Cosmic Questions

An Introduction

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ABSTRACT: This introductory talk at the Cosmic Questions conference sponsored by the AAAS summarizes some earlier pictures of the universe and some pictures based on modern physics and cosmology. The uroboros (snake swallowing its tail) is an example of a traditional picture. The Biblical flat-earth picture was very different from the Greek spherical earth-centered picture, which was the standard view until the end of the Middle Ages. Many people incorrectly assume that the Newtonian picture of stars scattered through otherwise empty space is still the prevailing view. Seeing Earth from space shows the power of a new picture. The Hubble Space Telescope can see all the bright galaxies, all the way to the cosmic Dark Ages. We are at the center of cosmic spheres of time: looking outward is looking backward in time. All the matter and energy in the universe can be represented as a cosmic density pyramid. The laws of physics only allow the material objects in the universe to occupy a wedge-shaped region on a diagram of mass versus size. All sizes — from the smallest size scale, the Planck scale, to the entire visible universe — can be represented on the Cosmic Uroboros. There are interesting connections across this diagram, and the human scale lies in the middle.

KEYWORDS: cosmology; changing pictures of the universe; overthrowing vs. encompassing scientific revolutions, cosmic horizon

INTRODUCTION

Today cosmologists are telling each other at every conference that this is the golden age—or at least *a* golden age—of cosmology. It is a tremendously successful period because we are seeing the death of so many theories! Back in 1984 George Blumenthal, Sandra Faber, Martin Rees, and I published a paper[1] in which we created the theory of "cold dark matter" and worked out two versions of it in some detail. A couple of years later Jon Holtzman, a stu-

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dent with Sandra Faber and me, worked out 96 different variants of the cold dark matter scenario.[2] Now, I am proud to say, all but one of them are pretty convincingly ruled out. But the one that is left (which is closely related to one of the two in our original paper) may actually be right.[3] That is fantastic progress!

Now as we are trying to put together a picture of the whole universe, its origin, evolution, structure, and future—and that is what cosmology is all about—the question arises whether this has any broader implications. Does it matter to people as people, and not just as cosmologists (or other kinds of scientists)? I think it does, but that is for you to decide. I hope this *Cosmic Questions* volume of the *Annals* helps.

What I am going to do in the rest of this paper is to try to explain cosmology, not in a technical way, but rather through stories and pictures. That is the way most people throughout history have experienced cosmology: not as a series of scientific theories that are put forward as hopeful explanations to be tested against data, which is what we do as professional cosmologists, but rather as an understanding that one can grasp and visualize: a picture.

The joke about cosmology used to be that it was the only field of science in which the ratio of theory to data was infinite. But now the situation is reversed, and the ratio has gone to almost zero. Today data are flowing in so fast from new instruments that the question is whether a single one of the current theories can survive. If one theory survives the present onslaught of data, it will be revolutionary.

The advent of a new cosmology can radically change the culture of its time. In particular, the scientific revolution of the sixteenth and seventeenth centuries helped end the Middle Ages and bring about the European Enlightenment. But it also split scientific knowledge from human meaning, which was at the time largely determined by religion. How will a new picture of the universe at the turn of the twenty-first century affect global culture? That is one of the questions explored in this volume.

SHIFTING PICTURES OF THE UNIVERSE

Traditional

The first panel of FIGURE 1 is an example of one kind of the many kinds of traditional representations of the universe and of time: the snake swallowing its tail. It is a symbol that is found all over the world.[4]

Biblical

This is a representation of the cosmos of the ancient Near East, the *Genesis* cosmos. It is a three-part picture: the heavens, the flat earth, the underworld.

