ANTHROPIC QUESTIONS

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The goal of science is to understand the natural universe as well as possible. After 400 years since Galileo and Kepler and others began modern science, we have succeeded in understanding the physical world around us. We know the particles (electrons, and particles like electrons but with an extra interaction, called quarks) that make up all that we see, from flowers to people to stars. We know how the particles interact through the gravitational and electromagnetic and strong and weak forces, according to the rules of quantum theory, to form the complexity and beauty of our world. We know the history of our planet and our sun and our universe back to their beginnings. Our description is a fully mathematical theory that is very well tested and established, called the Standard Models of particle physics and of cosmology (forgive the mundane names - the names arise as the phenomena are being studied and then it is hard to change them). Now we would like to understand why it is these particles and these interactions, why they have the properties they do, and to explain as much as possible about why the universe not only works as it does but even why it exists at all, and why we exist.

With the Standard Models we can formulate such questions scientifically. We can work out how various quantities and forces affect the conditions for life. For example, we know that carbon and other heavier elements are necessary for our life. In the big bang only helium and hydrogen are made in large quantities. Carbon and heavier elements are made in stars, and then distributed over large regions when the stars die in supernova explosions after billions of years. That means life could only arise on the second or third generation planets that incorporate the heavy elements, after they were formed in a first or second-generation star. So we can basically understand a "why" question, "why is our universe so old as it is (about 13 billion years)". It is because universes with life like us have to be at least a few billion years old, so stars will have formed and died. We also understand why the universe is not very much older because after many billion years it will have expanded to have such a small density in any region that solar systems with planets will no longer form.

Some aspects of how things work seem to have to be rather precise if life is to exist. One example is the strengths of the forces. Stars "burn" protons to make the light that provides energy for us to live. To give life time to evolve stars need to live billions of years. The rate at which stars burn protons depends on a balance between the attractive strong force and the repulsive electromagnetic force. It was realized in the 1960s that if the strong force were a little stronger, only a few percent, stars would burn too fast and only provide light for a few years. Similar reasoning tells us that all the forces have to be about the strength they are or we would not exist. Can we explain why the forces have to be "just so" in astronomer Craig Hogan's phrase?

It turns out that such arguments are less stringent as they first seemed to be. More recently we have understood that the forces are not to be thought of independently. They can be unified, in an extension of the Standard Model for which there is good indirect evidence, called the supersymmetric Standard Model, or a string theory. Then if we imaging increasing the strong force we must simultaneously increase the electromagnetic force. The increased attraction of the strong force is balanced by an increased repulsion from the electromagnetic force, and the amount of increase that allows life is significantly larger than if we treat them independently. Even then, though, there is still a limited range of strengths that allows life - if the force strengths were very much larger than they are the world would be a lot different. It is an interesting and legitimate question to ask if we can understand why the force strengths are what they are.

I and many scientists think of these and similar questions about particle properties and other quantities as "anthropic questions" that we would like to answer. We would like to understand why the force strengths are what they are. Other issues that need understanding are (1) a complicated relation between the masses of the up and down quarks and the electron, (2) a quantity that affects the curvature of the universe, called the "cosmological constant", whose actual value is much smaller than the value simple calculations imply for it. Unless these quantities don't differ much from what they actually are we would not exist. Although all the needed analyses have not yet been carried out, I think most of the anthropic quantities that have to be "just so" in order for us to exist can be reduced to these three in the unified theories today.

In the past there were more anthropic questions that have since been explained by normal physics, so an anthropic explanation is not needed. Probably the universe went through what is called inflation, a very early period of rapid increase in size, called inflation, which culminated in the big bang expansion. Then the resulting universe would live a long time, so we have a likely explanation of why the universe is old. Another example is that the universe is made of matter but not antimatter. If there were equal amounts of each probably life would not exist, because matter and antimatter annihilate each other, leaving too little matter to form galaxies and stars. We do not yet know for sure how the universe evolves from an initial state with equal amounts of matter and antimatter to today's asymmetry, but there are several possible explanations that are being explored and tested. We expect one of them to be valid so we think we will understand the matter asymmetry. We don't know yet if all the anthropic questions will be explained, but the remaining three described above are all addressed by supersymmetric string theory, so we hope they will be.

