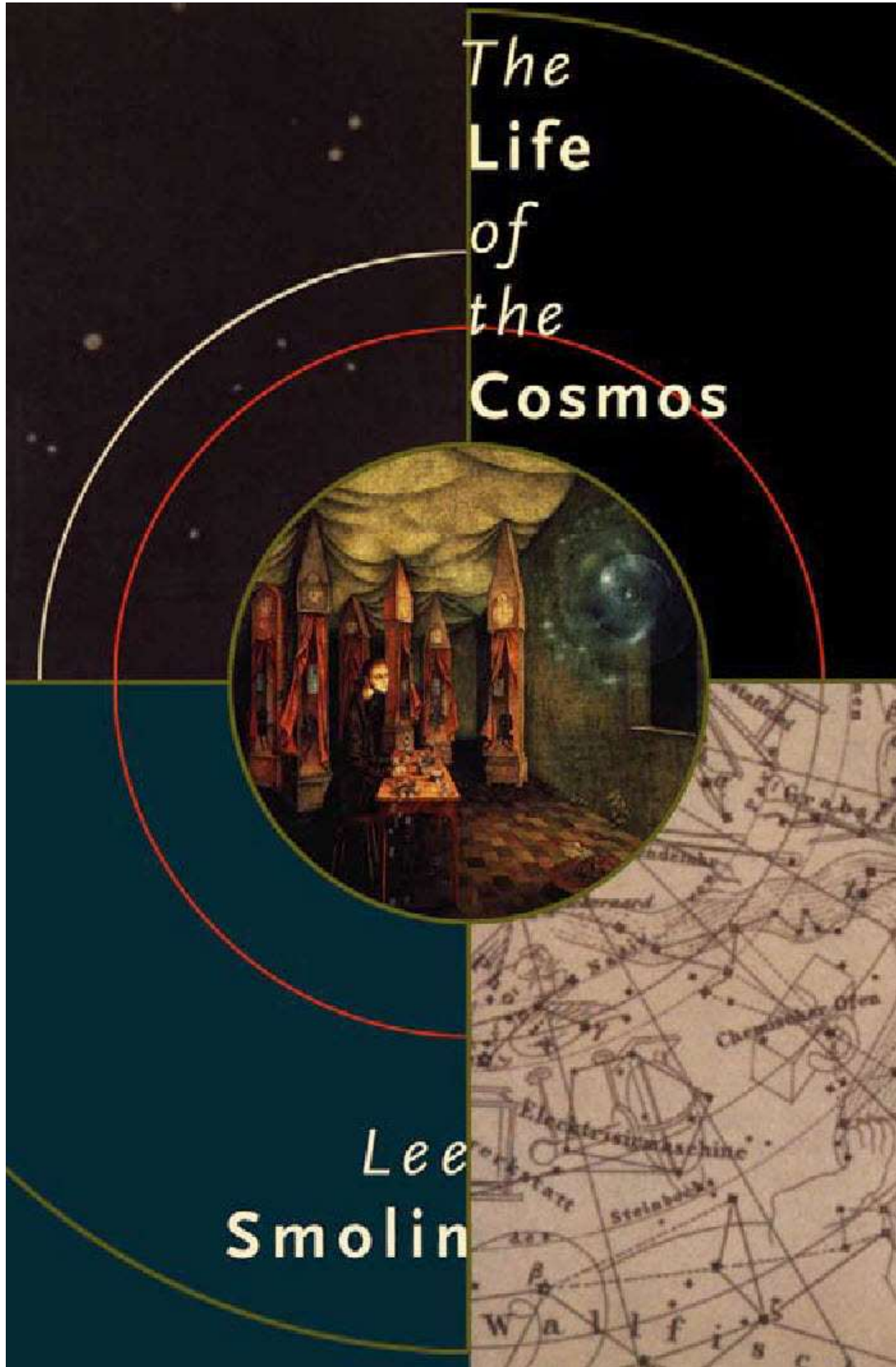


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Life of The Cosmos

By: Lee Smolin



- The theory that we do have, the standard model of particle physics, is very far from being unique. In spite of the fact that it represents our deepest knowledge about what the world is made of, it leaves open many questions about the properties of the elementary particles. These open questions have to do with the values of certain numbers that characterize the particles. These numbers measure things like the masses of the different particles and the strengths of their electrical charges. According to our best present understanding, these numbers are free to vary within wide ranges. They are then parameters, whose values may be set arbitrarily. Physicists set the values of the parameters so as to make the theory agree with observation. By doing so, for example, we make the electron, proton, neutron and neutrino all have the right masses. But as far as we can tell, the universe might have been created so that exactly the same laws are satisfied, except that the values of these parameters are tuned to different numbers. [Lee Smolin: *The Life of the Cosmos*, Oxford University Press, Inc., 1997. P37]
- There are about twenty of these parameters in the standard model of particle physics. The question about why the universe has stars can then be posed in the following way: We may imagine that God has a control panel on which there is a dial for each parameter. One dial sets the mass of the proton, another the electron's charge and so on. God closes his eyes and turns the dials randomly. The result is a world governed by the laws we know, but with random values of these parameters. What is the probability that the world so created would contain stars? The answer is that the probability is incredibly small. This is such an important conclusion that I will take a few pages to explain why it is true. In fact, the existence of stars rests on several delicate balances between the different forces in nature. These require that the parameters that govern how strongly these forces act be tuned just so. In many cases, a small turn of the dial in one direction or another results in a world not only without stars, but with much less structure than our universe. [Lee Smolin: *The Life of the Cosmos*, Oxford University Press, Inc., 1997. P37]
- The incredible smallness of the gravitational constant is one of the mysteries associated with the parameters of particle physics. Suppose we had a theory that explained the basic forces in the universe. That theory would have to

