20
Anthropic Selection

The properties of every object in the universe, from subatomic particles to giant galaxies, are determined, in the final analysis, by a set of numbers that we call "constants of nature". These include the speed of light, Planck's constant, and Newton's gravitational constant; the parameters in the Standard Model, like the mass of the electron, Higgs boson, quarks and so on, and the strengths of the four forces. There are also several cosmological parameters that shape the character of our world. These include the relative contributions of radiation, atomic matter, dark matter and dark energy to the density parameter and the magnitude of the initial density inhomogeneities. Altogether there are about 30 numbers,[1] which beget an intriguing question: Why do these numbers take the particular values that they have? It has long been a dream of physicists to be able to derive all the constants of nature from some fundamental theory. But there has been very little progress in this direction.

If you write the known constants of Nature on a piece of paper, they look pretty random (see Fig. 20.1). Some of them are very small, others large, so there seems to be no system behind these numbers. However, some people noted that there may be a system, but not of the kind that physicists have been hoping for. The values of the constants appear to be fine-tuned to allow for the existence of life. In other words, if we ask what would happen if we

[1]The values of the constants depend on the units we use to measure them. Physicists therefore focus on dimensionless combinations of the constants, like the ratios of particle masses, which do not depend on the units. The number we quote (30) is the number of independent dimensionless combinations of the constants.

D. Perlov and A. Vilenkin, *Cosmology for the Curious*,
DOI 10.1007/978-3-319-57040-2_20

Photon and Gluon	0
W-boson	157 000
Electron	1
Neutrino	$< 10^{-8}$
Muon	207
Up-quark	8
Bottom quark	9200

Fig. 20.1 Masses of some particles, in units of the electron mass. The values appear to be rather random

change one of the constants by a relatively small amount, we find that we would get a universe that is inhospitable to life. Let us consider a few examples that illustrate how tinkering with the constants leads to catastrophic results.

20.1 The Fine Tuning of the Constants of Nature

20.1.1 Neutron Mass

The mass of the neutron is very finely tuned. If we adjust it just a little, we change the structure of matter so much that chemistry is almost completely destroyed. Let's see why. Neutrons are 0.14% heavier than protons. Outside of the nucleus, they decay into protons, electrons and antineutrinos: $n \rightarrow p^+ + e^- + \bar{\nu}$. These "free" neutrons have an average life of about 15 min. But inside nuclei neutrons are stabilized by nuclear forces. If the neutron's mass were *increased* by 1%, then neutrons would decay even inside nuclei, turning into protons. The electric repulsion between the protons would then tear the nuclei apart, so the only stable nucleus would be that of hydrogen, consisting of a single proton. On the other hand, if the neutron's mass were *decreased* by 1%, neutrons would become lighter than protons. This would mean that protons would decay into neutrons, positrons and neutrinos: $p^+ \rightarrow n + e^+ + \nu$. Consequently, atomic nuclei would lose their charge and would consist only of neutrons. The unattached electrons would fly away, so no atoms would exist. Thus, by adjusting the mass of the neutron just a little, we either end up in a world that only contains one type of chemical element—hydrogen—or a neutron world.[2]

20.1.2 Strength of the Weak Interaction

When a massive star runs out of nuclear fuel, its core collapses in a supernova explosion. The strength of the weak interaction is perfectly suited to allow neutrinos to stream out of the core and drag along the outer layers of the star. This is a critical part of the cycle that enriches the interstellar medium with heavy elements. If weak interactions were much stronger, neutrinos would remain stuck in the core. If they were much weaker, neutrinos would stream out without dragging along other particles. If the heavy elements were not spewed into space, later generations of stars and planetary systems like ours would not have formed, and the raw materials for complex life would be missing.

20.1.3 Strength of Gravity

Gravity is by far the weakest force—it is 10^{36} times weaker than electromagnetism. Because gravity is so weak, we can increase its strength quite a lot, and it will still be weak. For example, if we make it ten billion times stronger, it would still be 10^{26} times weaker than electromagnetism. Stars would then be the size of mountains, and they would live for only a year or so. Intelligent life would hardly have enough time to evolve. Planets as massive as the Earth would be about 100 m in diameter, and the force of gravity on their surface would crush any object heavier than an ant.

