

ENDLESS UNIVERSE
Beyond the Big Bang

Paul J. Steinhardt and Neil Turok

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Excerpt

Preface

"There is a theory which states that if ever anyone discovers exactly what the Universe is for and why it is here, it will instantly disappear and be replaced by something even more bizarre and inexplicable. There is another theory which states that this has already happened."

Douglas Adams, *The Restaurant at the End of the Universe*

Theories of the universe have abounded throughout human history, but the last forty years have been exceptional. A single theory, the hot big bang picture, has dominated scientific and public discourse and has even become part of the standard curriculum for schoolchildren. A central element, the idea that the universe emerged from a very hot, dense state 14 billion years ago and has been expanding and cooling ever since, has been firmly established through many independent measurements. But nearly every other feature of the theory has had to be modified during this period. One ingredient after another — “dark matter”, “inflation,” “dark energy”— has been added and separately adjusted to fit the observations, and each of these adjustments has critically altered the history of the expansion of the universe. Even so, the picture remains far from complete. The big bang is conjectured to be the beginning of time and space, but there is no clue as to how or why the big bang occurred. Nor is there a firm prediction about the future of the universe. Most cosmologists do not consider these flaws to be worrisome. They think that the theory will ultimately be simplified and made more complete. And perhaps they are right, Douglas Adams’s theory notwithstanding.

This book concerns the emergence of a new theory of the universe, according to which our cosmic history consists of repeating cycles of evolution. Each cycle begins with a bang, but the bang is not the beginning of space or time. Rather, it is an event with a “before” and an “after” that can be described by the laws of physics. Each cycle influences the next. The events that occurred before the last bang shaped the large scale structure of the universe observed today, and the events that are occurring today will determine the structure of the universe in the cycle to come. Perhaps space and time sprang into being many cycles ago, but it is also possible that they are literally “endless.”

In this new, more integrated picture, the components that had to be added one by one to the conventional picture are either jettisoned, as in the case of inflation, or become essential, interwoven elements of the machinery that keeps the universe cycling. Most remarkably, this new theory of a cyclic universe is able to match all current astronomical observations with the same accuracy as the modified big bang picture, and it may explain some aspects of the universe that the big bang picture cannot.....

Chapter Two

“Act Two”

You can't make a man unsee what he has seen, — Bertolt Brecht, *The Life of Galileo*

The history of the universe can be compared to a play in which the actors — matter and radiation, stars and galaxies — dance across the cosmic stage according to a script set by the laws of physics. The challenge for the cosmologist is to figure out the story line after arriving at the show 14 billion years too late, long past the crucial opening scenes.

Observations of nearby galaxies and stars provide an accurate picture of the present scene. By gathering light emitted long ago from more distant objects and applying the physical principles learned and tested on Earth, astronomers have been able to reconstruct more and more of what happened in the past. The epoch we call Act Two, which began just one second after the big bang and continues to the present day, is the period of cosmic history that is best understood. During this nearly 14 billion year span, the universe expanded a billion times in size, and the hot primordial gas that filled the infant universe cooled to one billionth of its initial temperature and condensed into structures of increasing mass and complexity: the first atomic nuclei, the first atoms and molecules, and, ultimately, the first planets, stars, galaxies, galaxy clusters, and superclusters.

One might imagine that, armed with this detailed knowledge of Act Two, scientists could straightforwardly determine what happened before or what will happen next. The big surprise is that this is not the case. The inflationary and cyclic models both incorporate Act Two, but they sandwich it between completely different first and third acts. In the case of the cyclic model, Act Three is not even the final act: the plot eventually leads to a new Act One, in which the story begins all over again. To appreciate how two radically different views of the history of the universe can *both* be consistent with the plethora of observations available today, one must first understand what is and is not known about Act Two.

