The Anthropic Principle Revisited

Berndt Müller
Department of Physics, Duke University
Durham, NC 27708-0305, USA

Abstract

The usage of the anthropic principle in modern cosmology is reviewed. It is argued that its recent use to explain the observed values of cosmological parameters as most probable values for an ensemble of universes, is not justified. However, the anthropic principle can be invoked to argue that a vast number of universes must exist, in which the cosmological parameters and constants of nature take on different values. This argument lends support to the hypothesis of eternal inflation and suggests that at least some of the parameters of the Standard Model cannot be quantitatively derived from an underlying theory.

1 Introduction

The anthropic principle[1, 2, 3, 4, 5] occupies a peculiar place in the arsenal of scientific reasoning. On the one hand, physicists generally harbor a deeply held belief that the fundamental laws of nature have an objective origin and are not human constructs or random accidents. On the other hand, some numerical coincidences in the natural laws appear far too contrived to be easily reconciled with our sense of “naturalness”. The anthropic principle is concerned with those fortuitous coincidences that have relevance for our own existence.

There are many well-known cases of such coincidences. As one example, consider the resonance in the excitation spectrum of $^{12}$C at 7.65 MeV. The precise location of this state is of critical importance for the fusion of three $^4$He nuclei into a $^{12}$C nucleus, and thus is a determining factor for the abundance of carbon and heavier atoms in the universe. Indeed, the presence of this resonance is so essential, that its existence was predicted by Hoyle[6] in order to explain the observed pattern of stellar nucleosynthesis. Obviously, the position of this state depends in extremely subtle ways on the strength of the nuclear force which determines the structure of the $^{12}$C nucleus. It has been estimated[7] that almost no carbon would be synthesized in stars if the nucleon-nucleon interaction were weaker by just 4%.

Other well-known instances of apparent fine-tuning of fundamental physical constants [4, 8, 9] are the neutron-proton mass difference, and the relation ($G$ is the...
gravitational constant, \(m_e\) and \(m_p\) are the electron and proton mass, respectively, and \(\alpha\) denotes the electromagnetic coupling constant)

\[
Gm_p^2/\hbar c \approx 3\alpha^{12}(m_e/m_p)^4 \approx 6 \times 10^{-39},
\]

which is an essential prerequisite for the existence of hydrogen burning stars with similar mass and luminosity as our sun.

Of course, if intelligent life had not developed anywhere in the universe, no one would be around to worry about those problems. But we do exist and hence face the challenge of having to explain this fact. The question I address in this article is, in which terms the discussion should be framed within the rules of scientific reasoning and common sense. I first review some of the traditional formulations of the anthropic principle (in Section 2) and describe its usage in modern cosmology (in Section 3). In Section 4, I present my own, somewhat different, view of the subject.

## 2 Forms of the Anthropic Principle

In its weakest form, the anthropic principle states that the laws of nature and the evolution of our universe must be compatible with the fact that we exist. In this form, the anthropic principle is almost a tautology. It might be used, in this weak form, to invalidate an experimental result, e.g. if it could be rigorously established that the result would imply our nonexistence. However, such a reasoning is unlikely to be of great usefulness, because we do not have a firm grasp of all the requirements for the formation of intelligent life in the universe. In its weak form the anthropic principle also serves to remind us that certain aspects of the history of our universe may be biased by the outcome, i.e. the fact of our existence.

In a stronger form, the anthropic principle is understood to explain (if they have already been measured) or to predict (if they are not yet known) certain aspects of nature, such as numerical values of physical constants or the properties of atoms and nuclei. The prediction of the fusion resonance in \(^{12}\text{C}\) is a famous example of such an application of the anthropic principle. Another recently much debated example is the “unnaturally” small value of the cosmological constant\(^\text{[10]}\)

\[
\Lambda \approx (2 \times 10^{-3}\text{eV})^4.
\]

If \(\Lambda\) were larger than the observed value by a factor 200 or more, the universe could not have gone through the slow period of expansion that is required for the formation of large galaxies, and it is unlikely that life could have developed\(^\text{[11]}\). On the other hand, the “naturally” expected value of the cosmological constant as the vacuum energy in the standard (supersymmetric) model of particle physics is at least 60 orders of magnitude larger than the observed value\(^\text{[12]}\). The anthropic principle thus permits to select a much reduced range of expected values of the cosmological constant, even before its measurement.

In its strongest form, the anthropic principle has been used to explain, why the laws of nature and especially numerical constants in these laws, such as the coupling
constants of fundamental forces and the ratios of elementary particle masses, or the parameters of cosmological models, have the specific forms or values that are observed. Of course, this use of the anthropic principle makes sense only where we lack other explanations. As the laws of physics have become ever more unified and better understood, the number of truly fundamental, still unexplained parameters has been reduced to less than thirty.