produce, out of some calculation, this ridiculous number, 10^{-38} . How is it that nature is so constructed that one of the key quantities that govern how it works at the fundamental level is so close to zero, but still not zero? This question is one of the most important unsolved mysteries in all of physics. It may seem strange that a force as weak as gravity plays such an important role on earth and in all the phenomena of astronomy and cosmology. The reason is that, in most circumstances, none of the other forces can act over large distances. For example, in the case of the electrical force, one almost always finds equal numbers of protons and electrons bound together, so that the total charge is zero. This is the reason that most objects, while being composed of enormous numbers of charges, do not attract each other electrically. [Lee Smolin: *The Life of the Cosmos*, Oxford University Press, Inc., 1997. P39]

- The incredible weakness of the gravitational constant turns out to be necessary for the existence of stars. Roughly speaking, this is because the weaker gravity is, the more protons must be piled on top of each other before the pressure in the center is strong enough that the nuclear reactions ignite. As a result, the number of atoms necessary to make a star turns out to grow as the gravitational constant decreases. Stars are so huge exactly because the gravitational constant is so tiny. It is fortunate for us that stars are so enormous, because this allows them to burn for billions of years. The more fuel a star contains the longer it can produce energy through nuclear fusion. As a result, a typical star lives for a long time, about ten billion years. [Lee Smolin: *The Life of the Cosmos*, Oxford University Press, Inc., 1997. P39].
- Were the gravitational force somewhat stronger than it actually is, stars would still exist, but they would be much smaller, and they would burn out very much faster. The effect is quite dramatic. If the gravitational force were stronger by only a factor of ten, the lifetime of a typical star would decrease from about ten billion years to the order of ten million years. If its strength were increased by still another factor of ten, making the gravitational force between two protons still an effect of order of one part in 10^{38} , the lifetime of a star would shrink to ten thousand years. [Lee Smolin: *The Life of the Cosmos*, Oxford University Press, Inc., 1997. P39]
- But the existence of stars requires not only that the gravitational force be

incredibly weak. Stars burn through nuclear reactions that fuse protons and neutrons into a succession of more and more massive nuclei. For these processes to take place, protons and neutrons must be able to stick together, creating a large number of different kinds of atomic nuclei. For this to happen, it turns out that the actual values of the masses of the elementary particles must be chosen very delicately. Other parameters, such as those that determine the strengths of the different forces, must also be carefully tuned. [Lee Smolin: *The Life of the Cosmos*, Oxford University Press, Inc., 1997. P39]

