Cosmic Chemistry: Cosmogony

Cosmology

APPENDIX A

Big Bang, quarks, dark matter, general relativity, red-shift, non-Euclidean geometry, worm holes—all words that are mysterious in their details, but often translated into the vernacular with relative ease by journalists and science writers. These words form part of the core of the science of cosmology, a science in which the questions usually are easy to state, but equally difficult to answer. Questions like, “Has the universe existed forever?” or “Is there an edge to the universe?” or “Where did the matter in the universe come from?” are good examples. Each culture that has existed formulated answers to questions like these. Until the 20th century, the answers were rooted exclusively in superstition, philosophy, or religious belief. In the 20th century, science began to provide a few answers, although it was not until the latter part of the century that cosmology itself began to be widely recognized as a science.

In 1963, astrophysicist Malcolm S. Longair listed what he considered to be the known facts about the universe. Surprisingly, Longair’s facts numbered only 2.5:

Fact 1—The sky is dark at night.

Fact 2—The galaxies are receding from each other as expected in a uniform expansion.

Fact 2.5—The contents of the universe have probably changed as the universe has grown older.

The status of cosmology as a science was underlined in 1992 by Longair in *Modern Cosmology - A Critical Assessment* [see references].

It is instructive to note the advances made during the following 30-year period by listing what Longair considered as additional facts that were in place by 1992. The number had grown to 9!

Fact 3—The universe is isotropic on very large scales to an accuracy of better than one part in 100,000. [Note: An isotropic universe is one that looks the same in every direction.]

Fact 4—The spectrum of the Cosmic Microwave Background Radiation has a pure blackbody spectrum at a radiation temperature of 2.735 K. [Note: More details about this later.]

Fact 5—Standard General Relativity has passed the most precise tests that have been devised so far and there is no astrophysical motivation for seeking any different theory. [Note: General Relativity is Einstein’s famous work.]

Fact 6—Many different classes of extragalactic systems show changes in their average properties with cosmic epoch. [Note: Cosmic epochs are discussed in the student text on quarks.]

Fact 7—Most of the mass of the universe is in some dark form and it exceeds the amount of visible matter by a factor of at least ten. [Note: Dark matter is the subject of a student activity.]

Fact 8—The light elements, helium, deuterium, helium-3, and possibly lithium, were created primordially. [Note: See the Student Activity, “Quarks—Getting Down to Fundamentals.”]

Fact 9—The distribution of galaxies on large scales in the universe, although uniform on the cosmological scale, possess large-scale irregularities on a scale much greater than that of clusters of galaxies.

It might be noted that in 1996 Longair reiterated (and modified slightly) the points mentioned above [see Malcomb Longair, *Our Evolving Universe*]. However, the total number of facts remained at 9.

It is not intended here to attempt an understanding of the experiments leading to these facts or of their implications. Rather, this is an attempt to convince you that although cosmology is a speculative science, it does rest on a few well-established facts.

Facts in science usually lead to the construction of models (see Appendix B, "Assumptions, Models, and the Scientific Method"), so it is not surprising that cosmologists often talk about constructing "cosmological models." Such models are mathematical in nature and they capture the principal features of the structure and history of the universe. At the present, the basic precepts of the standard cosmological model, according to *The Whole Shebang* by T. Ferris [see references].

1. The physical laws adduced [proven] on earth pertain throughout the observable universe.
2. The universe is expanding.
3. The universe is isotropic and homogeneous.
4. General relativity accurately describes the behavior of gravitation in the universe today.
5. The early universe was in a state of high density and high energy.
6. The universe is evolving.

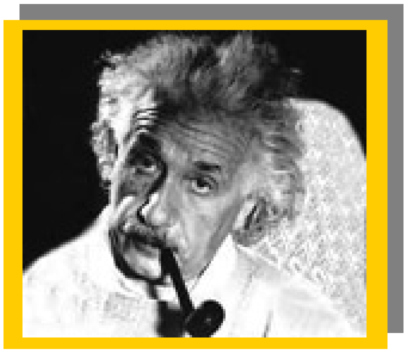
One should note the parallels between Ferris's model and the facts presented by Longair.

We now will turn to some of the specific issues raised in the standard model. Recognize that the present discussion merely scratches the surface of these topics. Excellent detailed expositions may be found in the supplemental materials list, and the reader is urged to follow up on items of interest.

