3

Cosmic Evolution

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My topics are evolution on the grand scale and how to picture the entire universe. My goal is to try to provide images of the universe that are consistent with what we now know. I will first discuss some older pictures of the universe and then introduce the geography of the universe as we currently understand it. I will summarize the evidence for the Hot Big Bang, the modern theory of the beginning of the universe. Then I will tell our best modern story of the evolution of the universe, according to the standard theory. Finally, I will present a unique way of visualizing the universe as a whole.

OLDER PICTURES OF THE UNIVERSE

There have been countless pictures of the universe in different cultures (Figure 3.1). One of the most common, used by peoples as varied as Nigerian, Hindu, Chinese, and Northern European, has been the symbol of a snake swallowing its tail. The biblical Middle East, on the other hand, had not so much a symbol as a picture of what they believed was the real structure of the world.

The Old Testament picture was of water below the land, flat earth, and a solid dome called the firmament holding up the water of the sky. This picture is presented in the first of the two Biblical creation stories (Gen. 1.1–2:4a). Then a little later there is the Noah story, where "the windows of heaven" open as well as "the foundations of the deep," and waters flood the land. This is not an ordinary rain but a cosmic catastrophe—God is changing the organization of the cosmos with the flood. But you cannot really understand this biblical story unless you know the picture of the universe that people had in mind in the ancient Middle East, according to stories told for thousands of years.

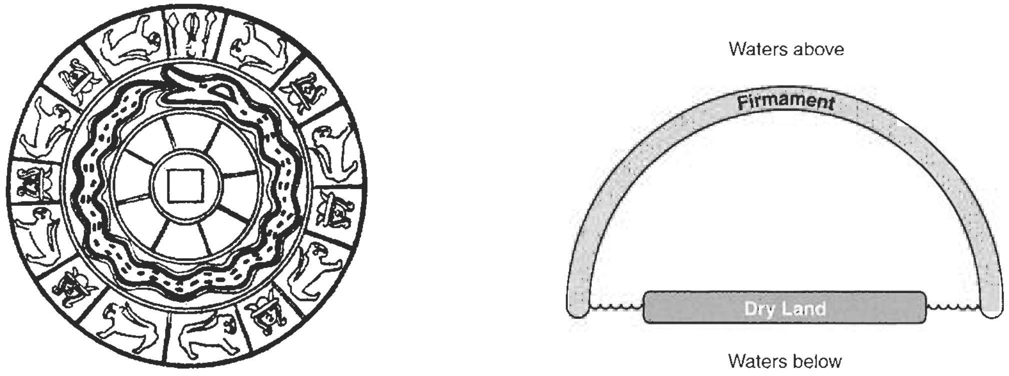
The Medieval picture had the moon, sun, planets, and stars riding on concentric spheres all revolving daily around the earth at the center. This was based on Greek ideas. It is completely different from the biblical picture but was not regarded as being in contradiction to it. The Newtonian picture is of a vast, infinite space in which stars are scattered randomly. Newtonian space is an arena, and time is absolute. What is our modern picture?

THE GEOGRAPHY OF THE VISIBLE UNIVERSE

One of the ways to visualize the modern universe is by a series of cosmic leaps (Figure 3.2).

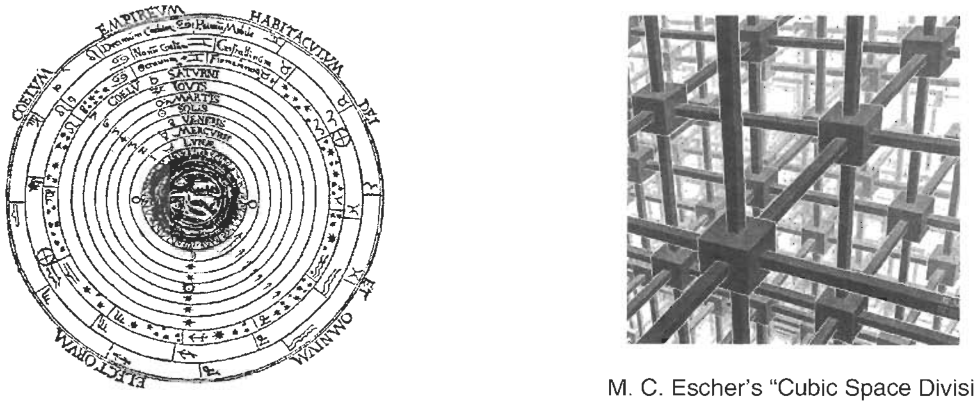
We know that we live on the third rock from the sun, the third of the rocky planets that are the inner planets of the solar system. The fourth is Mars. Then comes the asteroid belt, then four giant gaseous planets, small icy Pluto, and the much smaller icy comets. Light takes about half a day to cross the solar system, but it takes four years to get to the nearest star, and 100,000 years to cross the Milky Way (our galaxy). We live about two-thirds of the way out from the center of the Milky Way, near one of the spiral arms of our fairly large but typical spiral galaxy. Our galaxy is one of the two big galaxies of the thirty or so galaxies we call the Local Group, which is about 3 million light years across.