As it is described in *Genesis*, God separated the waters, providing a space. The firmament held up the upper waters, making space for dry land where animals, plants, and people could find a home. But the firmament had the possibility of breaking, and in the Noah story, the "chimneys" in the firmament and the "fountains" of the deep open up. The Flood was understood as not just a rainstorm but a cosmic catastrophe, a threat to recreate the primordial chaos.[5]

Medieval

The Medieval picture is based on the Ptolemaic and even earlier Platonic and Aristotelian conceptions of the crystalline spheres, with the spherical earth at the center and the whole pattern of spheres revolving around the earth every day. The spheres also revolve slowly against each other. The innermost sphere carries the moon, and then Mercury and Venus and the sun (with Mercury and Venus closely linked to the sun). Beyond the sun were Mars, Jupiter, and Saturn (the Seventh Heaven), the fixed stars, and then angels.[6] This basic picture was reflected in many ways in Medieval culture. For example, in a mystical Jewish kabbalistic representation, there are also the ten spheres, but the story is different. In the Lurianic Kabbalah, God creates the universe by withdrawing from the center, a process called *Tzimtzum* in Hebrew. The ten spheres—or *spherot,* the numbers—represent the emanations of God back into the universe. *Ein Sof*—the infinite God—surrounds all.[7]

Newtonian

Galileo's observations with the telescope provided the first convincing evidence that the Ptolemaic picture was wrong. This pulled the rug out from the entire Medieval conception of a hierarchical structure of the universe—including the human universe. Galileo's work, published in Italy in 1610, spread quickly throughout Europe. Already in 1611 in England John Donne writes:

> The new Philosophy calls all in doubt,
> The Element of fire is quite put out;[a]
> The Sun is lost, and th'earth, and no man's wit
> Can well direct him where to look for it …
> 'Tis all in pieces, all coherence gone;
> All just supply, and all Relation;
> Prince, Subject, Father, Son, are things forgot …[8]

Such was the impact of this change in cosmology.

[a] The sphere of fire, the highest of the spheres below the lunar sphere, does not exist.

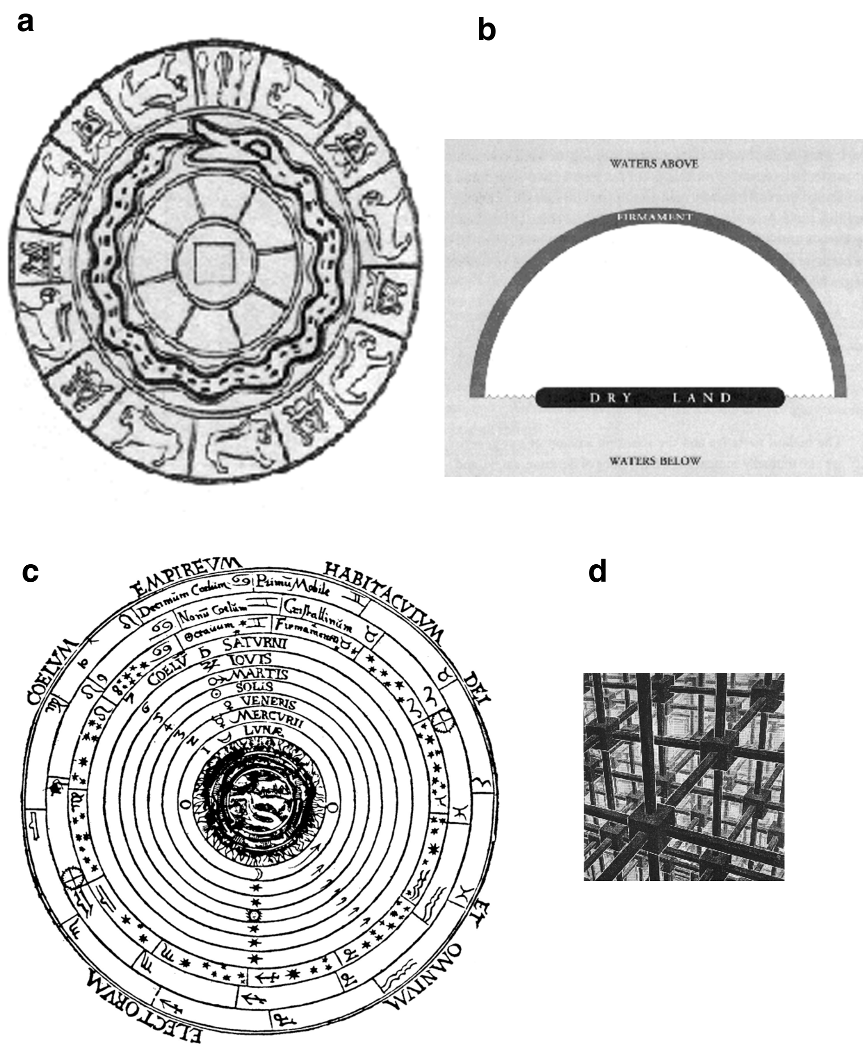

FIGURE 1. Views of the universe: traditional **(a)** the uroboros (snake swallowing its tail)**;** **(b)** biblical ; **(c)** medieval; (**d**) Newtonian.

