(\Omega_\Lambda)_{\text{theory}} \approx 10^{120}$. This astoundingly large deviation from the measured value of the cosmological constant is "probably the worst theoretical prediction in the history of physics."[50]

The Anthropic Explanation

The great discrepancy between the predicted and observed values of the cosmological constant is the ultimate example of fine-tuning in the universe. This paradox is known as the cosmological constant problem. Steven Weinberg[51] noted that the anthropic principle actually provided an upper bound for the value of the cosmological constant: if it were only a few times (less than one order of magnitude) greater than the observed value, our universe would have expanded so rapidly that there could be no formation of galaxies and stars.[52] Without stars, there would be no stellar

---

$l_P = \sqrt{\hbar G / c^3} = 1.62 \times 10^{-35}\,\text{m}$, where $\hbar = 1.055 \times 10^{-34}\,\text{Js}$, which is called the reduced Planck constant.

[48] That is to say, $(\Omega_\Lambda)_{\text{theory}}$ is greater than $(\Omega_\Lambda)_{\text{observed}}$ by one hundred trillion trillion trillion trillion trillion trillion trillion trillion trillion trillion times!

[49] Ta-Pei Cheng, *Relativity, Gravitation and Cosmology: A Basic Introduction* (New York: Oxford University Press, 2010), pp. 272–273.

[50] M. P. Hobson, G. P. Efstathiou and A. N. Lasenby, *General Relativity: An Introduction for Physicists* (New York: Cambridge University Press, 2006), p. 187.

[51] Steven Weinberg received the Nobel Prize in Physics in 1979 for his pioneering work on the unification of the electromagnetic interaction and the weak interaction.

[52] Steven Weinberg, *Dreams of a Final Theory: The Scientific Search for the Ultimate*

nucleosynthesis to produce heavy elements[53] such as carbon and oxygen, and without heavy elements, life and consciousness would not have been possible.

While anthropic phenomena such as the cosmological constant problem have been viewed as evidence of purposeful design by a cosmic creator, many scientific minds continue to explore alternative explanations. The hypothesis of multiple universes, otherwise known as the multiverse, is the most discussed scientific explanation for the many remarkable coincidences which have led to the evolution of intelligent life. In the multiverse scenario, many universes, each with different natural laws and physical constants, could exist simultaneously or successively. Cosmologists estimate that an unimaginably large number of at least $10^{10^{10000000}}$ universes could exist in the multiverse.[54] Most of these universes would be uninhabitable; however, a few might harbour life under the right conditions. Our own universe, with its very special laws and physical constants, fortuitously succeeds in producing and sustaining life in the midst of the many universes that are incapable of doing so. The odds are extremely small, but like a winner in a sweepstakes, our universe has been given the prize of intelligent observers.

Popularized in science fiction and fantasy, the multiverse idea is now echoed in some modern physical theories such as string theory and loop quantum gravity. Some think that the multiverse idea satisfactorily explains the fine-tuning of our universe; however, opponents dispute that this hypothesis is highly speculative and lacks

---

Laws of Nature (New York: Vintage Books, 1994), p. 228.

[53] In physical cosmology, no chemical elements heavier than beryllium could be formed in the early universe.

[54] Andrei Linde and Vitaly Vanchurin, “How Many Universes are in the Multiverse?” in *Physical Review D* (College Park, Maryland: American Physical Society, Apr. 2010, Vol. 81 Issue 8), 083525.

supporting scientific evidence.[55] The primary problem is that other universes are, in principle, unobservable; therefore, the hypothesis is not verifiable. Moreover, the existence of the multiverse itself may require further explanation, and in fact, the multiverse and cosmic creator may not be mutually exclusive ideas.

It is evident that the very small (but not zero) value of the cosmological constant, which allows the existence of life as it is presently understood, demands some explanation—whether by a cosmic creator or by the multiverse. While the idea of alternate universes is disputable, modern cosmology has clearly demonstrated that our universe is not only orderly, but also intelligible and awe-inspiring. Reflecting on the place of intelligence in the universe, Einstein remarked, "What I see in Nature is a magnificent structure that we can comprehend only very imperfectly, and that must fill a thinking person with a feeling of 'humility'. This is a genuinely religious feeling..."[56] This anthropic reasoning is, in fact, a good starting point for the dynamic and imperative dialogues between science and religion, as it provides profound insight into the nature of humanity as part of the evolving cosmos. We certainly need further exploration of our relationship with the known universe. Perhaps, like the apostle Thomas, who did not believe in the witness of his fellows to the risen Jesus and demanded more empirical evidence by examining the nail-marks in Jesus' hands,[57] our search for the reality of the anthropic universe is also a journey of faith.

[摘要] 本文章探討宇宙常數問題及其人擇釋義。

---

[55] John Leslie, *Universes* (New York: Routledge, 1989), pp. 66–68.

[56] Helen Dukas and Banesh Hoffman (editors), *Albert Einstein, The Human Side: New Glimpses from His Archives* (Princeton, New Jersey: Princeton University Press, 1979), p. 39.

[57] John 20: 24–25.