Hardly any galaxies are isolated. They usually come in little groups, or bigger groups, or clusters, which are then grouped into superclusters with voids in



(a) Traditional Uroboros

(b) Biblical



M. C. Escher's "Cubic Space Division"
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(c) Medieval

(d) Newtonian

*FIGURE 3.1 Traditional pictures of the universe. (**3.1a** From* Antique works of art from Benin, *Augustus Pitt-Rivers (London, 1900), reprinted (New York: Dover Publications, 1976), p. 37, plate 18, figure 102.* ***3.1b*** *From* The Disappearance of God: A Divine Mystery, *Richard Elliott Friedman (Little, Brown and Co., 1995), Figure 1, p. 232. Used with permission.* ***3.1c*** *From Peter Apian,* Cosmographicus liber, *ed. Gemma Frisius (Antwerp, 1533) in* The Cosmological Glass: Renaissance Diagrams of the Universe *(San Marino, CA: The Henry E. Huntington Library, 1977), Figure 28, p. 38.)*

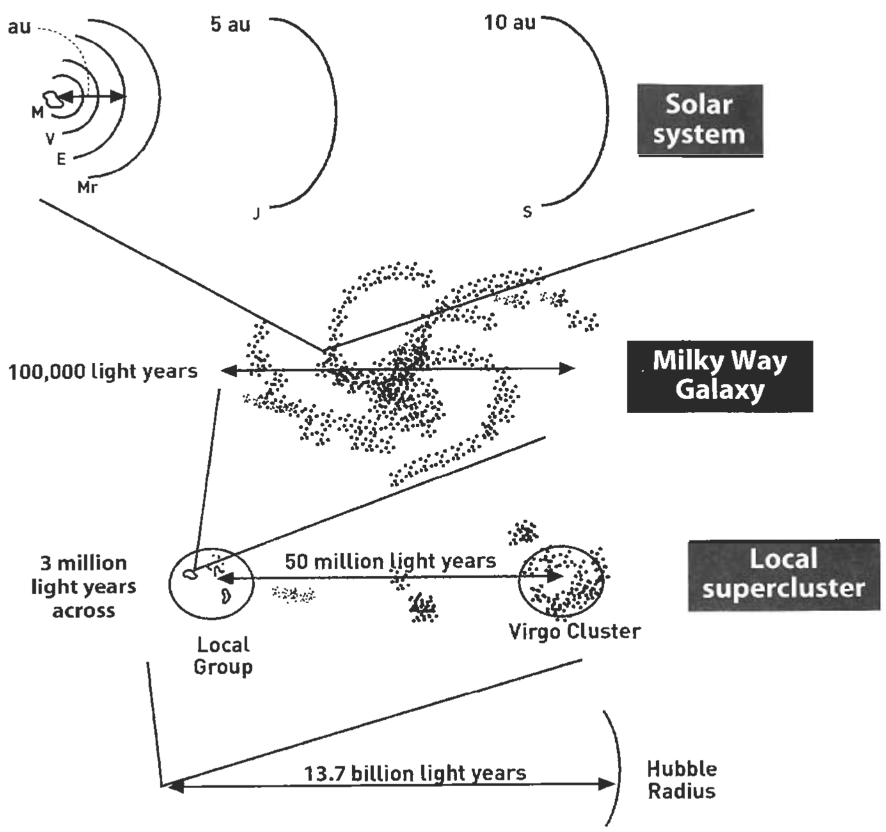


FIGURE 3.2 The "cosmography" of the universe. (au = astronomical unit—distance from Sun to Earth.)

between. The Local Group itself is part of a very large collection of roughly 10,000 galaxies that we call the Local Supercluster. About 50 million light years away from us, there is a cluster of perhaps 1000 galaxies, called the Virgo Cluster, which is more or less the center of the Local Supercluster. And all of this is but a dot on the scale of the whole visible universe—everything we can see out to the Hubble Radius.

How far is that? Well, we think that the universe started about 13.7 billion years ago. So we cannot see any farther back than about 13.7 billion light years. As we look out in space, we look back in time. In order to picture the universe, we have to think in both space and time. Now that is a tricky thing to do. Let me try to give you a sense of how you can picture that.