The Universe is Expanding

In the early part of this century, Albert Einstein (recently named "Man of the Century" by *Time* magazine) published his revolutionary work on a new theory of gravity called general relativity. Einstein's theory successfully addressed an issue involving the motion of the planet Mercury that had been left unresolved by the classical gravitational mechanics of Newton, and it predicted the bending of the path of light by gravitational fields. It also produced the first modern cosmological model of the universe.

Einstein made two important assumptions [see Appendix B]. First, he assumed that the universe is static and eternal, that is, the universe does not change in time. Second, he assumed that the matter in the universe is evenly scattered fog-like throughout space. These assumptions, along with his theory of gravitation, enabled him to derive equations describing the overall structure of the universe. In passing, it might be noted that all modern models prescribe a homogeneous universe as well, simply because the math becomes unmanageable without this assumption.



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Albert Einstein is considered one of the greatest and most popular scientists of all time. Three papers he published in 1905 were pivotal in the development of physics and, to a large degree, Western thought.

However, in addition to mathematical challenges, Einstein faced a puzzling paradox. His theory of gravitation (General Theory of Relativity)—like Newton's—describes gravity as a universal attraction acting among all bodies in the universe. A collection of unsupported, mutually attracting bodies cannot remain static. Gravitation should cause the bodies to collapse to a single mass. The universe, in other words, should collapse under its own weight!

To skirt this enormous difficulty, Einstein proposed that static equilibrium in the universe is achieved because of the presence of a new type of repulsive force, which is fine-tuned to counter balance the crushing gravitational attractions of the cosmos. He included this new force in his equations, calling it the "cosmological term" or "cosmological constant." On the scale of the solar system, the repulsions associated with the cosmological constant are very weak and are far outweighed by other forces. The cosmological repulsions make themselves known only over intergalactic distances—a strange force indeed.

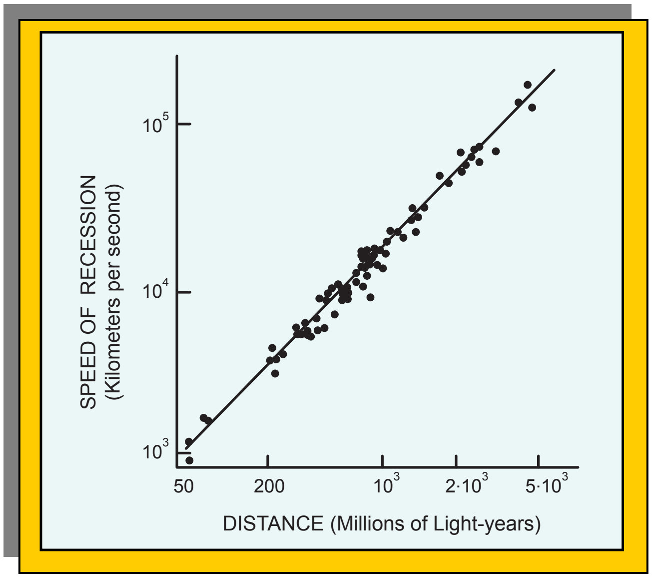
Einstein later came to regret the invention of the cosmological constant and called it “the greatest blunder of his life.” However, as we shall see later, it is just possible that it may turn out to be one of his greatest achievements!

Soon after Einstein’s work was published, Alexander Friedmann (a Russian) and Georges Lemaitre (a Belgian) re-examined the situation and challenged the assumption of a static universe. Beginning with Einstein’s equations of general relativity, they found alternative solutions that correspond to a universe that began in a state of incredibly high density and then expanded with the march of time, thinning out as it did so. This model of the origin of the universe eventually came to be known as the “Big Bang” model, the basic framework of which has received wide, but not universal, acceptance. The remainder of this briefing will focus on various aspects of the Big Bang model, but the reader should recognize that the model is controversial, speculative in many aspects, and believed by some to be downright wrong. For a good presentation of an alternative point of view, the reader is referred to a book by Eric J. Lerner entitled *The Big Bang Never Happened* [see references].

