Chapter 13
The Multiverse

In the last chapter we considered evidence that the universe began with a period of rapid inflation. Data from the CMB, type Ia supernovae, and other observations indicate that our universe includes substantial components of dark energy and dark matter giving it just exactly critical density and a very small cosmological constant. That begs the questions: what caused the inflation? From what pre-existing conditions? And why is our universe apparently fine-tuned, just right for our existence?

In this chapter, we present arguments at the interface between quantum mechanics and cosmology. According to models favored at present (2016), our universe originated as a fluctuation in a scalar field. Phase transitions in the field caused inflation and released enormous energy. Hence our universe.

But if our universe resulted from such a process, there must be other universes produced by the same mechanisms. Theory implies that those universes may operate under very different physical laws. Ours, if this scenario is correct, is just one of an infinite number of universes. That there is such a universe “fine-tuned” for our existence follows from the statistics of large numbers. Out of an infinite number of possible universes, chances are one of them (or many, or an infinite number) will have conditions in which life and consciousness evolve.

Quantum fields and a universe from nothing

Where did it come from, this universe of ours? All those galaxies in clusters scattered across the sky, and twenty times more stuff we can’t see, the dark matter and dark energy? Here’s where the physics of the very large scale, the universe, meets the very smallest scale, quantum fields.

Our familiar world includes the stuff accessible to our senses. We pay most attention to solids and motion and light, but the world is filled with matter in various states, sounds, and chemicals we can taste and smell. Quantum physics claims that fields underlie all phenomena. Mass/energy generates a gravitational field. A moving electric charge generates an electromagnetic field. All the particles and forces of nature have associated fields. More properly, what we regard and particles and forces are manifestations of the underlying fields.

As a rough analogy, think of a boat out on the ocean. Waves represent a field interacting with the boat. The boat rises and falls in response to changes in the field. Crew occasionally detect particle spray generated by the field.

Fields themselves may undergo changes of state. Again in rough analogy, those waves out on the ocean may evaporate, or they may freeze.

Prior to the universe, the thinking goes, was a scalar field. “Scalar” means the field had no preferred direction and its value could be measured at each point in space-time. One value describes the field at each point.

The primordial field had an associated energy. This field was unusual (though not unique) in that the minimum energy state sat at a non-zero field value. In such a field, it takes work to push the field value to zero. Or, looking at it the other way, if the field value starts at zero, the state will roll down the energy hill driving the field to a non-zero value at the energy minimum. The process can release a lot of energy. Maybe a universe.

(figure – slow roll)

A warning: energy is a relative value. We can only compare energies in two different states. Lift a can of soup to the shelf, and it has greater potential energy than when it was in the box on the floor, but it has lower energy than the cans on the shelf above. “Zero energy” more properly should be described as the lowest available energy state in a system compared to other states.

Physicists give the primordial field a name: the “inflaton” field, the field that caused inflation. We don’t know its exact nature. We do know, however, that such scalar fields exist. The Higgs field is such a creature. It takes a non-zero value in the vacuum. And we have detected its presence by producing Higgs field quanta, the Higgs particle, in accelerator experiments.

Other plausible scenarios have been proposed. One of the simplest, by Andre Linde, starts with a scalar field that oscillates because of quantum fluctuations around its minimum. If the Hubble value, measuring the ratio of the rate of expansion to the size of the universe, depends on the square of the field value, oscillations can bring the universe into a regime of inflation.

Here’s the math, using Linde’s original inflation model. Suppose the Hubble parameter, the ratio of the rate of expansion to the scale factor (size of the universe), is proportional to the inflaton field.

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{m^2}{2}\varphi^2 \qquad 13.1$$

Suppose, further, the field φ obeys the wave equation. That is, there is a restoring force that returns the field to its equilibrium value if it is displaced, just as mass on a spring returns to its resting position (and overshoots and continues to oscillate) when the spring is stretched.

$$\ddot{\varphi} + 3H\dot{\varphi} = -m^2\varphi \qquad (13.2)$$

The coefficient $3H$ on the left hand side is the viscosity term. It determines the rate of fluctuation of the field in a viscous medium, as if our mass-on-spring was oscillating in water, not in the air. By equation 13.1, H is proportional to the field, so the greater the field the more viscous it is. At high field strength, the field changes very slowly. This is the regime of inflation. We have

$$\left(\frac{\dot{a}}{a}\right)^2 = H^2 \qquad (13.3)$$

Solving for the scale factor

$$a = a_0 e^{Ht} \qquad (13.4)$$

The universe grows exponentially with time.