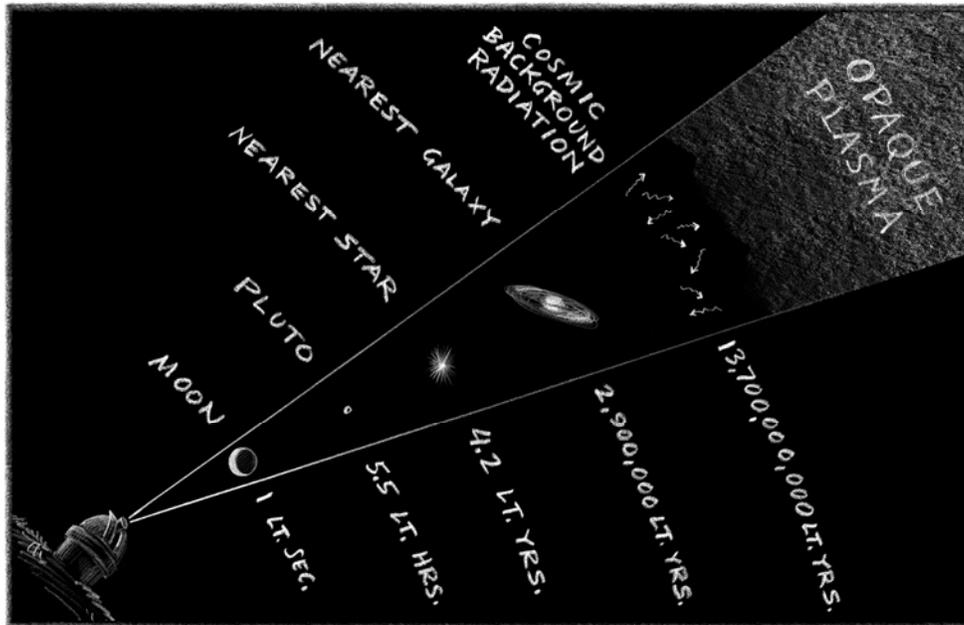
The Cosmic Sphere

We live on a minor planet orbiting an ordinary star, the Sun, one of a hundred billion stars making up the Milky Way galaxy, which is visible on a clear night as a smear of light stretching across the sky. Beyond the Milky Way, powerful telescopes can see a hundred billion other galaxies, spread through space in a complex, hierarchical pattern of clusters and superclusters.

The key to discovering the structure of the universe, the way it evolved, and where it is headed is to gather light from distant sources. Light travels through empty space at a finite speed, 186,000 miles per second, so the light collected today from a distant source must have been emitted long ago. This is why astronomical images show objects as they once were, rather than as they are now. Once one understands this simple notion,

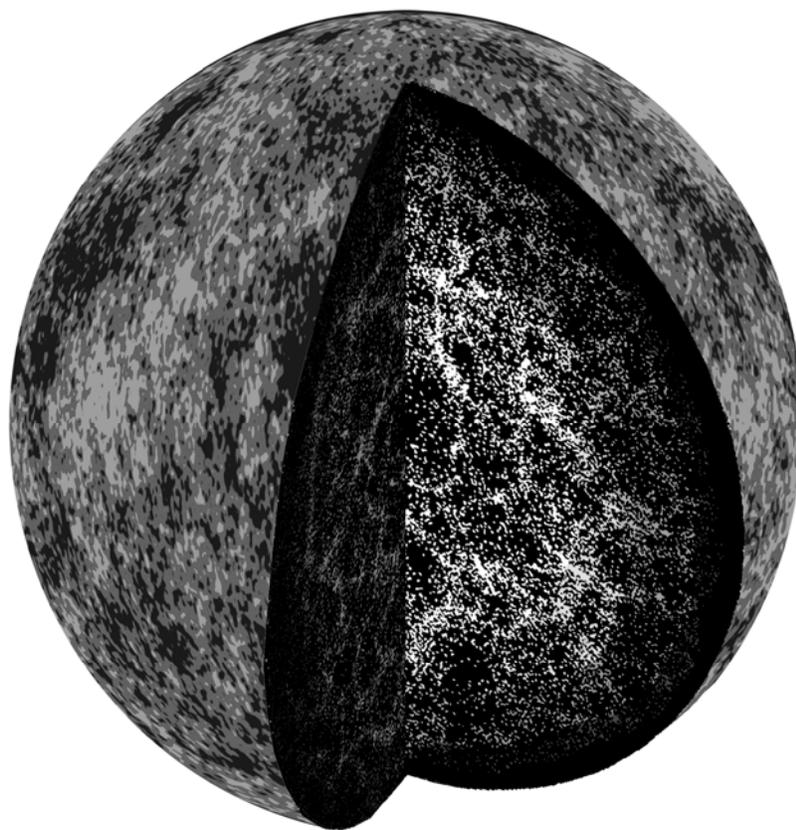
powerful telescopes can be used as time machines to study the evolution of the universe from very early times up to today.

To emphasize the point, astronomers label distances according to the amount of time required for light to travel from the source to the Earth. For example, the average Earth-Moon distance is called 1.282 “light-seconds” because light takes 1.282 seconds, on average to travel from the Moon to the Earth. By the same reasoning, Pluto is five and a half light-hours away. The nearest star, Proxima Centauri, is 4.2 light-years away.