3 Inflationary Cosmology

The philosophical basis of the anthropic principle has been radically changed by the inflationary model of the universe [13, 14, 15]. The hypothesis, that our universe went through a period of exponential growth about 14 billion years ago, provides a natural explanation for several astounding astrophysical facts. In particular, the inflationary model can explain the observed isotropy and homogeneity of the cosmic background radiation, the vast size of the universe compared with the fundamental scales of particle physics, and the near flatness of the geometry of the universe on large scales[16].

Cosmic inflation occurs naturally when the some region of space-time gets trapped in an excited vacuum state, usually called the “false” vacuum. The vacuum energy density and pressure induce an effectively repulsive gravitational force, which dictates the expansion of space-time. As long as the false vacuum persists the universe expands, doubling its volume in equal periods of time. When the false vacuum finally decays, the expansion slows down, the universe heats up to a very high temperature, and the familiar “Big Bang” occurs. In order to explain the observations, the linear size of the universe must have grown by at least 26 orders of magnitude, and possibly much more, during the inflationary period.

However, the inflationary cosmological models have brought us another philosophically important and unanticipated insight. In most models, an infinite sequence of universes are created once inflation has started[17, 18]. The reason for this behavior is that the volume of space filled by the excited vacuum state inflates faster than the excited state can decay. In other words, as the false vacuum decays in one bubble-like region of space, creating a new universe, the remaining space continues to grow exponentially, allowing for the formation of other bubbles in which the excited vacuum decays, and so on ad infinitum. This scenario is called “eternal” inflation.

The various universes created by this process are causally disconnected, and observers in different ones cannot communicate with each other. In the true sense of the word, eternal inflation leads to a “many worlds” picture where an unlimited number of big-bang universes develop in isolation, separated by rapidly stretching regions of space filled with the undecayed false vacuum. This has important consequences for the anthropic principle, because it is easy to construct models where certain “constants” of nature differ in value from one universe to the next. The anthropic principle in its weakest form will then simply assert that we live in one of those universes that are conducive to the formation of intelligent life.

A slightly different scenario is “open inflation”, where each created universe is composed of infinitely many regions with different values of the cosmological parameters.
and possibly of physical constants that depend on the vacuum structure [19, 20, 21]. Because each universe has an infinite volume, these regions can be so large that each extends beyond the horizon of an observer living in it. Thus any observer would measure unique values for all cosmological and physical parameters throughout the entire range of the observable universe.

These cosmological scenarios invite novel applications of the anthropic principle, because one can now, at least in principle, define the probability distribution for various cosmological parameters and other vacuum state dependent physical constants over the entire set of universes [19, 22]. If this distribution can be calculated for a specific model, one can determine the most probable set of parameters and ask whether it permits the evolution of intelligent life. In other words, one postulates that we probably live in the most common type of universe or subuniverse. This postulate is sometimes called the principle of mediocrity [22].

If we denote the set of physical parameters that can take different values in different regions of space-time by \( \chi \), the probability for measuring a particular value at some space-time point will be proportional to the space-time volume \( V(\chi) \) of the region in which this value is realized. The probability that this value will actually be measured by an intelligent observer will, furthermore, be proportional to the number \( \nu(\chi) \) of large galaxies formed in the presence of this value of \( \chi \), and the number \( c(\chi) \) of advanced civilizations developing in each galaxy. Altogether, one has the following relation for the probability density that the value \( \chi \) will be observed:

\[
P_{\text{obs}}(\chi) d\chi \sim c(\chi) \nu(\chi) V(\chi) d\chi.
\] (3)

The mediocrity principle then postulates that the value \( \chi^* \) measured experimentally is near the maximum of \( P_{\text{obs}}(\chi) \).

For the case, in which each bubble universe is characterized by a unique value of parameters, the definition of a probability density encounters certain ambiguities due to the infinity of universes created by the process of eternal inflation. These problems are connected with the ambiguities in the definition of a universal time coordinate [19, 23]. In the case of open inflation, the definition of a unique probability measure is much simpler, because all possible values of the parameters are realized in the subregions of each universe, and the volume of each homogeneous region at a fixed cosmological time can be used as a basis for the probability measure [24].

Applications of this concept to the cosmological constant problem are able to provide a possible explanation for the smallness of the observed value of the cosmological constant [25, 26], as well as for its close coincidence at present with the total matter density in our universe [27, 28, 29]. However, it has been pointed out recently that the anthropic argument loses its predictive power, when not just isolated parameter changes are considered, but correlated changes in the values of several cosmological parameters are considered simultaneously [30]. It then appears possible to construct cosmologies with widely differing values of their parameters, which allow for the formation of sun-like stars with planetary systems.
4 A Modified Form of the Anthropic Principle

Now I want to address the question whether the “principle of mediocrity”, i.e. the notion that we live in an average, or most probable, universe among all possible universes, constitutes a logically compelling use of the anthropic principle. I will argue that it does not, and that the anthropic principle should instead be applied in a slightly different, but still very powerful way.