(figure – Linde's field)

Esoteric stuff, and hard to picture. Maybe think of it this way. Watch a pot of water start to boil. At first you see tiny bubbles of steam form on the bottom then disappear. You can hear the bang as they collapse. Later, as the temperature rises, the bubbles get bigger and last longer. Finally, when the pot reaches full boil, steam bubbles burst into the surrounding liquid and continue to expand as they rise to the surface.

(figure – boiling water)

As we'll see, this may not be such a far-fetched analogy to universes bubbling out of the Calabi-Yau string vacuum.

The Big Bang

So far we've got inflationary expansion but no universe. There's nothing yet in the vacuum. No stars or galaxies. No light. No protons or electrons. No stuff. How do we get stuff out of the vacuum?

By phase transition. As the inflaton field rolls to a new, lower energy, it undergoes a series of phase transitions, dumping energy into the creation of particles. Like raindrops forming out of vapor in a cloud.

Or perhaps it's Calabi-Yau dimensions unrolling. Those dimensions carry new fields, new particles.

Because of quantum fluctuations in the value of the inflaton field, phase transitions occurred at different times in different regions of the vacuum. That's why we see those temperature fluctuations on the CMB. Different patches of sky precipitated out earlier, so had more time to cool. Other patches precipitated out later and didn't have as much time to expand and cool by the usual thermodynamic processes of our universe.

(figure – CMB as differential cooling)

The multiverse

Such a scenario allows at least two mechanisms for a multiverse.

A what?

Multiverse is the notion that ours is just one of many, maybe an infinite number, of other universes. Those universes may be spatially separated, or they may overlap but operate on different physical laws, so we can't detect them.

One way to get a multiverse is by "eternal inflation." During inflation, exponential expansion outpaces the expansion of any universe that has bubbled out by a phase transition. Because of quantum fluctuations in the field, different regions of the field cross the critical boundary for phase transition at different times, pushed away from each other faster than they can grow. The result is inflation forever and multiple universes bubbling out of the inflaton field.

Alternatively, maybe a multiverse originated a step back. Maybe quantum fluctuations in the inflaton field initiated inflation here and there so there's a multiverse of multiverses. Physicists have proposed other model multiverses, as well.

String theory and the cosmic landscape

Here's where string theory and the multiverse overlap.

String theory offers an over-abundance of riches. It's not a simple set of equations with clear solutions. Not at all. It's a tangled morass, with a zillion possible solutions depending on the exact configuration of the underlying Calabi-Yau vacuum. String theorists were hoping to derive a theory of everything, a tidy package that predicts all the particles and forces. Instead they got a theory of everything and nothing. Some solutions look kind of sort of like our familiar laws of nature, others nothing like.

Then a light went on. Wait a minute. Maybe all those solutions (estimates are in the range 10^{500}), all those vacuum configurations, are describing different universes. String theory may be describing a cosmic landscape. A multiverse.

We have a grand convergence. Inflation theory, well supported by observational data, meets string theory, well supported by rigorous mathematical logic. And, all of a sudden, the path lies open to solve a whole bunch of outstanding questions, like the fine-tuning problem.

Fine tuning and the multiverse

Physicists have long puzzled why the constants of nature have the values they do. Why is the mass of the electron only about one two-thousandths the mass of the proton? Why is the neutron slightly more massive than the proton, and not vice versa? Why is the vacuum energy only very slightly greater than zero, to about one part in 10^{120} ? If any of these parameters – or any of a long list of other physical constants – were different, the universe would be a very different place, and we wouldn't be here to observe it.

There are several possible explanations. God made the universe just so, with all the parameters fine-tuned for our existence. Or the underlying laws of nature require those values; we just haven't yet discovered the underlying laws, the theory of everything.

Starting out in left field a few decades back was the anthropic conjecture. The universe is the way it is because we are here to observe it. At first it seemed nonsense, or just trivial. If it was a different universe, we wouldn't be here. So what? How does that conjecture contribute to our understanding?