What was the new picture? The Newtonian cosmos replaced the Medieval picture. There is simply empty space, the void, stretching on indefinitely in all directions. In the Middle Ages, when one went out at night and looked up, one saw majestic height, not infinite vastness. The statement in Pascal's *Pensées*, "the eternal silence of these infinite spaces alarms me,"[9] is a sort of statement that one simply never encounters in Medieval writings.[10] But it is

TABLE 1. Three cosmologies: Medieval, Newtonian, and Modern

Size R Age T Center	Composition	Unifying Ideas	God's Role?
	Medieval Cosmos		
Finite R Finite T Geocentric	Sublunary: Earth, water, air, fire Heavens: Ether	Circular motion Great Chain of being	Prime mover, hierarch, savior
	Newtonian Cosmos		
Infinite R? Infinite T? No center	Atoms, void ether?	Deterministic mechanics Universal gravitation;	Clockmaker
	Modern Cosmos		
$R = 10^{28}$ cm $T = 10^{10}$ yr Homogeneous & isotropic	Atoms, quarks, electrons Radiation Dark matter Vacuum	Gravity = space curvature Nondeterministic quantum theory Evolution	Before the Big Bang? Immanent?

a very common view once one is living in the Newtonian universe, represented in a work by Escher.[11]

Modern?

Our modern conception bears some elements of all these pictures, but it is very different from all of them. Let me start by summarizing the differences between the Medieval, Newtonian, and modern pictures.

The Medieval cosmos is of finite size: It began a finite length of time ago —which could be calculated by adding up the begats in *Genesis*—and it was geocentric. The physical part had to be finite in size because the whole thing goes around once every day. There is a distinction between the material contents of the sublunar world and of the perfect, unchanging heavens. The unifying ideas are constant circular motion and the Great Chain of Being: hierarchy, continuity, plenitude.[12] God—or gods—pervades the entire structure: pagan planetology coexisted with Christian cosmology.

Newton argued that if the cosmos were finite, then everything would fall to the center,[13] so it was probably infinite. But there were paradoxes associated with this: Kepler had already pointed out that the night sky would be bright as day in an everlasting infinite universe ("Olber's paradox"[14]). It also was not clear whether the Newtonian universe was created a finite length of time ago. The unifying ideas were deterministic local mechanics and universal gravitation: the laws of motion were the same on Earth as throughout the

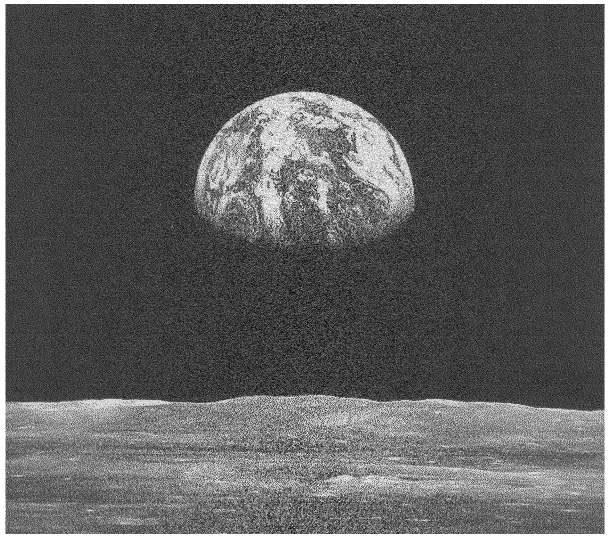

FIGURE 2. Earthrise from Apollo 11 in lunar orbit.

universe. God's role was the creator of this clockwork universe at the beginning. For Newton at least, God also kept setting the clock right again every so often.