4.1 There’s No Reason for Being “Average”

The principle of mediocrity is the complete opposite of the idea of geocentrism, which fell into disrepute after the successive discoveries of the heliocentric structure of the solar system, the great extent of our galaxy, and the vast number of galaxies in the visible universe. In fact, modern cosmology has entirely done away with the concept of a central point in the universe, rendering all locations equivalent, at least on very large scales. However, the knowledge that any two points in our universe are equivalent, if viewed on a very large scale, does not imply that the Earth looks like the “average” planet that harbors life. As long as we have not detected a single other earth-like planet in our galaxy, let alone one inhabited by intelligent beings, we have no reason to believe that astronomers will eventually find that intelligent forms of life usually develop on planets similar to ours.

It is important to recognize that the demise of the geocentric model was the result, not of logical reasoning, but of observations that rendered it obsolete. But we have no such observations as guidance concerning the multitude of universes and, almost certainly, will never have them. We are only assured of our existence and the fact that the values of the fundamental physical constants and cosmological parameters conspire to make our existence possible.

In order to better expose the fallacy of the mediocrity principle, it is useful to consider the following question: Can we explain the peculiar properties of the planet Earth and explain our existence on this planet, given the physical laws that we know? Many fortuitous circumstances have made intelligent life possible on this planet: The sun has just the right mass to radiate enough energy to sustain life based on organic compounds and water, and its longevity as an active star is large enough to permit higher life forms to evolve. Earth has the right size and just the right distance from the sun to retain large amounts of liquid water at its surface. And the solar system exhibited just the right intensity of asteroidal impact activity during earlier periods to drive the evolution of higher forms of life by producing moments of punctuated equilibrium, without wiping life totally out or suppressing anything but simple organisms. And so forth.

Because we do not yet understand the processes governing the formation of solar systems in sufficient detail, we cannot reliably estimate the probability for the presence of a planet with similar properties as the Earth in a galaxy like ours. We also cannot calculate the probability for the emergence of life, or even intelligent life, on a planet with these properties. What we can say with a fair degree of certainty, however, is that the probability for finding the right combination of circumstances capable of creating
intelligent life in the vicinity of a given star must be quite small[31].

Unless we want to claim that we are the product of unlikely coincidences, or of purposeful and clever design, we must therefore assume that the universe contains a great number of stars, so that the probability for us to exist somewhere in the universe is not small[32]. This does not assert that the Earth looks like the average planet inhabited by intelligent life forms. There is no justification for this assumption. In view of the many fortuitous circumstances which facilitated the emergence of intelligent life on Earth – just imagine how life might have developed if the asteroid that wiped out the dinosaurs had missed the Earth’s path – it would not at all be surprising if another civilization were found to inhabit a very different looking planet. But there is no need to make this assumption. All that we need to assume is that there are so many solar systems in the universe, that the probability for finding one on which intelligent life can and will develop is close to one[32].

By virtue of this reasoning, an intelligent observer could have anticipated the vast size of our universe and the multitude of stars contained in it, even if the view outside our solar system were shrouded by a thick cover of an interstellar dust. Precisely the high degree of improbability of the emergence of intelligent life on our planet would force this conclusion upon the imagined observer, unless he or she would want to believe that somehow all the fortuitous events and circumstances were arranged purposefully by some higher power[33].

4.2 The Case for a Multitude of Universes

We are now ready to apply the same reasoning to the physical laws of nature and our universe as a whole. Without doubt, most random choices for the values of the fundamental physical constants (the coupling strengths of fundamental interactions, the masses of the elementary particles, and the cosmological parameters) would not have permitted anything even remotely resembling intelligent life to emerge. Then universe could have recollapsed after a fraction of a second, its expansion could have begun to accelerate long before galaxies formed, a proton and a neutron might not form a bound state, or the neutron might have a much shorter lifetime.

Even if the dream of particle physics, the unification of all forces and the formulation of a “Theory of Everything”, were fulfilled, one would have to wonder why we are blessed with this particular set of fundamental laws and cosmological parameters that facilitate the emergence of intelligent life. Could the formation of life, especially intelligent life, be the necessary, or even probable, consequence of the fact that there is unique set of laws governing all processes in our universe? I find this hard to believe, and there is no evidence supporting this hypothesis.