20.1.4 The Magnitude of Density Perturbations

Structure formation in the universe crucially depends on the magnitude of primordial density perturbations. If these perturbations were much weaker, then galaxies may never have coalesced. (Note that structure formation

[2]On a more fundamental level, protons and neutrons are made up of quarks, so it is more appropriate to regard the quark masses as fundamental constants of nature. But the general conclusion does not change: we are driven to either a hydrogen world or a neutron world, unless the quark masses are suitably fine-tuned.

freezes at the onset of dark energy domination, thus if galaxies fail to form prior to this epoch, they will never form.) Without galaxies there would be no buildup of heavy elements, and it is unlikely that planets, and life, would have emerged.

If the initial density perturbations were much stronger, then galaxies would form earlier and would be much denser. Close stellar encounters would be much more frequent; they would disrupt planetary orbits, with disastrous consequences for life.

20.2 The Cosmological Constant Problem

We now come to the most striking fine-tuning of all. The observed accelerated expansion of the universe is caused by a vacuum energy (mass) density, or cosmological constant, which is about twice the average density of matter today, $\rho_v \sim 2\rho_m$. This value is in blatant conflict with theoretical expectations.

20.2.1 The Dynamic Quantum Vacuum

When you think of a vacuum, you intuitively picture a state of pure "emptiness" or "nothingness". However, quantum theory tells us that the vacuum is an inextinguishable sea of virtual particles that spontaneously appear and disappear. All particles in the Standard Model—electrons, quarks, photons, W-bosons, and so on—are relentlessly fluctuating in and out of existence. Although these virtual particles are very short lived, they have important and measurable effects.[3] Most importantly, they contribute to the energy density of the vacuum. The problem is, however, that calculations of the resulting vacuum energy density give values that are absurdly large, $\rho_v \sim 10^{120}\rho_m$ (see the box at the end of this section). So we seem to have a mismatch between theory and observation that is about 120 orders of magnitude! This has been called "the worst prediction in physics", "the mother of all physics problems", or less dramatically, the "cosmological constant problem".

[3]One of these is the Casimir effect which predicts that there will be an attractive force between two uncharged parallel conducting plates in a vacuum. The reason is that electromagnetic field fluctuations are restricted between the plates and unrestricted outside them. This results in more pressure from the outside pushing the plates towards one another. This effect has been measured. Also, the energy levels of the hydrogen atom have been measured and agree with the theory to a very high precision if we take into account the virtual particles which swarm inside the hydrogen atom.

Why is the observed value of the vacuum energy density so small? Is it possible that some mechanism could cause contributions from different particle species to cancel one another? It turns out that fermions and bosons do indeed contribute to the vacuum energy density with opposite signs. Bosons have a positive contribution and fermions contribute a negative energy density.[4] But these contributions would need to cancel precisely to the 120th decimal point in order to predict a value that is as low as measured by the supernovae observations. Such a precise cancellation would be a dramatic example of fine-tuning.

20.2.2 Fine-Tuned for Life?

Let us now see what would happen if the value of the cosmological constant were very different from what it actually is. Suppose first that ρ_v is positive and is 1000 times greater than ρ_m. It would still be 117 orders of magnitude below its theoretically expected value.

The vacuum energy would then start dominating the universe at $t \sim 0.5\,\text{Byr}$. At that time, galaxy formation was just beginning and only very small galaxies had enough time to form. But once the vacuum energy dominates, galaxy formation comes to a halt. The problem with miniature galaxies is that their gravity is too weak to keep heavy elements expelled in supernova explosions from flying away into outer space. Thus the galaxies would be left without the elements necessary for the formation of planets and for the evolution of life. If we further increase ρ_v by another factor of 100, then it would come to dominate well before the epoch of galaxy formation, and the universe would be left with no galaxies at all.

Suppose now that ρ_v is negative and has magnitude 1000 times greater than ρ_m. Then the gravity of the vacuum would be attractive and would cause the universe to contract and collapse to a big crunch at $t \sim 0.5\,\text{Byr}$. This is hardly enough time for the evolution of intelligent life (which took about 10 times longer here on Earth). A further increase in the magnitude of ρ_v would make the lifetime of the universe even shorter and the evolution of life and intelligence even less likely.