In the modern cosmos, we know how big the visible universe is—about 10^{28} centimeters (cm)—a distance called the "cosmic horizon." We know how long ago the universe started: about 14 billion years ago. We know that on large scales, the universe is homogeneous and isotropic (the same in all directions). It is made of atoms, dark matter, and radiation. Gravity is curvature of spacetime and can create horizons, and nondeterministic quantum mechanics and evolution are the key ideas. It is not clear whether there is a role for God.

SCIENTIFIC REVOLUTIONS

Now, what is the relationship among these three pictures? It is clear that the Copernican–Galilean–Keplerian–Newtonian revolution overthrew the Ptolemaic system, in the sense that Ptolemy is only taught as history and never as science. But I predict that Newton will always be taught, because Newton's picture is basically right—*on the scale of the solar system*. The scientific revolution that led to the modern cosmos, including the early twentieth century contributions of relativity and quantum mechanics, have encompassed Newtonian physics with physics that works at astronomical scales and velocities. But Modern cosmology reduces to the Newtonian treatment for

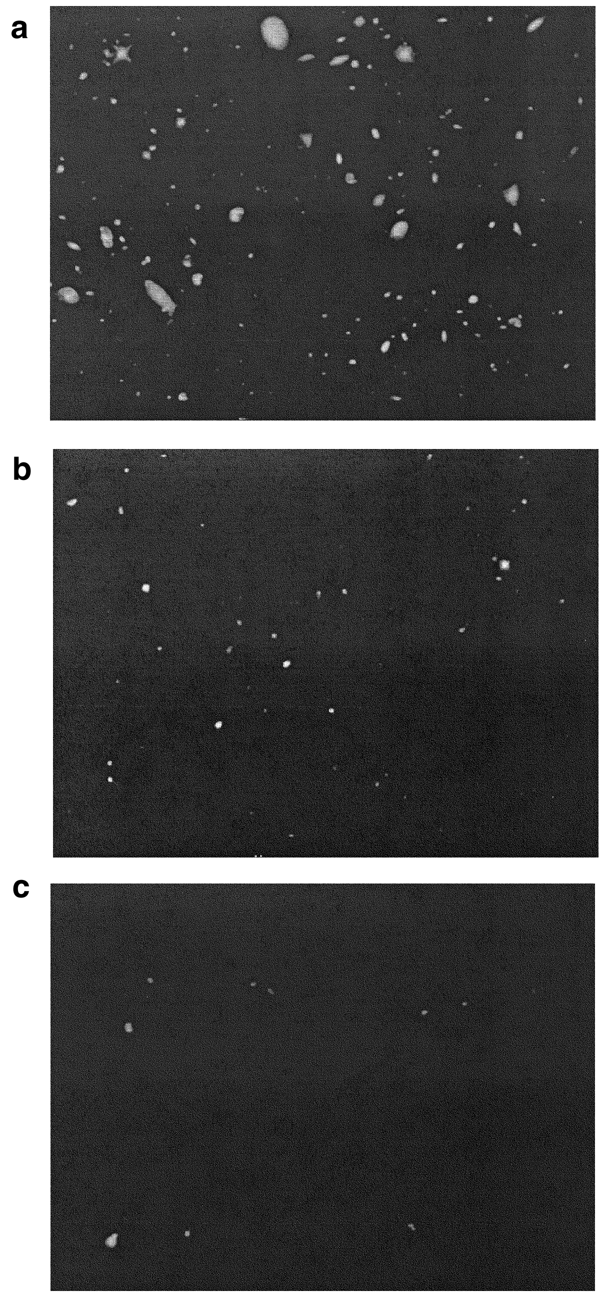

FIGURE 3. The Hubble Deep Field image. *Top:* a portion of the Hubble Deep Field. *Middle*: When the universe was about half its present age. *Bottom:* Back to the first two billion years.

the solar system, for normal-sized things on Earth, and generally for conditions where speeds are not too high and gravitational forces are not too great. So we can really only say we know that a theory is right when we know where it is wrong.[15] Inside the boundary where the theory begins to fail, the theory is correct (to some prearranged accuracy). Modern cosmology is undergoing an encompassing revolution as opposed to an overthrowing revolution.[16]

SOME MODERN PICTURES

Well, what is the modern picture? I do not think there is one— instead there are many, each of which captures part of the universe.