First, as we look back in space, we see light that has been traveling through expanding space. As space expands, the wavelength of the light expands. When we see it, the wavelength is bigger—sometimes much bigger. The red light in our spectrum has a bigger wavelength than blue light, and so this increase in wavelength is called "redshift." The amount of redshift tells us how much the universe expanded while the light was traveling.

You can picture space in many different ways, but spacetime you can only picture by slicing it. If you want to make a picture in two dimensions, you have to just represent two dimensions. Let one dimension, the radial distance outward, represent time. And the other dimension, around, represents space. If you want to imagine a second dimension of space, think of these circles as representing spheres that come out of this two-dimensional surface. But the full three dimensions of space and one dimension of time, a four-dimensional picture, we cannot represent on two dimensions. So think of a slice through it (Figure 3.3).

The first circle (dashed lines) represents all of space at an early time. Now consider a later time, let us say today. The point where the line labeled "lightcone" crosses another similar line represents "us"—our galaxy, now. We look back in time as we look out in space along our lightcone, and we see a galaxy as it was a long time ago. The light was emitted when the galaxy was far away from our galaxy. That distance is labeled "emission distance." The light then traveled toward us as space expanded. The galaxy that emitted the light is now farther away than when it emitted it, because space has expanded. Figure 3.3 also shows its distance now as we receive the light ("reception distance"). Note that at early times the lightcone approaches the origin of coordinates (the "Big Bang").

THE THREE PILLARS OF THE BIG BANG

Why should anybody believe that this curious picture is accurate? There are basically three main arguments in favor of this standard Big Bang picture: the Hubble expansion, the cosmic background radiation, and the abundance of the light

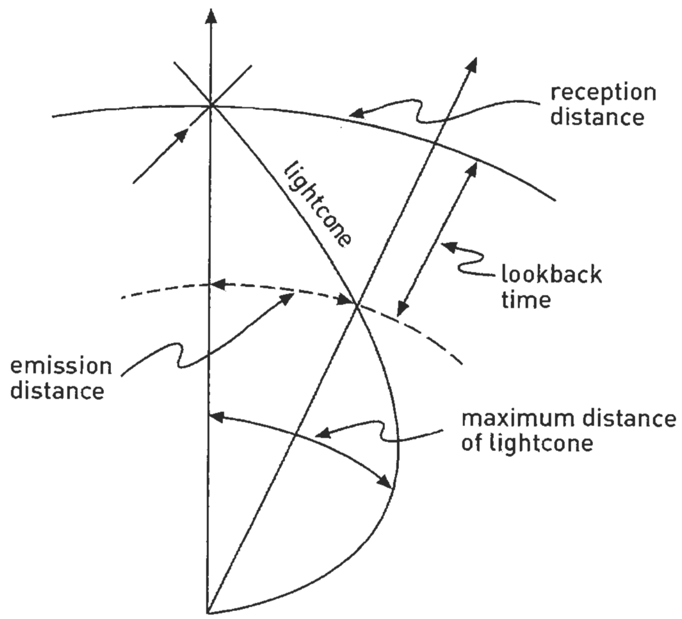


FIGURE 3.3 Picturing the expanding universe.

elements. I am going to go through these arguments in a little bit of detail. The conclusion is going to be that the universe, when it started, was filled with hot, dense, and very homogeneous gas.

The Hubble Expansion

The first piece of evidence is based on the Doppler effect. If you have a light source that is moving toward an observer, the light waves are squeezed together. To an observer watching from the opposite side, from which the source is moving away, the wavelength is expanded. We all have heard this effect. When an ambulance is coming toward us, we hear the sound or the siren at a higher pitch. As the vehicle passes us, the sound drops in pitch. This was demonstrated by the Dutch meteorologist Christopher Buijs-Ballot in 1845 by having trained musicians stand on the side of a railroad track while other musicians on a passing train played particular notes. The notes sounded sharp as the train approached and flat as it receded, just as Doppler's theory had proposed.

What makes this useful for astronomy is that chemical elements have characteristic energies. Hydrogen is the simplest of all. There is a certain characteristic pattern of energies, so that there are certain characteristic kinds of light that are emitted when transitions between energy levels take place. Light of characteristic colors is emitted when there is a transition downward, and the same wavelengths are absorbed when there is a transition upward. The pattern is unique for each chemical element. Light from a star like the sun has particular absorption lines indicating the presence of certain elements (for example, sodium). If you heat sodium, you see these same bright lines emitted as you see being absorbed in sunlight. And it is the pattern that is important. Now if you see those very same lines, but with the wrong colors, with the colors shifted, then you know that the source is moving toward you or away from you. If they are shifted toward the blue, then the source is moving toward you. If they are shifted toward the red, the source is moving away from you. This is the Doppler effect for light. And this is how we can measure the speed with which galaxies are moving toward or away from us.