One should note that the early models were based on theoretical calculations, not observational data. At the time, there was really only one fact to go on—that the sky is dark at night—and this does not provide much in the way of verification of the correctness of the model. An obvious need, among many, was a method to determine distances on an astronomical scale. In effect, an astronomical ruler was required before convincing arguments could be advanced.

Enter the American astronomer Edwin Hubble. Astronomers had busied themselves for a number of years with the measurement of distances to certain special stars (the Cepheid variables) within our own galaxy by measuring their luminosity (energy emitted per second; in effect, their wattage) and brightness. In 1924, Hubble studied a star in what is now known as the Andromeda galaxy, establishing that this was a separate galaxy located far away from the Milky Way. Subsequent work by Hubble and others established that many of the faint mysterious patches of light in the night sky that vaguely had been called nebula were, in fact, galaxies. Thus galaxies, not stars, became the basic benchmark units of matter in the universe.

Then, in 1929, Hubble made an astounding discovery of what may be the most important precept of modern cosmology: that the entire universe is expanding. Hubble combined his measurements of galactic distances with the results of studies employing a technique called the Doppler shift (see student activity on the Doppler effect). This technique showed that many of the galaxies were moving and, in fact, were speeding away from the Earth. The combination of these measurements led Hubble to discover that the distance to each galaxy is proportional to the speed of its recession from the Earth. That is to say, a galaxy two times as far away as another galaxy is moving outward two times as fast. This observation has come to be known as Hubble’s Law and a modern illustration of this law showing the direct relationship between the recession speed of galaxies and their distance is shown in the figure at the left.



In other words, the universe is dynamic. It is not standing still, as had been proposed originally by Einstein. It is expanding, meaning that the distance between any two widely separated cosmic objects is increasing with each passing moment of time. Understand, however, that it is only those extremely distant structures, such as galactic clusters, that have been moving away from each other since the Big Bang. Structures that are close to each other experience mutual gravitational attractive forces that prohibit them from participating in the overall expansion of the universe. For example, we might note that our solar system planets are locked tightly in place by gravitational forces that vastly overwhelm the effects of universal expansion. On an even larger scale, the Andromeda galaxy is moving toward us because of the gravitational forces between that galaxy and our Milky Way galaxy.

Conceptualizing the Big Bang is difficult and overwhelming, to say the least. The Big Bang should not be regarded as a gigantic explosion with stuff being thrown about haphazardly into a non-moving space. Instead, it should be looked at as an explosion that occurred everywhere, since there was no space into which the universe could move. Why not, you say? Well, because any such space, by definition, would be part of the universe. Space is everything there is. Not only does the Big Bang stretch space, it also stretches our minds!

The conclusion that the universe is expanding leads to an immediate implication. Since the universe is expanding as galaxies move away from each other, then it clearly would be the case that the galaxies would have been closer together in the past. Consequently, if we mentally reverse the direction of history, we envision a smaller, denser universe. If we reverse time for a sufficiently long period, it is difficult not to conclude that at some moment in the past all of the matter in the universe was packed into a small volume of almost infinite density. Based on the rate of expansion, astronomers estimate that this situation prevailed about 10 to 15 billion years ago. While this is widely accepted as the approximate age of the universe, there is some recent evidence that the lower limit should be dropped to 8 billion years. While the interpretation of certain astronomical data does suggest an age for the universe of 8 billion years, this is in conflict with the age of certain types of star clusters, which are known to be older than this. Some ways of interpreting observations must not be correct. The cosmological jury is still out on this question.

So, what is the fate of this expanding universe? Astronomers believe it ultimately boils down to the outcome of a tug of war between gravity and expansion [see student activity on density and gravity]. The various components of the universe tug on one another through gravitational attractions, slowing the expansion. This competition leads to three different possibilities for the ultimate fate of the universe.

In the cosmic tug of war, expansion may win out and the universe will expand forever to provide what is called an “open universe.” Or, the inward forces of gravity may win out, resulting in a reversal of the expansion. This situation is referred to as a “closed universe.” A pulsating, closed universe reaches a maximum size and then collapses in what some call the “big crunch” or, humorously, the “gib gnab.” A closed universe has both a beginning and an end in time. The third possibility is that of a universe midway between closed and open, a universe called “flat.” Flat universes keep expanding forever, the gravitational forces being so exquisitely matched and finely tuned to the expansion that the universe simply coasts toward infinity. In other words, the flat universe would expand without limit, but the rate of expansion would become closer and closer to zero with the passage of time.