One of the modern icons, one that is engraved on every person's imagination, is the view of the Earth from space—in particular, perhaps, the view that the astronauts first had from orbiting around the Moon, with the dead gray lunar landscape in the foreground, and the gorgeous blue ever-changing Earth in the distance (FIG. 2).[17] Now we understand Earth viscerally as a small, fragile, very special planet, as most people did not until these pictures became available. I think this helps to show the power of a picture.

The Hubble Deep Field was the longest time exposure with the Hubble Space Telescope's camera of any region of the sky. For two weeks, the telescope looked at this same patch of sky continuously whenever the satellite was on the right side of the earth to see it. It is a very small region of the sky, about four arc-minutes across. That is the size of the intersection of two crossed sewing needles held at arms' length. A video of this image was made by Ken Lanzetta and his colleagues at the State University of New York at Stony Brook.[b] First the video simply pans across the picture, and every single bright spot you see is a galaxy. Many of these are giant galaxies like the Milky Way, big spiral galaxies that contain a hundred billion stars or so. The picture was taken looking out of the disk of the Milky Way so that there are very few stars in the way, but there are a few stars. The bright cross in the upper left corner of FIGURE 3a is what a nearby star looks like. Now the thing that one has to appreciate as one looks at an image like this is that one is seeing galaxies superimposed in front of other galaxies. We see all the galaxies that are reasonably bright, all the way out to the edge of the visible universe.

It would be wonderful to be able to see these galaxies not stacked on top of each other, but spread out in space and time, and that is what the video is about. It is possible to measure the red-shift of about five hundred of the galaxies and, based on those measurements, to estimate the red-shifts for all the rest from their colors. That is what the Lanzetta group did. And so what this

[b]This video is contained in the CD-ROM entitled *Cosmic Questions*, which recapitulates all the text in this volume with color illustrations among other features and which will be available in 2002 from the AAAS.

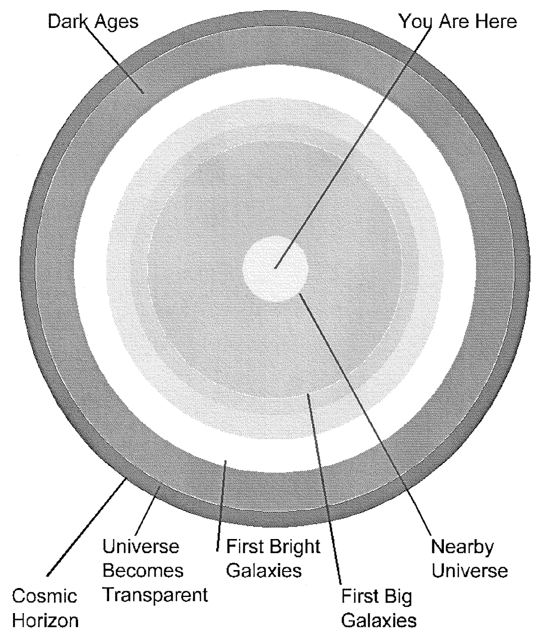

FIGURE 4. Cosmic spheres of time.

lets us do is to zoom into the picture. We see first the nearby galaxies go sliding away to the sides of the picture, and then, as we go farther and farther in, only the galaxies that are very far away from us are still visible.

The first galaxies to disappear are within the nearest billion light years or so. The colors are reasonably accurate, and the fact that the galaxies we can still see are now looking somewhat yellower reflects their red-shift: their light is shifted toward the red end of the spectrum because of the expansion of the universe since their light was emitted. Even about four billion light-years away, there are still plenty of big galaxies, but at about seven billion years back there are no more big galaxies visible in this field.

By the time we get back to about one billion years after the beginning, the sky is suddenly dark. If there were bright galaxies there, we would see them. We are now at the threshold of the real cosmic dark ages, before the cosmic night was pierced by the first beacons of bright starlight.