[4]The reason for this difference is that fermions are mathematically described by so-called Grassmann numbers, which are rather different from ordinary numbers. When you multiply ordinary numbers, the result does not depend on the ordering of the factors; for example, $3 \times 5 = 5 \times 3$. But for Grassmann numbers the product changes sign under factor ordering: $a \times b = -b \times a$.

Virtual particles and vacuum energy density

According to quantum physics, the vacuum is awash with virtual particles constantly popping in and out of existence. Particles and antiparticles appear in pairs and almost instantly annihilate. The lifetime of a virtual pair Δt depends on the energy of the particles E: the higher the energy, the shorter is the lifetime. Quantitatively, this can be expressed as $E \cdot \Delta t \sim \hbar$, where $\hbar$ is the Planck constant. Virtual particles move at nearly the speed of light, so the whole process occurs on a length scale $L \sim c\Delta t \sim \hbar c/E$. Space is packed with virtual pairs, and once a pair annihilates, another instantly appears in its place. So, if you look at a small cubic region of size L at any time, you are likely to find a pair of particles with energies $E \sim \hbar c/L$.

The energy density due to the virtual particles can now be estimated by dividing the energy E by the volume L^3:

$$E/L^3 \sim \hbar c/L^4 \tag{20.1}$$

As L is decreased, the energy density grows, indicating that energetic pairs popping out on smaller distance scales give a greater contribution to the vacuum energy density. As we include virtual pairs on smaller and smaller scales, the energy density appears to grow without bound.

However, there may be a limit to how small the length L can be. At super-small distances, quantum gravity effects become significant and the geometry of spacetime undergoes large quantum fluctuations. Below a certain characteristic distance, spacetime acquires a chaotic, foam-like structure (see Fig. 20.2). We can estimate this distance scale using dimensional analysis. It can only depend on the fundamental constants $\hbar$, c and G, and the only combination of these constants that has the dimension of length is

$$\ell_p = \sqrt{\frac{\hbar G}{c^3}} \tag{20.2}$$

This is the Planck length, which we introduced in Sect. 19.1. On much larger scales, the spacetime appears to be smooth, just as the foamy surface of the ocean appears smooth when viewed from an airplane.

The physics of spacetime foam is not well understood, but physicists expect the virtual pair production to cease on scales smaller than ℓ_p. (This fits well with string theory, where the typical size of vibrating strings is ~ℓ_p.) The vacuum energy density can then be estimated by setting $L \sim \ell_p$ in Eq. (20.1) and the corresponding mass density can be obtained by further dividing by c^2:

$$\rho_v \sim \frac{c^5}{\hbar G^2} \sim 10^{97}\ \mathrm{kg/m^3} \tag{20.3}$$

This is greater than the observed vacuum energy density by a factor of about 10^{123}.

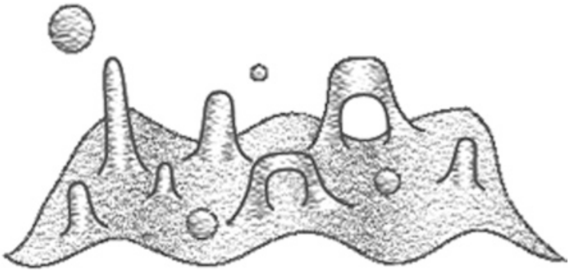

Fig. 20.2 As space is viewed at higher and higher resolution, a foamy structure emerges at the Planck scale

20.3 The Anthropic Principle

Why are the constants of nature fine-tuned for life? There are a few ways to address this question, and we shall consider them in turn.