Astronomers discuss the tug of war between expansion and gravity in terms of omega (Ω), which is the ratio of the actual average mass density of the universe to the critical density. The latter is defined as the density of mass required to halt the outward expansion of the universe. If $\Omega < 1$, the universe would be open; if $\Omega > 1$, the universe would be closed; and if $\Omega = 1$, the universe would be flat. In principle, omega can be measured, but in practice, the measurements are uncertain, difficult, and controversial. An obvious problem is the question of homogeneity. Is the universe smooth and uniform on a cosmic scale or is it lumpy with regions of alternating high and low density (see section below on Large Scale Structure)? If the latter is true, how does one determine “average density?” And what about dark matter? If there is a large amount of dark, undetected matter “out there” that vastly enhances the average density of the universe without our knowing it?

In spite of all of these uncertainties, current measurements indicate that omega probably has a value of less than one, suggesting that the universe is of the open variety. In other words, the density of mass in the universe is insufficient by a large measure to effect a slowing down of expansion and eventual collapse. The cosmic density required to bring on a big crunch is around one-half dozen atoms per cubic meter. That is a far, far better vacuum than can be achieved in scientific laboratories.

Measures of Cosmic Distances and Looking Backward

How do you measure distance? With a micrometer?…With a ruler?…With a tape measure? Of course, the answer depends on what you are measuring. Would you want to measure the distance between New York and Los Angeles with a ruler? Probably not.

These same considerations apply when one makes astronomical measurements. We use a scale appropriate to the distances involved. Within the solar system, it is convenient to use the astronomical unit, AU, which is the average distance from the sun to the Earth. This measure is not very useful in a cosmic sense because it is much, much too small. For example, the distance to Alpha Centauri (the star nearest our sun) is about 25,000,000,000,000 miles (approximately 250,000 AU).

Because of the enormity of the situation, it is convenient to think of cosmic distances in terms of how long it takes light to travel between objects. Light travels at a rate of about six trillion miles in a year. This distance is called a light year, and a light year thus becomes a convenient measure of distances in the universe. The Andromeda galaxy (our nearest galactic neighbor) is two million light years away.

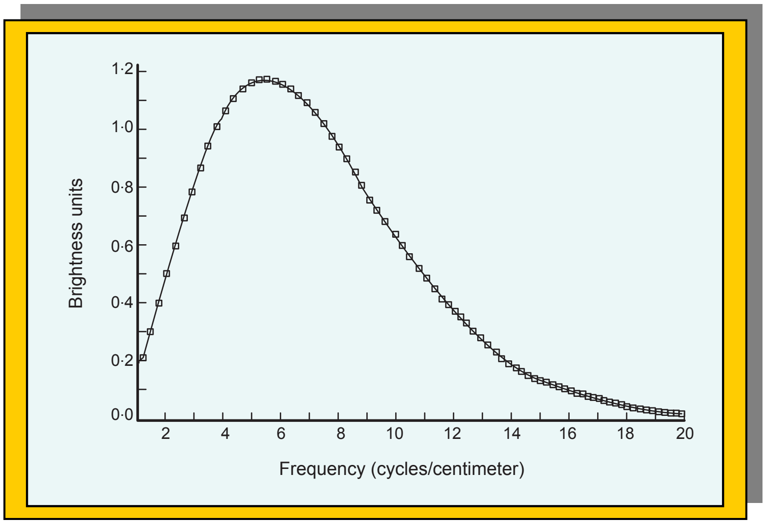
Another very important concept encompassed by the process of cataloging distances in terms of light years is the idea that by the time light from a distant object reaches us, it is "old." For example, light reaching us today from Andromeda actually left there two million years ago! We do not know what Andromeda actually looks like at the instant in time when you read these words. We only know what it looked like two million years ago. Light arriving from galaxy M87 departed on its voyage 50 million years ago. We do not know what M87 looks like today. Maybe it is no longer there!

The Hubble Space Telescope has been enormously successful in gathering "old" light emitted long ago from extremely distant galaxies and letting us peer farther and farther back into the history of the universe. With each increase in telescopic capability, we are able to turn back another page in the history book, in effect peeling off layers from the onion of time. If we were to gather light from a galaxy eight billion light years away, the image would be of an object having an age comparable to that of the universe. We would have a glimpse of what the universe was like shortly after it was formed. With even better telescopes, we might be able to see back to the Big Bang itself.