- Let us think of the three most familiar particles: the proton, neutron, and electron. The neutron, it turns out, has almost the same mass as the proton, it is in fact just slightly heavier, by about two parts in a thousand. In contrast, the electron is much lighter than either, it is about eighteen hundred times lighter than the proton. In the masses of these three particles there are as many mysteries. Why are the neutron and proton so close in mass? Why is the electron so much lighter than the other two particles? But what is most mysterious is that the two small numbers in this problem, the electron mass and the tiny amount by which a neutron is just slightly more massive than a proton, are quite comparable to each other. The neutron outweighs the proton by only about three electron masses. [Lee Smolin: *The Life of the Cosmos*, Oxford University Press, Inc., 1997. P39-40]
- We are so used to the idea that protons and neutrons stick together to make hundreds of different stable nuclei, that it is difficult to think of this as an unusual circumstance. But in fact it is. Were the electron's mass not about the same size as the amount that the neutron outweighs the proton, and were each of these not much smaller than the proton's mass, it would be impossible for nuclei to stick together to form stable nuclei. These are then facts of great importance for the world as we know it, for without the many different stable nuclei, there would be no nuclear or atomic physics, no stars and no chemistry. Such a world would be dramatically uninteresting. [Lee Smolin: *The Life of the Cosmos*, Oxford University Press, Inc., 1997. P41]
- Since stars cannot burn if there are not stable nuclei, only those possible universes that lie within that small region may have stars. These are not the only parameters that must be tuned carefully if there are to be stars. For

example, there is the mass of the neutrino. Here we face an embarrassing situation: we still do not know whether the neutrino has any mass at all. The experimental evidence is inconclusive, but we can assert that if it does have a mass, it is no more than one hundred thousandth that of the electron. But in spite of our ignorance as to its actual value, we do know that the mass of the neutrino cannot be too large if the nuclear reactions that energize the stars are to happen. [Lee Smolin: *The Life of the Cosmos*, Oxford University Press, Inc., 1997. P41]

- While we are discussing physical constants that must be finely tuned for the universe to contain stars, we may consider another kind of question. Why is the universe big enough that there is room for stars? Why is it not much smaller, perhaps even smaller than an atom? And why does the universe live for billions of years, which is long enough for stars to form? Why should it not instead live just a few seconds? These may seem silly questions, but they are not, because the fact that the universe can become very big and very old depends on a particular parameter of the standard model being extremely tiny. This parameter is called the cosmological constant. [Lee Smolin: *The Life of the Cosmos*, Oxford University Press, Inc., 1997. P41]
- The cosmological constant can be understood as measuring a certain intrinsic density of mass or energy, associated with empty space. That a volume of empty space might itself have mass is a possibility allowed by Einstein's general theory of relativity. If this were si/able, it would be felt by matter, and this would effect the evolution of the universe as a whole. For example, were there enough of it, the whole universe would quickly pull together and collapse gravitationally, as a dead star collapses to a black hole. In order that this not happen, the mass associated with the cosmological constant must be much smaller than any of the masses we have so far mentioned. In units of the proton mass, it can be no larger than about 10^{-40} . If this were not the case, the universe would not live long enough to produce stars. [Lee Smolin: *The Life of the Cosmos*, Oxford University Press, Inc., 1997. P41]
- It seems that physics is full of ridiculously tiny numbers. For example, we may wonder what might be the most massive elementary particle that could be imagined. This is one that would be so massive that it would be overwhelmed by its own gravitational force and collapse instantly to a black

hole. There is an actual mass, above which this must happen. It is called the Planck mass, after Max Planck, the founder of quantum mechanics. The Planck mass is enormous compared to the scale of the elementary particles. In units of the proton mass it would be about 10^{19} . In ordinary units it is about 10^{-5} of a gram—about the size of a living cell. To turn it around, this means that in units of the largest possible mass, the proton's mass is 10^{-19} , the electron's is 10^{-22} and the cosmological constant is no larger than 10^{-60} . [Lee Smolin: *The Life of the Cosmos*, Oxford University Press, Inc., 1997. P41-42]