We are thus led to formulate a new version of the anthropic principle:

The physical laws of nature and the values of the fundamental constants and cosmological parameters must allow for the probable emergence of intelligent life forms. The values of these constants must be probable ones.

In other words, we understand the anthropic principle to mean that our own existence should not be the consequence of an unlikely coincidence nor the result of divine design.
But note that it was precisely the recognition that our existence is predicated on various highly improbable coincidences, which brought the anthropic principle to the attention of scientists.

The simplest resolution of this conundrum is to postulate the existence of many different universes, or of large unobservable regions in our infinitely extended universe, where the physical laws and parameters differ from those observed by us. There must exist so many of them that the probability for finding one that allows intelligent life to form is not much less than one. This hypothesis implies that some of the physical constants, if not all, can take different values. It also implies that it is impossible to calculate and predict all physical constants from fundamental principles, because their values are not fundamentally unique. It may well be possible to relate them to some underlying geometric structure of space-time, such as the arrangement of D-branes in higher dimensions[34], but then this arrangement must be – to a certain extent – random and unpredictable.

When one adopts this form of the anthropic principle, the fact that eternal inflation predicts just such a scenario, entailing the creation of infinitely many almost flat universes with quasi-random values of the fields that determine the values of the physical constants, becomes a highly desirable aspect of this cosmological theory. The fact that superstring theory seems to have great difficulty predicting a unique vacuum state, becomes a benefit, rather than a drawback of this theory, as well. In the framework of our version of the anthropic principle, these are actually aspects that one would demand of any sensible Theory of Everything.

5 Summary

I have argued that the proper resolution of the various unnatural coincidences among values of physical constants that have permitted intelligent life to develop in our universe is the hypothesis that there must exist so many universes with different values for these constants that, overall, the probability of finding one with favorable conditions is reasonably close to one. This postulate has several far-reaching implications. It dictates that not all constants of nature are uniquely predictable, that some must be able to take a range of random values. It demands that our observable universe is only one among many in existence, and there is no reason for the assumption that our universe has highly probable characteristics within this ensemble.

It is quite remarkable that many modern cosmological models and unified theories of the known interactions exhibit the required properties. The arguments presented above make these properties appear far less astonishing predictions; they rather become desirable and compelling aspects of these models. While eternal inflation seems to be an extremely natural scenario explaining the formation of (infinitely) many, globally flat universes, there are many different ways in which one can imagine the randomness of fundamental constants to be realized in nature. Superstring theory or M-theory provides an intriguing framework, if the conjecture of a multitude of nearly degenerate vacuum states is confirmed (but see [35] for a different view). The recently investigated models, in which our observed four-dimensional space-time is localized on Dirichlet
branes existing in a higher-dimensional flat or warped space\cite{34, 36}, exhibit enough freedom to allow for the scenario advocated here. But other explanations, such as the idea that the laws of nature are microscopically random\cite{37}, are also possible.

Acknowledgment: This manuscript is dedicated to Sergei Matinyan on the occasion of his seventieth birthday. I wish to thank the students in my fall semester 2000 class (Physics and the Universe) for asking the penetrating questions which inspired this article. This work was supported in part by a grant from the U. S. Department of Energy (DE-FG02-96ER40945) and by a Senior Scientist Award from the Alexander von Humboldt Foundation.

References

[12] This estimate assumes that the physical vacuum energy is determined by the scale at which supersymmetry is broken, $\Lambda \approx M_{\text{SUSY}}^4 \geq (1\text{TeV})^4$. For some recent suggestions, how a much smaller value for $\Lambda$ could be explained, see e. g.: S. R. Beane, Phys. Lett. B 358, 203 (1995); S. Kachru, J. Kumar, and E. Silverstein, Phys. Rev. D 59, 106004 (1999); E. Guendelman and A. Kaganovich, Phys. Rev. D 60, 065004 (2000); N. Arkani-Hamed, L. J. Hall, C. Colda, and H. Murayama, Phys. Rev. Lett. 85, 4434 (2000); T. Banks, M. Dine, and L. Motl, JHEP 0101, 31 (2001); V. G. Gurzadyan and S. S. Xue, astro-ph/0105245.
[31] Attempts to estimate the rate of emergence of civilizations capable of intelligent communication are usually based on Drake’s equation, see: F. D. Drake, *Intelligent Life in Space* (Macmillan, New York, 1960). See also the October 1994 issue of *Scientific American*.
[32] A. Feoli and S. Rampone, *Nuovo Cim. B* **114**, 281 (1999). These authors formulate the anthropic principle as follows: “The universe (and hence both the fundamental parameters on which it depends and the amount of places where the evolution can take place) must be such as to admit the creation of observers at some stage, and to assure them a nontrivial living time.”