1. The universe is what it is. The constants have to have some values, and they just happen to be consistent with life. We simply got lucky. This is not very satisfactory: getting lucky many times in a row calls for an explanation. And a fine-tuning by 120 orders of magnitude is hard to dismiss as simply an accident.
2. One day we will have a complete theory of physics that will allow us to calculate all the parameters from first principles. We just have to buckle down and keep working towards such an understanding. But how likely are the constants derived from the fundamental theory to fall in the narrow ranges allowing life to exist? If they do, that would be a tremendous stroke of luck. Once again, it would not be satisfactory to leave it unexplained.
3. The constants were fine-tuned by a benevolent creator, just so we can exist. There is often a temptation to invoke God whenever we encounter something that seems very hard to explain. But this "God of the gaps" approach has a poor success record in science. Isaac Newton, for instance, suggested that a supernatural deity was responsible for sustaining a homogeneous distribution of stars against gravitational collapse and for the fact that the planets are "opaque" and the stars "luminous". Of course, it has been a great triumph of science to discover the expansion of the universe and to explain how thermonuclear reactions cause an opaque body to become a luminous star.

4. Finally, there is a possibility that the constants of nature can take on a variety of different values, which can be realized in distant parts of the universe beyond our horizon. Then we should not be surprised to find ourselves living in a *special* corner of the universe which has constants of nature that are hospitable to life. We cannot live in environments that are not bio-friendly—even if most of the universe is of this sort. We live only where we can! This is the so-called "anthropic principle".

To illustrate the anthropic principle at work, let us think about the Solar System for a moment. About four centuries ago, when the Solar System was thought to be the universe, Johannes Kepler asked the following question: What determines the number of planets and their particular distances from the Sun? At that time only five planets were known, and Kepler was struck by the fact that this was exactly the number of highly symmetric polyhedrons, called Platonic solids.[5] He came up with an elaborate construction where the solids were nested inside one another and suggested that their sizes were proportional to the radii of planetary orbits (see Fig. 20.3). But today it is obvious that Kepler was asking the wrong question. We have detected thousands of extrasolar planets, and we have every reason to expect that there are billions of them in the observable universe. The planets orbit their suns at a great variety of distances, but most of them are not well suited for the evolution of life. If our Earth were significantly closer or farther away from the Sun, the oceans would either boil or freeze, and life of our kind would be impossible. The reason why we live on a planet that is "hospitably" located is simply because we can't live on a planet at an inhospitable distance. If the Solar System were the only one in the universe, then it would be very mysterious that it contains a bio friendly planet. But if there are many types of planets with varied conditions, then it is not so surprising that some of them have environmental factors that are hospitable to life—and it is common sense that we live on such a planet.

Similarly, if we are living in a multiverse, where there are many distant regions that have different constants of nature, then it is not at all surprising that we find ourselves in a very special place with "fine-tuned" parameter values. We simply can't live anywhere else. In the multiverse context, asking why a given parameter has a specific value is to ask the wrong question—like Kepler.

[5] This fact was discovered by the ancient Greeks. The Platonic solids are the tetrahedron, cube, octahedron, dodecahedron and icosahedron.

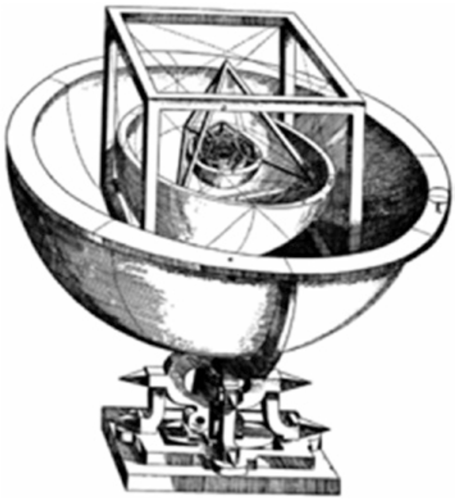

Fig. 20.3 Kepler's model of the Solar System with five Platonic solids nested within one another

The anthropic principle, which was introduced in 1974 by the Australian born astrophysicist Brandon Carter, has a dubious reputation among physicists. On the one hand, the principle is trivially true (we cannot live where life is impossible), and its application to our location in the Solar System is uncontroversial. On the other hand, its use for explaining the fine-tuning of the constants of nature has often been viewed with great suspicion.

20.4 Pros and Cons of Anthropic Explanations

Anthropic explanations assume the existence of a multiverse consisting of remote domains where the constants of nature take different values. In the 1970s this assumption appeared to be rather far-fetched, but this has now changed due to subsequent developments in particle physics and cosmology. Modern particle theories predict the existence of multiple vacuum states with diverse properties, and eternal inflation provides a mechanism for populating the universe with large regions of all possible vacua.