- To an elementary particle theorist, there is no greater mystery than the values of the different masses of which we have been speaking. Mystery number one is why the proton mass is so tiny compared to the Planck mass. Mystery number two is why the cosmological constant is so much tinier still. Between the scale of the cosmological constant and the Planck mass is a ratio of 10^{60} . It is extraordinary that such a huge ratio should come into fundamental physics. But this is not all. Taking these values into account, it turns out, apparently coincidentally, that the lifetime of a typical star is about the same as the lifetime of the universe, measured as best we can by the speed of its expansion. Why should the expansion rate of the universe have been set to the scale of the lifetime of stars, if the first stars formed millions of years after the big bang? What kind of physical mechanism could account for this? It is in mysteries like this that we see most clearly the limitations of the philosophy of radical atomism, according to which properties of the elementary particles (such as the mass of the proton or the strength of the gravitational force) should have nothing to do with the history of the universe. [Lee Smolin: *The Life of the Cosmos*, Oxford University Press, Inc., 1997. P42]
- The importance of electromagnetism for our modern picture of nature cannot be overstated, as almost all of the phenomena of everyday life which are not due to gravity are manifestations of it. For example, all chemistry is an aspect of electromagnetism. This is because chemical reactions involve rearrangements of electrons in their orbits around atomic nuclei, and it is the electrical force that holds the electrons in those orbits. Light is also an aspect of electromagnetism, for it is a wave traveling through the fields that convey the electric and magnetic forces. [Lee Smolin: *The Life of the Cosmos*,

Oxford University Press, Inc., 1997. P42]

- Electromagnetism differs in two important respects from gravity. The first is that the electrical force between two fundamental particles is much stronger than their gravitational attraction. The strength of the electrical interaction is measured by a number, which was called alpha by the physicists of the last century, because it is a number of the first importance for science. Alpha, which is essentially a measure of the strength of the electric force between two protons or electrons, has a value of approximately $1/137$. Physicists have been wondering about why alpha has this value, without resolution, for the whole of the twentieth century. The second way in which electricity differs from gravity is that its effect is not only attractive: two electrical charges may attract or repel each other, depending on whether they are like or unlike. [Lee Smolin: *The Life of the Cosmos*, Oxford University Press, Inc., 1997. P42-43]
- However, the existence of electrical forces makes another problem for stars. Like charges repel, and the nucleus of most atoms contain a number of protons, all of like charge, which are packed closely together. What keeps the nuclei from being blown apart by the repulsion of all the protons in them? There is no way either electricity or gravity could save the situation. What is needed if nuclei are to exist is another force with certain properties. It must act attractively among protons and neutrons, in order to hold the atomic nuclei together. It must be strong enough to counteract the repulsions of all the protons. But it cannot be too strong, otherwise it would be too difficult to break the nuclei apart, and chain reactions of nuclear reactions could not take place inside of stars. This force must also be short-ranged, otherwise there would be danger of its pulling all the protons and neutrons in the world together into one big nucleus. For the same reason, it cannot act on electrons, otherwise it would pull them into the nuclei, making molecules and chemistry impossible. It turns that there is a force with exactly these required properties. It is called the strong nuclear force, and it acts, as it should, only over a range which is more or less equal to the size of an atomic nucleus. [Lee Smolin: *The Life of the Cosmos*, Oxford University Press, Inc., 1997. P43]
- Remarkably, the existence of more than a hundred kinds of stable nuclei is