The Milky Way’s cosmic neighbor, the Andromeda Galaxy, lies 2.9 million light-years from the Earth; the light received from its stars today was emitted before the earliest humans roamed the Earth. At a distance of 52 million light-years lies the giant Virgo cluster, consisting of well over a thousand galaxies. And the farthest region ever observed is 13.7 billion light-years away, the layer of space portrayed by the WMAP satellite. The radiation collected to form the WMAP image, known as cosmic background radiation, was emitted from this layer only 380,000 years after the big bang. Prior to that moment, the universe was too hot for atoms to exist. Instead, atoms were broken apart into a gas of charged atomic nuclei and electrons called *plasma*. The plasma scattered light so strongly that the universe was completely opaque. After 380,000 years, the plasma cooled off enough for the nuclei and electrons to combine into a transparent gas of neutral atoms. From that moment on, light traveled freely through the universe.

One can imagine using all the astronomical observations that have ever been made to construct a scale model of the optically visible universe in the form of a filled “cosmic sphere” with the Earth at its center. The cosmic sphere represents the universe as seen from the Earth. A similar sphere could be drawn around a planet in any other galaxy. Although the fine details would be different, the average appearance of the sphere would be the same.



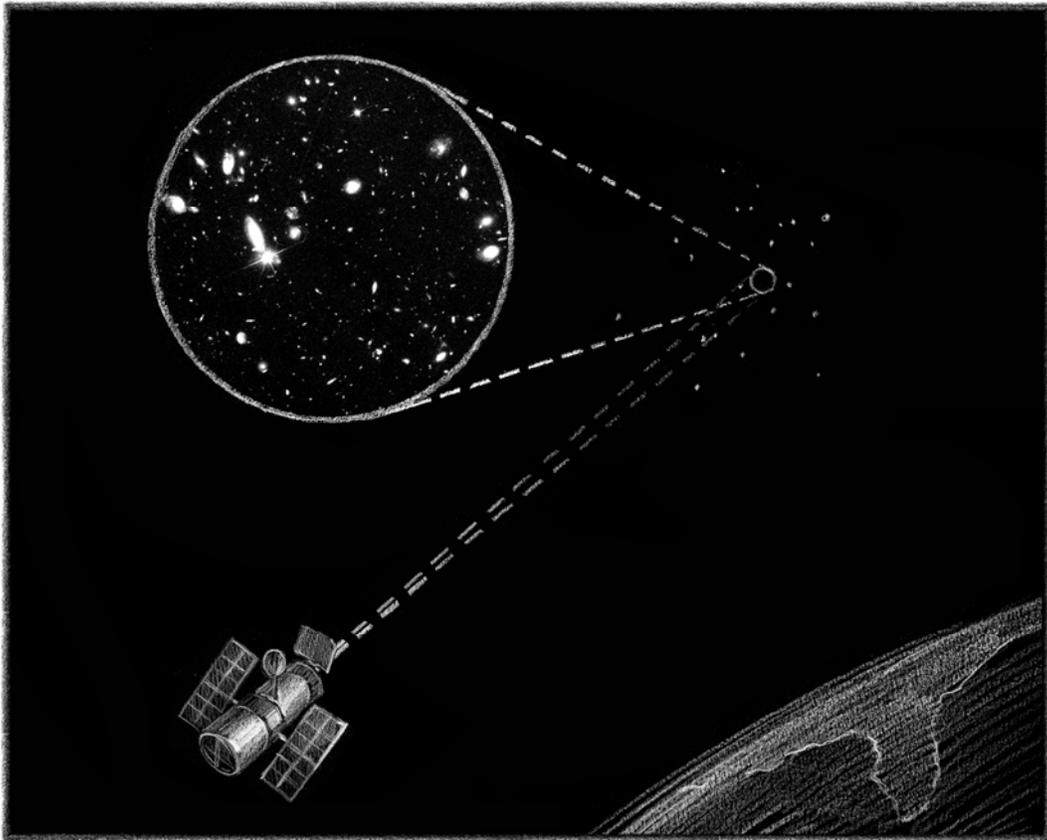
If each galaxy in today's universe occupied a region the size of a grain of sand, the billions of galaxies within reach of telescopes would fill a space a few meters across. Galaxies near the Earth are seen more or less as they are today. Distant galaxies appear as they were billions of years ago, because the light received from them had to travel for billions of years to reach us. The outermost galaxies are pictured as they were when they were forming their first stars. Some contained bright quasars, believed to be giant black holes devouring clouds of hot gas swirling about them. Beyond all the visible galaxies lies a dark shell of space, which appears to be totally devoid of stars or galaxies. In actuality, the dark shell is no different than any nearer region of space. Galaxies and stars formed there at about the same time as the galaxies and stars nearby. The dark shell only seems to be vacant because it is so far away that it appears as it was before the galaxies formed. Finally, the outer skin of the cosmic sphere displays the WMAP image, whose light has taken almost 13.7 billion years to reach us. This light was emitted as the atomic nuclei and electrons in the hot plasma combined to form the first atoms, long before the formation of galaxies.