Now, how do we visualize the whole universe in our minds? We cannot paint a picture, because we cannot see it from outside—a picture is taken from outside the object, but we're inside the universe. We cannot see all times. As we look out in space, we look back in time. And most of the universe anyway is invisible stuff that we call dark matter. We do not know what it is. We know roughly *where* it is, but we cannot see it, so we cannot picture it in the sort of direct way that we are used to. An effective image should say something about the universe as a whole, but it does not need to say everything. Let me show you some examples:

Again, as we look out into space, we look back in time. The nearby universe surrounds us, and this is the part that we are busy exploring now, with the Sloan Digital Sky Survey and other very ambitious projects, but most of the volume of the universe remains only very partially explored. The way we do that exploration is by "drilling holes" through the distant universe in very narrow little images like the Hubble Deep Field. Then we study the pictures and try to take them apart to see the evolution of structure. Beyond a certain distance, we do not see any bright galaxies—there may be none!

The universe first became transparent about two hundred thousand years after the Big Bang. It is from this sphere—represented by the inside of the outermost band in FIGURE 4—that the Cosmic Background Radiation was emitted. This heat radiation from the Big Bang has been traveling to us through all of space ever since. And the very earliest stages of the Big Bang are concentric circles right at the edge of the figure that represent the eras of the great annihilations of the particles that initially populated the universe. There were initially almost equal amounts of matter and anti-matter, but now only the tiny remnant of matter survives. Even earlier were the eras of symmetry-breaking and cosmic inflation. We are surrounded by cosmic spheres of time—spheres somewhat different from the Medieval conception, however, and much larger.

There is another kind of picture (FIG. 5a), which represents not time but what the universe is made of.

FIGURE 5a. Cosmic density pyramid (top)

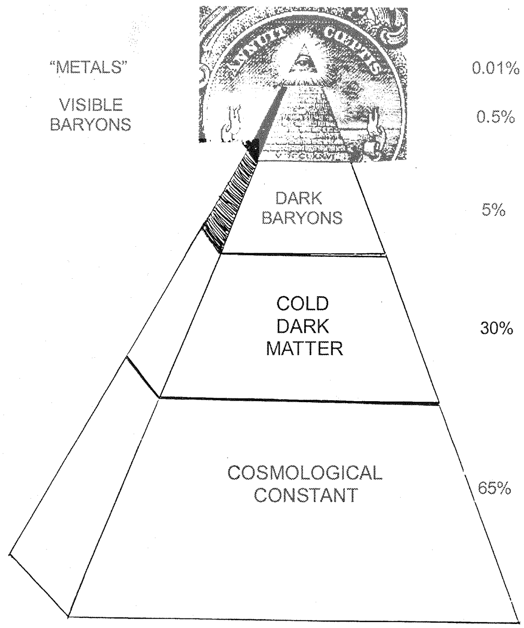

FIGURE 5b. The full cosmic density pyramid.

Now this is a picture that you probably all have in your pockets. It is the reverse of the Great Seal of the United States, which appears on the back of the dollar bill. It was an Egyptian symbol later adopted by the Masons (several of the Founding Fathers were Masons). The pyramid, I am told, symbolizes strength and solidity. Above is the all-seeing eye of God. Now, I am going to use this pyramid in a somewhat different way to represent all the visible matter in the universe. The part on top with the eye, which is about a quarter of the height of the full pyramid, represents the heavy elements, from lithium upward in atomic weight. Astrophysicists call all these elements—carbon, oxygen, nitrogen, silicon, iron, and so on—metals. They total about a hundredth of a percent of critical density. Critical density is the minimum density required for the expansion of the universe to be turned around by the gravitational attraction of all the matter in it. Hydrogen and helium, the two lightest elements, make up more than 99% of the mass of the elements in the universe. The volume of the rest of the pyramid represents all the hydrogen and helium we can see in the form of stars and gas, and this amounts to about half a percent of critical density. But there is much more mass than that. Invisible ordinary matter (atoms that are not lit up) amounts to about 5% of critical density, so ten times more than everything visible.