Does this mean that we are at the center of an expanding system? Well, yes it does. Does this mean we are in an unusual position? No. Any other galaxy is also at the center. How can that be (Figure 3.4)?

Well, let us suppose we live in Galaxy A. You see on opposite sides Galaxies B and Z moving away. They are the same distance away moving at the same speed in opposite directions. Twice as far away is Galaxy C moving twice as fast. Galaxy D, three times as far away, is moving three times as fast.

Suppose we were instead sitting on Galaxy B. We would see exactly the same pattern. Galaxy A is moving away at the same speed that we thought Galaxy B was moving away. Galaxy Z, twice as far away, is moving twice as fast. Galaxy D is moving in the opposite direction twice as fast. I hope you can see that there is only one way that the universe can be homogeneous and also expanding. And that is for every point to be the center of expansion. Every point and no point. There is no center or, equally well, we are all at the centers. Nicholas of Cusa said something very much like that a hundred years before Copernicus.

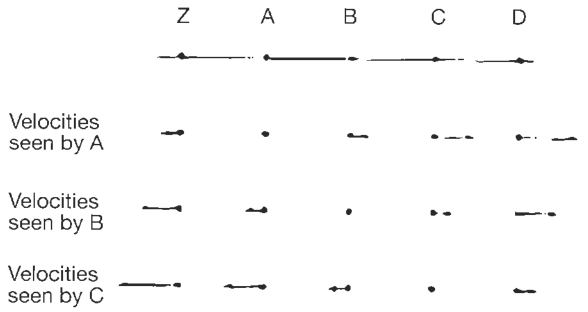


FIGURE 3.4 Every galaxy is at the center in a uniformly expanding universe. From The First Three Minutes *by Steven Weinberg (Basic Books, 1977), p. 22. Used with permission.*

Of the three pieces of evidence that I mentioned before, the one I have been discussing so far is the expansion of the universe, discovered by Edwin Hubble in 1929 by the method I have described, measuring the speed of a galaxy and relating that to its distance from us (Figure 3.5a). What one finds, even going out to much greater distances than Hubble could reach, is that the speed remains proportional to distance.

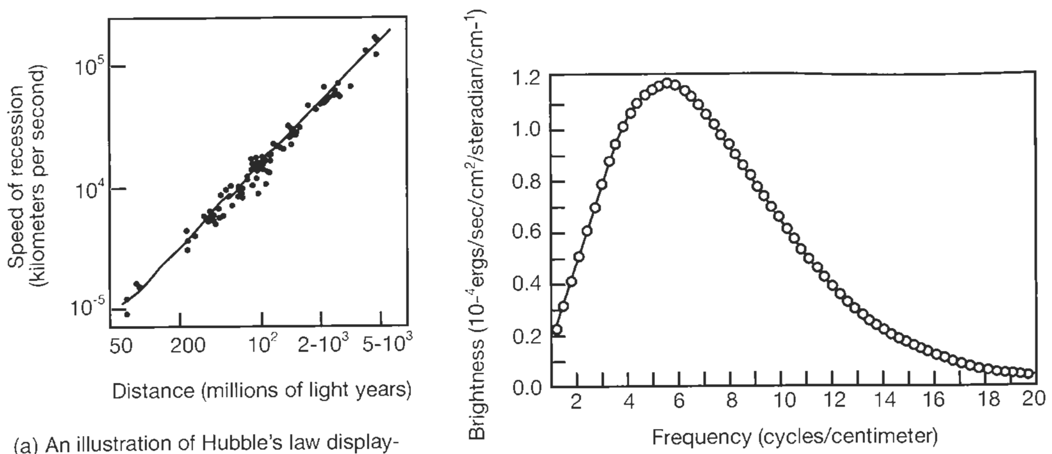
The Cosmic Microwave Background Radiation

At the turn of the twentieth century, Max Planck discovered the law of heat radiation, of the brightness versus the frequency of light. The dark line on Figure 3.5b is the Planck heat law. Heat radiation always follows that pattern. The little boxes represent the measurements of the Cosmic Background Explorer Satellite (COBE), which was put up in 1989 and was still working until 1993, when it was turned off. You will notice that the boxes fit perfectly on the line. Usually when you see a picture like this, the boxes represent the uncertainty. But if you actually represent the uncertainty in the measurements, the boxes would be much smaller than the line. They have been magnified 100 times. The data points fit so perfectly on the predicted line that you cannot see any deviation. In fact, the fit is better than a part in 10,000, which means that the radiation is definitely heat radiation.

What could have filled the entire universe with uniform heat radiation? No one has come up with an explanation other than the one proposed by George Lemaître in 1927: It is the heat left over from the Big Bang. Today we measure the temperature as about 2.7 degrees Kelvin. As you go back the temperature must go up.