Remnants of the Big Bang

We know the universe is expanding. Now, let's play a video game in our mind and reverse the expansion. What would we see? Just the reverse of what is thought to have occurred from the Big Bang to the present time. As the universe contracts in our video image, the galaxies move closer together, collapse, and turn into clouds of gas. As further compression occurs, stars lose their identity and virtually all matter is in the form of atomic and molecular gases. As is the case for all gases, the temperature rises with further shrinking and compression. Continuing with the reverse Big Bang, we imagine that temperature continues to increase, and finally it becomes so hot that molecules decompose into atoms. The atoms become so hot that they can no longer hold onto their electrons, the universe at this point is a boiling cauldron of atomic nuclei and free electrons. Continuing toward the Big Bang, we find the temperature soaring, and it finally becomes so hot that atomic nuclei break up into protons and neutrons. Finally, when the temperature reaches about 10^{13} kelvin, matter as we know it ceases to exist. The familiar, fundamental particles of chemistry and physics—protons and neutrons—have decomposed into the elementary particles called quarks. Quarks were observed very recently for the first time in a laboratory here on the Earth.

The Big Bang model thus predicts a hot universe at the beginning. There are two major pieces of evidence that support this idea. The first is that the observed abundances of hydrogen, helium, and lithium in space match the abundances predicted from the model. In a sense, these abundances are remnants of the Big Bang. The second is what is called "cosmic background radiation." Physicists know that "blackbody radiation" [see activity on infrared spectroscopy in *Cosmic Chemistry: Planetary Diversity*] arises when subatomic particles collide with each other at high rates. This clearly would have been the case shortly after the Big Bang.



Blackbody radiation is identified by its spectral or color characteristics and it can be characterized by a single parameter, the wavelength of maximum intensity that corresponds to the temperature of the radiation. According to theory, hot blackbody radiation would have been produced uniformly throughout space in the early universe, colliding with subatomic particles until the universe had cooled enough for atoms to form. Basic thermodynamic principles show that blackbody radiation remains blackbody radiation irrespective of the expansion of the universe. However, its temperature changes because of the Doppler effect. Thus, we would expect to find cooled and thinned remnants of this radiation throughout the universe today. The predicted temperature (wavelength of maximum intensity) of the radiation being around 3 kelvin.

Such radiation was first observed by Penzias and Wilson at Bell Labs. Subsequently in 1989, NASA's Cosmic Background Explorer (COBE) spacecraft gathered spectral data on the radiation above Earth's atmosphere. The results were in almost perfect agreement with theory. A plot of the logarithm of the observed intensity of this microwave radiation against its frequency provided a blackbody radiation curve for a temperature of 2.7 kelvin. This ancient radiation is steaming through your hair as you read this sentence, and about one percent of the flickering static specks seen on a TV screen are triggered by this ancient radiation that traces its origin back to the Big Bang.

Large Scale Structure

Earlier it was mentioned that the universe usually is assumed to be homogeneous and that severe mathematical difficulties are introduced into the Big Bang model if this assumption is not made. But, is this assumption really valid? Certainly, if we look at the solar system, we do not find homogeneity [see *Cosmic Chemistry: Planetary Diversity*]. Looking beyond the solar system we might conclude that the universe is not filled with evenly distributed objects either. It is sometimes described as "lumpy," with matter clumped into galaxies, galaxies clumped into clusters of galaxies, and so on. These clusterings of galaxies are referred to by astronomers as "structures." Such structures of various sizes are found almost everywhere in the universe. Is the universe actually hierarchical, in which small structures are part of larger structures, which are part of even larger structures, and so on?

Evidence has been gathered over recent years for "lumpiness" that extends over distances of 20 million light years. Large congregations of galaxies, the so-called superclusters, have been found. Yet, at the same time voids exist that extend over distances of several hundred million light years where there are few galaxies. Other astronomers have identified chains and walls of galaxies, as well as galaxies that appear to be located on the surface of bubbles, with nothing inside the bubbles.