But there is still much more matter than that. Most of the mass of matter is dark matter, probably of the cold dark matter variety, possibly mostly made up of the lightest supersymmetric partner particles.[18] Although the key feature of dark matter is that it is *invisible*, not really "dark," the name dark matter has become standard for this mysterious stuff. It is gravitationally the most important matter in our own Milky Way galaxy and probably all other galaxies, and also in larger objects such as clusters of galaxies. It keeps the stars in their orbits around the galaxies, and keeps galaxies moving around inside the clusters. And the very same amount of dark matter is required to explain the bending of light around galaxies and clusters. The total mass of dark matter is probably about 30 percent of what we call critical density. Observations now convincingly indicate that the total density of all the matter, including dark matter, is significantly less than critical density.

The amount of matter is dwarfed by what seems to be the dominant stuff of the universe—whatever it is—which we call the "cosmological constant" or "dark energy." It makes up something like 65% of critical density.

This three-dimensional picture of the composition of the universe shows how very little there is of the metals we are made out of (and presumably all intelligent life could be made out of). The full Cosmic Density Pyramid shown in FIGURE 5b is also a picture of the universe— of an aspect of the universe, that is. Of course, we would love to know what the mysterious dark matter is, and also why there is a cosmological constant. These are two of the most important open questions in cosmology today.

Let us turn to one last pair of images: FIGURE 6 shows the possible densities of things. It is a plot of the mass of all things in the universe, from elementary particles up to the whole visible universe, versus their sizes. The ratio of mass to volume equals density. Interestingly, plants and animals, and stars, for that matter, all lie along one line. It is the water density line. As you can see, not all densities are allowed. The two great twentieth century laws of physics—general relativity and quantum mechanics—exclude two regions of the diagram.

The line that passes through points A and B (and continues in both directions beyond the figure) represents for every size on the X-axis the maximum mass that could possibly exist in it. If any more mass were crammed in, according to General Relativity it would collapse into a black hole.

The line through A and C (and beyond) represents the limit on sizes imposed by Quantum Mechanics (FIG. 6, top). The smallest physical size possible is the Planck size, and things close to that size are considered to be "on the Planck scale." It is a region 10^{-33} cm across. We cannot talk about, calculate, or conceptualize anything smaller in a way that has meaning in terms of our current concepts of physics

The largest size we know is that of the visible universe, but what exactly does this mean? Expansion of the universe means that space is expanding away from us faster and faster the further out we look. Since the velocity at

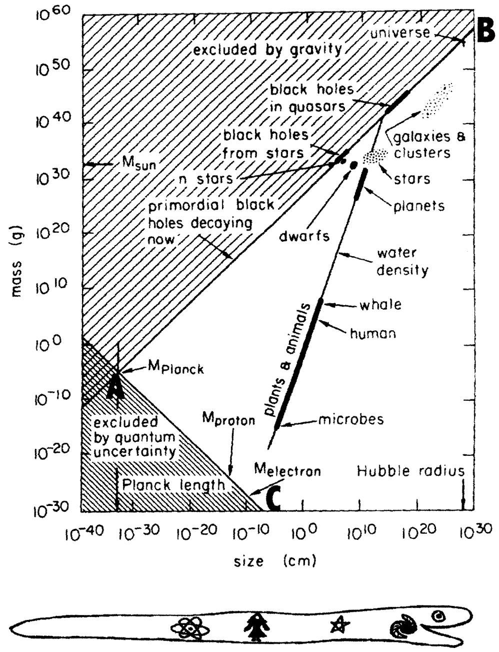

FIGURE 6. The wedge of material reality

which a point is moving away from us is always increasing with distance, far enough away space is expanding at the speed of light. That distance from us —which at this era in the history of the universe is about 10^{28} cm—is the radius of what we call the cosmic "horizon" and is the maximum distance from which we can receive information in principle. The horizon is a sphere, and we are at the center (FIG. 4). Although we have no reason not to believe space is just the same beyond our horizon, there is no way we can receive any direct information confirming it. Light cannot reach us from a region expanding away from us faster than the speed of light. On the figure there is an error bar for the density of the universe because we do not know more precisely than this the total amount of matter it contains and therefore its mass.

The wedge of material reality (FIG. 6) thus shows us that objects can only exist inside the wedge-shaped region of the plot. From the smallest size, the Planck size, to the largest, the horizon of the universe, is a difference of about 60 orders of magnitude. It is large, but not infinite.