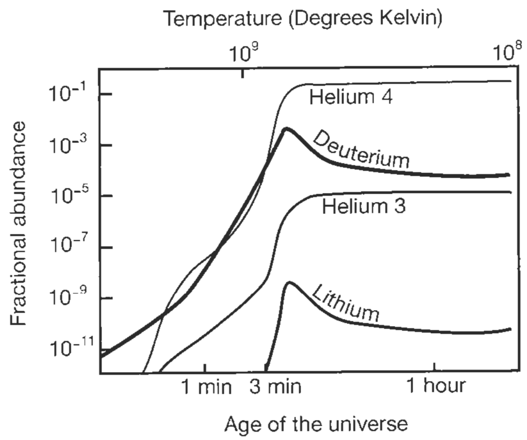
The Abundance of the Light Elements

At a time of around a minute after the Big Bang, the great fusion took place. Today fusion takes place inside the stars. But only a few percent of all the fusion that has occurred happened in the centers of stars. Almost all occurred within a



(a) An illustration of Hubble's law displaying the increase of recession speed of galaxies growing in direct proportion to their distance.

(b) The variation of the intensity of the microwave background radiation with its frequency as observed by the COBE satellite. The observations (boxes) match almost exactly the (solid) curve expected from pure heat radiation with a temperature of 2.73 K.



(c) The detailed production of lightest elements out of protons and neutrons in the first three minutes. The nuclear reactions occur rapidly when the temperature drops below a billion degrees Kelvin and then shut down because of the rapidly falling temperature and density of the expanding universe.)

FIGURE 3.5 Three pillars of the Big Bang.

few minutes after the Big Bang, when almost all of the helium in the universe was formed. First, deuterium (heavy hydrogen) formed, and then it was mostly locked up in helium. A mix of mostly hydrogen and helium, much less deuterium, then even less helium 3 and lithium, is the pattern predicted by standard Big Bang nucleosynthesis. That is exactly the pattern we see in the universe in the same ratios as predicted. These light elements are the relics of a few minutes, and as far as we can tell, the observed ratios agree very well with the predictions. If a theory is going to be right, it has to make lots of predictions—and lots of evidence must fit the predictions. That is the case with the Big Bang theory.

NEW PIECES OF EVIDENCE

Fluctuations in the Cosmic Microwave Background Radiation

Beside these three pillars of the Big Bang theory, there have been many recent discoveries that confirm predictions of the theory. One of the most important was the discovery that the temperature of space is not uniform in all directions. Although it is generally 2.7 degrees Kelvin in all directions, in the fifth decimal place there are slight differences in different directions. The size of these little temperature fluctuations was predicted in the early 1980s by the theory of cold dark matter (which I helped to invent and develop). COBE and subsequently a dozen more instruments have seen the differences just as they were predicted.

Supernovas of a particular kind, the brightest of all, can be seen at high redshift. They evolve more slowly than they are seen to evolve in the nearby universe by exactly the factor—1 plus the redshift—that they were predicted to have. We can now see them at a redshift of 0.9. They evolve almost a factor of 2 more slowly. They reach a maximum brightness; then the light falls off as much twice as slowly as nearby supernovas because of the expansion of the universe.

As I mentioned, temperature is predicted to increase with redshift. This increase is by the same factor I just mentioned, 1 plus the redshift. The temperature can be measured in galaxies in high redshift. The temperature should be higher, and sure enough it is exactly as predicted.

Gravitational Lensing

The final evidence that I will mention in support of the Big Bang is gravitational lensing (Figure 3.6). Telescopes on earth looking through clusters of galaxies see distorted images of more distant galaxies. In every case the distorted galaxies have a higher redshift. The distortion is caused by the huge gravitation of the cluster of galaxies through which the light of the distant galaxy passes. We have many such examples. They always fit the same pattern.

Let me give you a beautiful example of the gravitational lensing phenomenon. This is a picture from the Hubble Space Telescope. It is a cluster of galaxies at a redshift of 0.171, and we are looking back at much more distant galaxies when we see these arcs. Such an arc is not a galaxy in the cluster, but instead a distorted image of a galaxy far beyond the cluster, at 5 to 10 times greater distance than the cluster itself. How do we know? Because we can measure the redshift of the light. We can reconstruct what the galaxy looks like by undoing the effect of the lensing by the cluster. Einstein first discussed gravitational lensing in 1936, and we are