The multiverse shows how. If there are an infinite number of universes, each of them with a different set of physical laws, chances are one of them, or many, will have conditions that allow life. We live in one such universe. It's just the statistics of large numbers. Someone wins the lottery, guaranteed, even though the chances you yourself will win are exceedingly small.

It's the same observation, essentially, as why is there life on earth? There are zillions of planets out there. Why earth? Well, only a few planets among the zillions have conditions – temperature, radiation flux, presence of liquid water, etc. – conducive to life. We are here because our planet happens to have those conditions.

Physicists haven't given up the search for a final theory, a theory in which all the numbers – particle masses, fine structure constant, vacuum energy, etc. – all emerge naturally from the equations. Maybe we just haven't yet understood string theory, or maybe there's another, better theory awaiting discovery. Perhaps. But consensus is building that we may have reached a final understanding (at least in terms of the science) why the universe is the way it is and why we find ourselves here in it.

And if we have understood, then we've just scratched the surface. There's an infinitude of other universes left to explore.

Is it science?

Hold on a gol-durn minute. This is all theoretical speculation. It's not science, is it? It can't be tested. You can't measure the properties of other universes. Even if they exist, they operate under different physical laws. We don't have measuring tools constructed on those laws to measure their properties (but maybe – see below). The hypothesis cannot be falsified. There's no experiment you can perform to prove the hypothesis wrong. So it's not science.

Well . . . consider for a moment. The theory has in fact been tested, and it has passed all the tests so far. Other theories, meanwhile, have been proven wrong. The theory of inflation is very well supported by the evidence – CMB, CMB power spectrum, detection of dark energy, and other measures discussed in the previous chapter. By those measures and others, the predictions of inflation theory pass every test. And that's science. The multiverse is part of the package of inflation theory. If a hypothesis is supported by all the available evidence, and other hypotheses have been disproven, then we have some confidence that it is a good approximation to the truth. Or, in the words of Sherlock Holmes (via Andrei Linde), "once you eliminate the impossible, whatever remains, no matter how improbable, must be the truth."

And, by golly, we might even be able to detect those other universes after all. The essential element of (at least some of the versions of) string theory is the graviton. So gravity may be common to other universes, and maybe we can listen in on gravity waves from those universes. The LIGO team has just announced (2016) the detection of gravitational waves generated 1.3 billion years ago when two black holes went into a death spiral and merged. LIGO and its sisters open a whole new window on the universe(s), listening to gravity waves generated by super-massive objects and, possibly, the birth of our universe and others.

Or, consider this. Maybe, just maybe, we can produce other universes in the laboratory. If we can figure out how to tickle the scalar field, perhaps at high enough energies in particle accelerators, we might create a bubble universe. (Which may or may not be such a good idea . . .)

Gravy

The multiverse serves up some philosophical gravy, too. Among his many trenchant observations, Einstein famously said "the most incomprehensible thing about the universe is that it is comprehensible." Over the years I've interpreted the statement as a comment on the advance of science. Generations of searchers have pieced together a consistent story, how the universe got here and why it is the way it is. Isn't it amazing that we've done so? But, as Andrei Linde points out, the statement might even probe deeper. It goes to the "unreasonable effectiveness of mathematics in the natural sciences" (Wigner, Eugene Wigner, and many others, have pointed out the mystery. Why is it that mathematical logic, an apparently human invention, is so successful at describing the workings of nature and predicting new phenomena not yet observed? Maybe the multiverse solves the mystery.

Life as we know it originated in a universe with particular physical laws. It was those laws, in this particular universe, that allowed life. From the most primitive life forms, the molecular genetic code has captured information about structure and processes necessary to survive and reproduce. That information encodes the operative laws in this universe. Our cells carry that information. Our brains use that information to drive the thought process. The laws, perhaps, are wired into us. Our equations are expressing those laws, as understood and tested by 3.8 billion years of evolution. We are the laws.

Who knows what other laws, what other philosophies and philosophers, are out there in the multiverse.

References:

Wigner, Eugene. 1960. The Unreasonable Effectiveness of Mathematics in the Natural Sciences. Communications in Pure and Applied Mathematics, vol. 13, No. I.