Let us draw the possible size scales along the body of a snake instead of just the horizontal axis in the wedge of material reality (FIG. 7).[19] Sheldon Glashow was the first to draw an uroboros to represent the size scales in the universe.[20] The head swallowing the tail reflected his expectation that gravity controls on both the largest scales and also the smallest scales, and that there

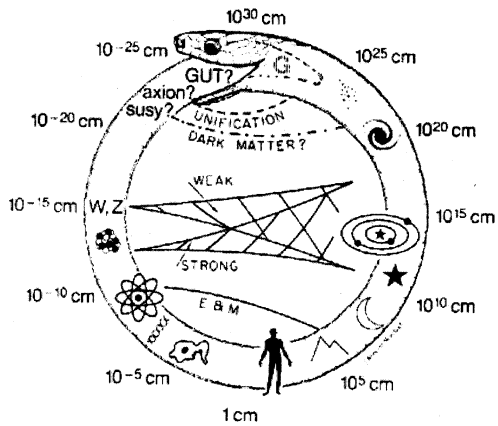

FIGURE 7. The cosmic uroboros.

will one day be a unification of all the laws of physics. A further thing that I find very interesting about this diagram is that there are connections across the Cosmic Uroboros. Electromagnetism controls on the scale from atoms up to mountains. Mountains are as high as they are on earth because of an interplay between the strength of materials—basically electromagnetic forces—and gravity. On a smaller planet, like Mars, the highest mountains are much higher, because they are made of essentially the same materials, but gravity is weaker and does not pull them down. There are also connections across the center of the diagram, from the very small to the very large. The weak and strong interactions, together with the electromagnetic interaction, control how stars burn, and thus also the compositions of planets. The processes at the center of the sun that ultimately generates sunlight involves conversion of two protons to two neutrons (that is a weak interaction) and their fusion (that is a strong interaction) to make a helium nucleus. On the still larger scales of galaxies and larger objects, dark matter is most important gravitationally, as we have seen. But dark matter is not associated with any of the forces that we know and understand on the scales we have probed so far, so we assume that it must be associated with laws of physics on still smaller scales—possibly supersymmetry ("SUSY") or other ideas such as "axions." We hope, as Glashow does, that maybe there is some unification of all the laws on the very smallest and the very largest scales.

Now, the laws that are important on different scales are different. The same physical laws apply on all scales, but they are not necessarily equally important. Electricity is much more important on small scales, gravity on large scales. Scale models can never work, because of the way the laws of physics work. Galileo pointed this out in the last of his great books, *The Discourses Concerning Two New Sciences*, where he showed that if the height of an animal were increased by a factor of three, it could no longer be the same shape. If its bones became three times longer in all directions, they would be 9 times thicker (because the cross-section is proportional to the area) but 27 times more massive (because the mass would scale as the volume, the *cube* of the height). To support so much weight, the bones would have to be much thicker.

We call the error of applying the laws and viewpoint appropriate to one size scale to phenomena on another scale, "scale incongruity." Imagining that the Big Bang can be understood using just commonsense physics is an example of scale incongruity. In the early universe, much of the material that we now see all the way out to the cosmic horizon was compressed into a much smaller volume, and such high densities and correspondingly high temperatures require relativistic quantum physics. Another example of scale incongruity is thinking of a molecule as ice or liquid. You need millions of molecules to make the tiniest piece of a snowflake. As one goes up in size scale, and thus complexity, such phase transitions show that one can get new "emergent" phenomena that are qualitatively different.

Many people believe the human size is insignificant compared to the cosmic scale. But perhaps you noticed on the Cosmic Uroboros that humans are essentially in the middle of the range of size scales in the universe. There is nothing arbitrary about that. That is where we are, and that is where creatures like us must be on this sort of diagram. Our brains must be as big as they are, to be as complex as they are. The universe is much bigger than we are, because it took billions of years for the universe to reach the level of complexity represented by human life, and it was expanding all that time. Just because we are so much smaller than the cosmic horizon does not mean that we are insignificant. After all, we may be the only creatures in the universe who are beginning to understand it.

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