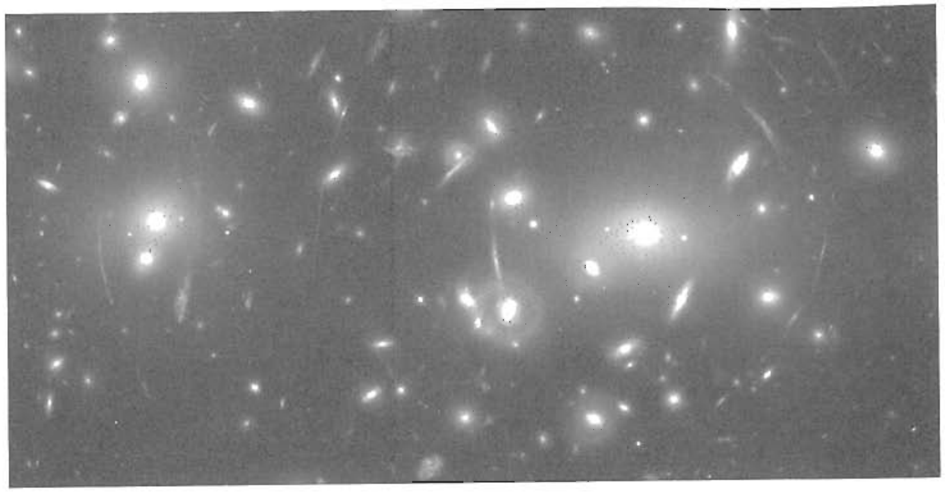


FIGURE 3.6 Gravitational lensing by a cluster of galaxies. (Hubble Space Telescope image of gravitational lensing in Abell 2218, April 5, 1995, STScI-1995-14. Credit: W. Couch [University of New South Wales], R. Ellis [Cambridge University], and NASA.)

using the formulas of Einstein's theory of general relativity, our modern theory of gravity. Clusters of galaxies are the greatest telescopes in the universe.

A BRIEF HISTORY OF THE EARLY UNIVERSE

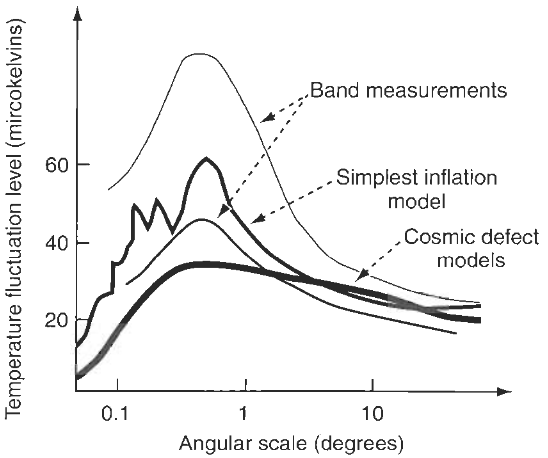
I have described older pictures of the universe, introduced the geography of the visible universe, and presented evidence for the Big Bang. Now I want to summarize briefly what we think the history of the universe was according to the Big Bang. The first few steps are speculative. We have no direct evidence that there ever was symmetry breaking, but what we see now is what particle physicists call a broken symmetry. Only electromagnetic symmetry is still unbroken. We think there was a standard model symmetry, which broke to make the laws of physics that we see today. And at an earlier stage, the universe perhaps had what we call the grand unified symmetry. Such theories make predictions that are testable, but they have yet to be tested. We hope to see direct evidence of some of this symmetry breaking when we can get to temperatures that the universe reached 10^{-8} to 10^{-10} seconds after the Big Bang with the next generation of accelerators. The great accelerator called the Large Hadron Collider being built in Geneva should allow us to do that. We are also looking for evidence for "baryogenesis," for the creation of a slight asymmetry between the amounts of ordinary matter and antimatter. The picture is that at about 10^{-4} seconds there was a great annihilation when all the antimatter annihilated with almost all the matter. Roughly for every billion antiquarks, there were a billion and one quarks. The billion annihilated with the billion, and the one quark left over is what we are made of. We have good evidence that that is about what the right numbers were. There was a subsequent annihilation of the electrons and antielectrons, which happened in the first few seconds. That is pretty secure, based on physics we understand and can duplicate in the laboratory.

WHAT BIG BANG THEORY DOES NOT EXPLAIN

Nuclear fusion is understood very well. People who learned to make nuclear bombs did lots of measurements and calculations, and we understand how the stars work based on the same calculations. The question we are working on now is, How do galaxies and larger structures form? There is a lot that the Big Bang theory does not explain. For example, what made the universe have these little ripples? There were until recently two competing theories, cosmic defects and cosmic inflation. Not long ago in *Science* magazine a figure appeared (shown here as Figure 3.7).