Have these observations convinced you that the universe is not homogeneous? Before you jump to a conclusion, let's think about the observational scale. If you approach the Rocky Mountains from a distance of 100 miles, they look like sort of an indistinct, uniform, homogeneous hump arising from the plains. It is only as you get closer that individual peaks and valleys begin to show up. As you get even closer, you begin to see mixtures of individual boulders and small rocks of various sizes randomly strewn about. Finally, if you get down on your hands and knees, you will find grains of sand mixed in among the rocks. Therefore, whether you characterize the Rocky Mountains as homogeneous or inhomogeneous depends on the observational scale. This is the problem faced by astronomers as they decide whether or not the universe is homogeneous. What is the scale?

If it is found that the "lumpiness" extends indefinitely, then the very foundations of the standard Big Bang model will be challenged. On the other hand, if the "lumpiness" averages out to be the same everywhere when the universe is viewed from very large distances, say several billion light years, then the idea of homogeneity will be preserved. Once again, the cosmic jury is still out. Stay tuned.

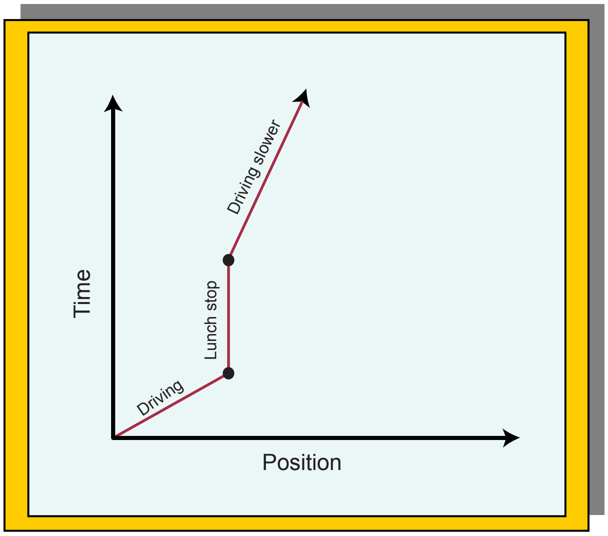
It is easy to conclude that there are many fundamental questions remaining to be addressed in the young science of cosmology. It is an exciting field. Perhaps you can someday provide some answers.

A Caveat

Much of cosmology is couched in highly mathematical and conceptually difficult terms. This module attempts to address some, but not all of the abstract concepts involved in cosmology. We feel that it is important to address one more issue—the concept of space-time.

The fundamental conceptual problem that arises in considerations of space-time arises from our inability to visualize in four dimensions. However, the idea of space-time is not uncommon and in fact, it is used in everyday life. If you tell a friend that you will meet her at the gym at 3:30 p.m., you are defining exactly where (space) and when (time) you will meet. You have defined a space-time.

In his book, *Physics for the Rest of Us*, Roger Jones illustrates the concept nicely by asking the reader to imagine a car traveling along a perfectly flat straight road with no curves, dips, or potholes. In other words, the car is constrained to move in only one dimension. Drawn on a roadmap, the car's path will be represented by a straight line. This representation portrays only the car's spatial path; it does not convey the idea of motion. Motion requires that time be represented as well. This can be done by showing distance and time on a single graph, providing a more accurate picture of the car’s motion. If elapsed time is plotted on the abscissa and highway miles on the ordinate, a line is obtained that represents the car’s motion in time. Curves on the line represent acceleration or deceleration. Where the line is parallel to the x axis, the car is stopped. Where it slopes upward at a constant angle, the car is moving at constant speed.



What is being done is to represent time in a spatial sense, which we ordinarily do not do. Nevertheless, if we choose to do so, we can see the interlocked roles played by space and time as we attempt to describe the entire story of the car’s journey. We would have a space-time picture.

Now, let’s imagine a spacecraft traveling to a faraway destination. To portray the story of this journey (as described by Jones) one would have to use the three dimensions of interplanetary space (X, Y, and Z) and add the fourth dimension (time). Herein lies the conceptual problem. We cannot graph this journey as we could with the car because we do not live in a four-dimensional physical space, nor can we imagine what it would look like. As stated by Jones, “The four-dimensional representation of the story of a moving body is really what we mean by space-time, and space-time, thus conceived, has been built into the mathematics and graphical representations of the theory of relativity.”