As people recognized the existence of anthropic questions over recent decades a variety of reactions occurred. Some scientists are annoyed by them, basically saying that anthropic explanations (such as something is the way it is because if it were not we would not be here to ask) are not explanations and science can do better. Others, including distinguished leaders such as Vaclav Havel (who have been unhappy that we learned in the past century that the earth was not only not the center of the universe, it was one planet in one of a huge number of solar systems in one of a huge number of galaxies, and the particles we are made of are not even the main form of matter in the universe) reacted by saying the need for anthropic explanations puts us back at the center because the universe is arranged so humans can exist. That argument seems to be refuted by recalling that the conditions for life on earth led to a world dominated by dinosaurs for over a hundred million years, until an accidental collision with an asteroid destroyed the dinosaurs and allowed mammals to evolve in new directions. Others have reacted by defining "anthropic principles" that are hypotheses for explaining anthropic questions. A widely accepted one is the reasonable Weak Anthropic Principle which roughly says that the forces and particles and laws must be such as to allow the universe to contain intelligent life, since we know that it does. There are a number of other versions of anthropic principles, including stronger ones, but for science it is understanding anthropic (i.e. "just so" phenomena) questions that is relevant, not formulating principles that may mislead us into missing some understanding.

Suppose one day we have a theory in which all anthropic questions are answered, in the sense that once the theory is written calculations correctly predict all the quantities that have to be just so for us to exist. Some people may still have an uncomfortable feeling, asking why the theory is one that leads to life instead of one that does not, and considering possible implications of that. Such a question is illuminated and perhaps answered by another feature of recent theories - today's theories seem to imply the existence of many "universes". These are not yet fully understood results, so "universes" is in quotes because its meaning is uncertain. It may be that they are all to be thought of as domains of one inclusive universe, or as entirely separate ones. Two paths at least lead to such ideas. One is inflation - inflation can happen repeatedly, even to small pieces of existing universes, with each patch that inflates turning effectively into a universe.

The second is string theory. In science theories provide equations or principles, and the behavior of actual phenomena are the solutions of the equations. A system will, most of the time, be in its state of least energy, the ground state, just as a ball will bounce down a hill to the bottom. A universe, like an atom, may form in any of many states, and it will settle into its ground state. It turns out that string theory implies a large number of apparently equivalent ground states. All of them may lead to universes. Both inflation and string theory may lead to many multiple universes.

One aspect of our universe we want to understand is the fact that we live in three space dimensions. There is an anthropic explanation. It was realized about a century ago that planetary orbits are not stable in four or more space dimensions, so planets would not orbit a sun long enough for life to originate. For the same reason atoms are not stable in four or more space dimensions. And in two or one space dimensions there can be neither blood flow nor large numbers of neuron connections. Thus interesting life can only exist in three dimensions. Alternatively, it may be that we can derive the fact that we live in three dimensions, because the unique ground state of the relevant string theory turns out to have three large dimensions (plus perhaps some small ones we are not normally aware of). Or string theory may have many states with three space dimensions, and all of them may give universes that contain life.

Each of the multitude of universes may have different laws of nature, or different values of quantities that determine how they behave, such as the speed of light or Planck's constant that determines the size of quanta in quantum theory. Some may be suitable for life and some may not. All those suitable for life may have life develop. Sometimes life will evolve into dinosaurs rather than something more intelligent. We cannot attach any meaning to the fact that a life form did develop in at least one universe that could ask anthropic questions. It is very much like a lottery. If you win the lottery you may feel very grateful, but someone had to win and no one selected whom that was, except randomly. Having a unique set of laws and parameters should not lead one to wonder if that set was designed.

One might worry that the multiple universe approach implies that we cannot hope to calculate and understand all the parameters of a physical theory from fundamental principles, since their values can differ from one universe to another. Hogan, for example, has argued that even a fully unified theory will not allow the calculation of all quark masses, in order to allow for different worlds to have different values for them. But from the string theory or inflation point of view each world leads to its own full set of masses and other quantities and laws. In any of them that we can study experimentally we may be able to learn to understand the laws and calculate the basic parameters.

At the present time neither inflation nor string theory are well enough understood to calculate how many universes there are, or even whether the number is finite or infinite, nor in what senses the laws of nature and the quantities that enter the equations can differ, so these arguments are informed speculation. But to many people it is exciting that these ideas are now finally the subject of basic physics research.