The data on the magnitude of the temperature fluctuations of different angular scales lie in the band between the two lighter lines. The cosmic inflation theories make predictions that agree with the data. The cosmic defects predictions lie outside the range of the new observations, so now the defects model is dead. Only inflation is left of the two models. But inflation is also at risk. The pattern of wiggles is crucial. The predictions have been clear for several years. The crucial data will be coming in very soon. In the year 2001, NASA launched the MAP satellite. In 2007, there will be a European satellite, called Planck. These satellites, together with several ground-based and balloon-borne instruments, will be able to measure fluctuations at even higher angular scales. They will see all the wiggles if they are there. So we will know pretty soon if inflation is right.

FIGURE 3.7 The death of cosmic defects. (Reprinted figure with permission from Andrew Watson, "Cosmologists celebrate the death of defects," Science *278, 574. Illustration: L. Carrol. Copyright 1977 American Association for the Advancement of Science.)*



A NEW PICTURE OF THE UNIVERSE

The Universe Is Mostly Invisible, so the "Picture" Is Metaphorical

I promised that I would help you try to visualize the modern picture of the whole universe. We cannot visualize it with our eyes alone because we cannot see it from outside. When you visualize something, you stand outside it and look at it. But we cannot stand outside the universe because it surrounds us. We are in it, and indeed we *are* it, on our scale. We cannot see all times; we only see a snapshot. We see farther back as we see farther out. The universe is all times. And what is more, most of the matter in the universe is invisible—it is dark matter. Probably 90 percent of all the matter in the universe is something we cannot see. We are trying to discover what it is. Theorists like me make suggestions for what it might be, but we will not know until we actually discover the particles. What I want to do is come up with a picture that suggests all of this.

Importance of Size Scales in Developing a New "Picture"

Let me give you another way of thinking about this by showing you all the sizes versus all the masses that we see. In Figure 3.8, objects are arrayed on a logarithmic scale from the size of people, which is about a meter, to smaller and larger sizes. We can plot all of living things on a diagram like this. Interestingly enough, they form a straight line because we are practically all made of water, and that is just the line of water density. Incidentally, planets and ordinary stars have about the same density as water. Galaxies are much less dense, and some stars are much more dense. But when a star gets even more dense than that and it reaches the upward-sloping line *AB*, it collapses to no size at all. Anything to the left of the line has a mass that is too great for its size and collapses to no size at all, according to general relativity. It becomes a black hole.

An interesting question then is this: Does the universe lie inside this forbidden region? If so, it will expand to the maximum size and then collapse. The uncertainty is represented by the little cross. We do not know how massive the universe is. That measurement is being made today, and the present indications are that the universe will expand forever. In the next 2 to 3 years I think we are going to know for sure. That will tell us the ultimate fate of the universe.

There is another line on the diagram, *AC*, which slopes downward. The uncertainty principle of quantum mechanics says that everything must lie to the right of that line. These two lines cross. That tells us there is a smallest scale, according to our present understanding of the laws of physics. This smallest size is called the Planck length, about 10^{-33} cm. There is also a largest size that we can see, the Hubble radius, about 10^{28} cm. It is the distance to the farthest things we can see, to the things that were emitting light close to the beginning of the universe (actually about 150,000 years after the Big Bang, when the universe first became transparent). All the sizes in the visible universe lie between the Planck length and the Hubble radius.