Furthermore, to explain the fine-tuning of the vacuum energy density ρ_v, the number of vacua in the energy landscape of the theory should be enormous. To understand why, let us imagine a long ribbon representing possible values of ρ_v, from $-10^{120}\rho_m$ to $+10^{120}\rho_m$. At the center of the ribbon is a minuscule anthropic range, between $-10^3\rho_m$ and $+10^3\rho_m$, where life is possible. Now, we want the number of vacua in the landscape to be sufficiently large, so that some of them happen to be located in the anthropic range. If we randomly throw a dart at the ribbon, the probability that it will hit the anthropic range is completely negligible,

$$P \sim \frac{10^3\rho_m}{10^{120}\rho_m} \sim 10^{-117}. \tag{20.4}$$

We will have to make more than 10^{117} attempts before we can expect to have a successful hit. Similarly, we need an energy landscape of more than 10^{117} vacua for the anthropic explanation of ρ_v to be successful.

Energy landscapes of grand unified theories typically include only a few vacua and fall far short of the mark, and this is where string theory comes to the rescue. As we discussed in Chap. 19, the energy landscape of string theory is estimated to have $\sim 10^{500}$ vacua. This completely dwarfs the required number 10^{117}. With such an immense landscape, we can expect to have googols of vacua in the anthropic range (see Question 7).

The anthropic principle has often been dismissed as being unpredictive and untestable—a philosophical cop out. It gives a ready explanation for any values of the constants of nature that we can measure, but does not seem to provide any means to verify that this explanation is correct. Today, however, many physicists are realizing that anthropic arguments may in fact lead to testable predictions, as we shall discuss in the next chapter.

Summary

In our observable universe there are roughly 30 constants of nature that have been measured empirically. Despite their best efforts, physicists have not been able to derive the values of these parameters from first principles. Interestingly, a relatively small change to the value of any of the constants tends to lead to a universe that is inhospitable to life. How can we explain this fine-tuning?

One possibility is that the constants of nature can take on a variety of different values, which can be realized in distant parts of the universe beyond our horizon. Then it is no surprise that we live in a fertile zone that has constants of nature that are hospitable to life. We cannot live in environments

that are not bio-friendly—even if most of the universe is of this sort. This is the so-called "anthropic principle".

The observed vacuum energy density, or cosmological constant, is about 120 orders of magnitude smaller than the theoretical value. This is called the "cosmological constant problem", and it is one of the biggest mysteries in theoretical physics. The anthropic principle, combined with the multiverse worldview, can be used to explain why the cosmological constant is so small.

Questions

1. Neutrons are slightly heavier than protons. What would happen if we could decrease the neutron mass by 1%, so that protons become the heavier of the two?
2. The orbit of the Earth around the Sun is nearly circular, while many of the extra solar planets are observed to have highly eccentric elliptical orbits. Why do you think we do not live on one of those planets?
3. Give two examples of constants of nature which appear to be fine-tuned. For each example indicate one way in which the universe would be very different if these constants had different values.
4. What is the "anthropic principle"?
5. Explain why a high value of vacuum energy density hinders galaxy formation.
6. How does the idea of a multiverse explain the apparent fine-tuning of the cosmological constant?
7. Using the expression for the typical energy of the virtual pairs in the box at the end of Sect. 20.2, find the length scale L below which the particles of the pair would form a black hole. This is one of the ways to find the length scale at which quantum gravity effects become important. Does your answer agree with the result of the dimensional analysis in the box? (Hint: Particles having combined mass M form a black hole if they are localized within a sphere of radius smaller than the Schwarzschild radius $2\,GM/c^2$.)
8. Suppose the range of possible values of ρ_v is from $-10^{120}\rho_m$ to $+10^{120}\rho_m$, and the anthropic range allowing for the existence of life is from $-10^3\rho_m$ to $+10^3\rho_m$. Furthermore, suppose the energy landscape includes 10^{500} vacua. Estimate the number of vacua in the anthropic range.