due to the fact that the strength of the attractive nuclear force balances quite well the electrical repulsion of the protons. To see this, it is necessary only to ask how much we have to increase the strength of the electrical force, or decrease the strength of the nuclear force, before no nuclei are stable. The answer is not much. If the strong interaction were only 50% weaker, the electrical repulsion is no longer overcome, and most nuclei become unstable. Going a bit further, perhaps to 25%, all nuclei fall apart. The same effect can also be achieved by holding the strong interaction unchanged and increasing the strength of the electrical repulsions by no more than a factor of about ten. Thus we see that the simple existence of many species of nuclei, and hence the possibility of a world with the complexity of ours, with many different types of molecules each with distinct chemical properties, is ultimately the result of a rather delicate balance between two of the basic interactions, the electromagnetic and strong nuclear force. [Lee Smolin: *The Life of the Cosmos*, Oxford University Press, Inc., 1997. P43]

- If we are to genuinely understand our universe, these relations, between the structures on large scales and the elementary particles, must be understood as being something other than coincidence. We must understand how it came to be that the parameters that govern the elementary particles and their interactions are tuned and balanced in such a way that a universe of such variety and complexity arises. Of course, it is always possible that this is just coincidence. Perhaps before going further we should ask just how probable is it that a universe created by randomly choosing the parameters will contain stars. Given what we have already said, it is simple to estimate this probability. For those readers who are interested, the arithmetic is in the notes. The answer, in round numbers, comes to about one chance in 10^{229} . [Lee Smolin: *The Life of the Cosmos*, Oxford University Press, Inc., 1997. P44-45]
- To illustrate how truly ridiculous this number is, we might note that the part of the universe we can see from earth contains about 1022 stars which together contain about 1080 protons and neutrons. These numbers are gigantic, but they are infinitesimal compared to 10^{229} . In my opinion, a probability this tiny is not something we can let go unexplained. Luck will certainly not do here; we need some rational explanation of how something this unlikely turned out to be the case. [Lee Smolin: *The Life of the Cosmos*,

Oxford University Press, Inc., 1997. P45]

- I know of three directions in which we might search for the reason why the parameters are tuned to such unlikely values. The first is towards some version of the anthropic principle. One may say that one believes that there is a god who created the world in this way, so there would arise rational creatures who would love him. We may even imagine that he prefers our love of him to be a rational choice made after we understand how unlikely our own existence is. While there is little I can say against religious faith, one must recognize that this is mysticism, in the sense that it makes the answers to scientific questions dependent on a faith about something outside the domain of rationality. [Lee Smolin: *The Life of the Cosmos*, Oxford University Press, Inc., 1997. P45]
- A different form of the anthropic principle begins with the hypothesis that there are a very large number of universes. In each the parameters are chosen randomly. If there are at least 10^{229} of them then it becomes probable that at least one of them will by chance contain stars. The problem with this is that it makes it possible to explain almost anything, for among the universes one can find most of the other equally unlikely possibilities. To argue this way is not to reason, it is simply to give up looking for a rational explanation. Had this kind of reasoning been applied to biology, the principle of natural selection would never have been found. [Lee Smolin: *The Life of the Cosmos*, Oxford University Press, Inc., 1997. P45]
- A second approach to explaining the parameters is the hypothesis that there is only a single unique mathematically consistent theory of the whole universe. If that theory were found, we would simply have no choice but to accept it as the explanation. But imagine what sense we could then make of our existence in the world. It strains credulity to imagine that mathematical consistency could be the sole reason for the parameters to have the extraordinarily unlikely values that result in a world with stars and life. In the end mathematics alone wins us our one chance in 10^{229} we would have little choice but to become mystics. This would be an even purer mysticism than the anthropic principle because then even God would have had no choice in the creation of the world. [Lee Smolin: *The Life of the Cosmos*, Oxford University Press, Inc., 1997. P45]

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