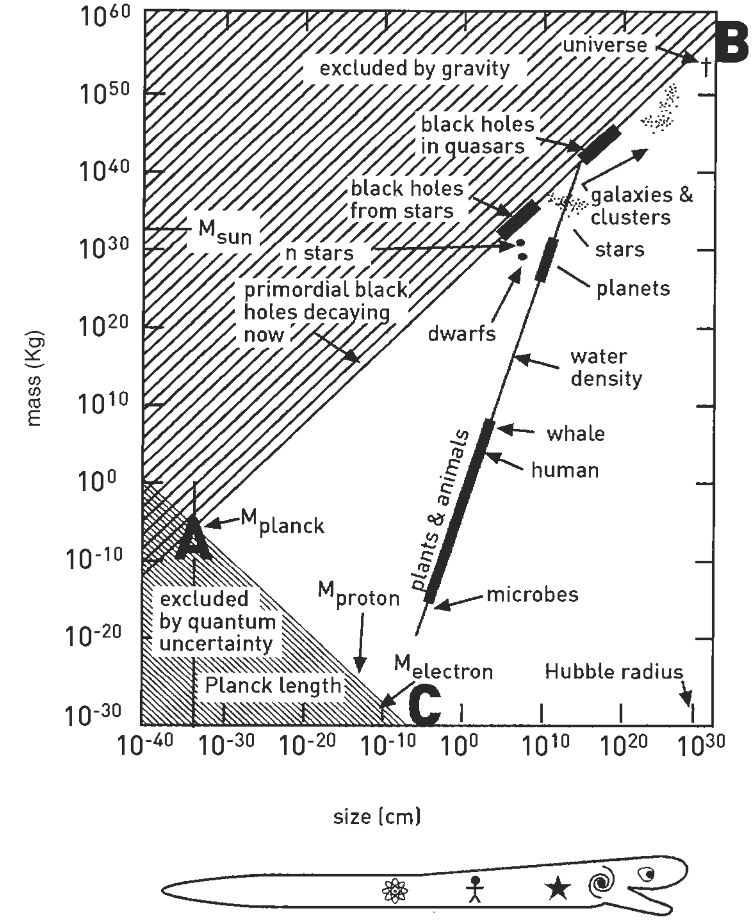


FIGURE 3.8 Size versus mass in the universe. (From J. R. Primack, "Dark Matter, Galaxies, and Large Scale Structures in the Universe," in *Proceedings of the International School of Physics,* "Enrico Fermi" XCII, Varenna, Italy, June–July 1984, N. Cabibbo, ed. [North-Holland, 1987], pp. 137–241.)

THE COSMIC UROBOROS

Let me come back to the ancient symbol of the snake swallowing its tail, called in the Greek the "uroboros" (Figure 3.9). I represent all the possible length scales from the smallest to the largest along the serpent. We now have a cosmic uroboros around which are arrayed all the length scales of the universe, from the smallest scale up to the Hubble scale, a range of 10^{60} to 60 orders of magnitude.

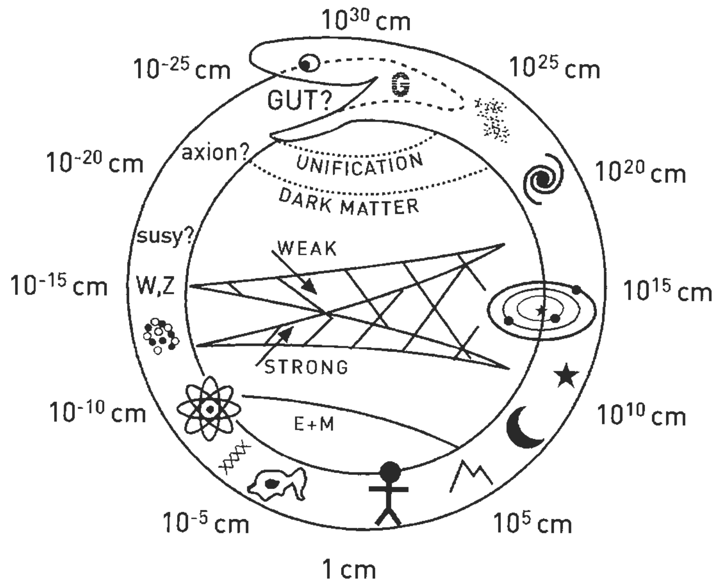


FIGURE 3.9 The cosmic uroboros. (From J. R. Primack, "Dark Matter, Galaxies, and Large Scale Structures in the Universe," in *Proceedings of the International School of Physics*, "Enrico Fermi" XCII, Varenna, Italy, June–July 1984, N. Cabibbo, ed. [North-Holland, 1987], pp. 137–241.)

This idea of representing it as a snake swallowing its tail is due to Sheldon Glashow, a physics professor at Harvard, a Noble Prize winner, and an originator of the idea of Grand Unification. Something I pointed out several years ago is that there are some interesting connections across the diagram of Figure 3.9. Electromagnetism controls the physics from atoms to mountains. Mountains are as high as they are because if they were any higher they would flow plastically or break, through earthquakes. On a smaller planet like Mars, mountains can be higher. It is where gravity, which controls the large side of the diagram, meets electromagnetism, which determines the strength of materials. What we call the weak and strong interactions control the physics of atomic nuclei and determine whether they are stable or not. They also control the composition and burning of the sun. The sun burns by a combination of weak processes turning protons into neutrons, and fusion, a strong interaction process combining two protons and two neutrons into helium.

On still smaller scales, there are forces we are trying to understand with our latest accelerators. And those are probably connected to the dark matter, which controls the structure of galaxies and all the larger things of the universe. Glashow's hope is that perhaps gravity controls both the smallest as well as the largest scales and there is only one way to close the circle and let the serpent swallow its tail.

What Does the Cosmic Uroboros Mean?

Humans are in a very interesting position, almost exactly in the middle of the cosmic uroboros, between the largest scale and the smallest scale. There are arguments that this is the only place we could be. We could not be much smaller because there would not be enough complexity for us to have brains enough to think. We could not be much larger because communication times would get too long between the parts of our brains. So we do live in a special place in the universe, but only if you think of it symbolically rather than geographically.