This concept of building a scale model of the universe is not too far from reality. With the help of powerful new technologies, astronomers have been gathering information needed to complete the cosmic sphere. One of the biggest challenges is measuring the distances to remote galaxies. The standard approach entails comparing the brightness

and colors of distant astronomical sources with those of similar objects seen nearby whose distances can be measured directly. The techniques are painstaking and time-consuming because the distant galaxies are extremely dim. A key technological breakthrough has been the invention of charge-coupled devices (CCDs), which are sensitive light detectors similar to those in digital cameras. Using a specially designed, ultralarge-format CCD camera designed and constructed by James Gunn at Princeton University and mounted on a 2.5-meter telescope at Apache Point, New Mexico, a team of astronomers from fourteen institutions have been engaged since 1998 in the Sloan Digital Sky Survey. This project has measured the distances to over 2 million galaxies in slices of space spread over a quarter of the sky in the Northern Hemisphere and extending outward a billion light-years, about a tenth of the way to the edge of the cosmic sphere. A similar survey, called 2dF (for “two-degree field”), conducted at the Anglo-Australian Observatory in central New South Wales, Australia, has mapped a large patch of sky in the Southern Hemisphere.

To see farther, cosmologists have been using the Hubble Space Telescope, the first space-based optical observatory, in orbit four hundred miles above the Earth. The Hubble telescope was not designed for this purpose. With its ability to focus on tiny patches of sky and study the fine details of individual objects, the telescope was considered to be incompatible with the kinds of broad surveys needed for cosmology. However, thanks to the ingenuity of Robert Williams, the director of the Space Telescope Science Institute in Baltimore, Maryland, the Hubble Space Telescope has proved to be remarkably useful.

Astronomers flood the Space Telescope Science Institute each year with proposals for using the Hubble telescope to study specific objects. One of the perks of being the Institute’s director is having personal control of a certain amount of telescope time. In 1995, after gathering advice from many leading astronomers, Williams made a selection that might at first sound bizarre. He chose to use a full ten days of telescope time, spanning 150 Earth orbits of the space telescope, to stare at “nothing,” an area that appeared to be totally blank, devoid of stars or galaxies. Williams figured that the region was ideal for obtaining an unobstructed view of what, if anything, lies beyond.



The chosen patch of the sky was a speck, roughly the size of Franklin D. Roosevelt's eye on a dime if you hold the coin out at arm's length. The patch appears blank to the human eye and to ground-based telescopes because it contains no stars or galaxies bright enough to be seen. But by adding up the light collected over ten days, the Hubble Space Telescope was able to gradually build a spectacular picture. The result, known as the Hubble Deep Field image, shows thousands of distant galaxies with a myriad of shapes and sizes, providing a direct view of the adolescent universe when the first galaxies were still forming, billions of years before they assumed the shapes observed today. The Hubble Deep Field image provides a good impression of what the cosmic sphere looks like all the way out to the most distant galaxies.

As we have already noted, the information needed to paint the outer skin of the cosmic sphere is being provided by the WMAP satellite. As of 2007, the satellite is continuing to orbit the Sun a million miles from the Earth and continuing to refine its image of the sphere's outer layer. As first pointed out over 30 years ago by cosmologists P. J. E. (James) Peebles and Jer Yu at Princeton University and Rashid Sunyaev and Yakov Zel'dovich at the Moscow Institute of Applied Mathematics, the tiny temperature variations in the cosmic background radiation across the sky contain a vast amount of information about the early universe. They provide a direct picture of how the density varied slightly from place to place in the early universe. The primordial density variations were critical to the later formation of galaxies and other large - scale structures in the universe. Where the matter was slightly denser than average, gravity caused it to clump

further. Eventually, it collapsed inward forming a galaxy or a cluster of galaxies. Hence the features seen in the WMAP image are the ancient progenitors of galaxies, and of the stars, planets and life within them. Each of us owes our own existence to early density variations like those seen in the WMAP picture.

The first experiment to detect variations in the temperature of the radiation across the sky was the Cosmic Background Explorer (COBE) satellite in 1992, but its resolution was too poor to depict the fine features. Nearly a decade later, in 2003, the WMAP satellite succeeded in producing the first all-sky, high-resolution picture. The image is packed with detailed information, which has been used to flesh out the story of Act Two. In the future, still more refined measurements of the cosmic background radiation may help to determine what happened in Act One and what is likely to occur in Act Three.

The boundary of the cosmic sphere is the surface from which the cosmic background radiation was emitted, 380,000 years after the bang. This surface is the outer limit of what can be seen using light and other forms of electromagnetic radiation, because the hot plasma described earlier obscures the view of the universe at greater distances, or earlier times.

To learn about the universe at yet earlier times, cosmologists use indirect methods. One of the most powerful involves studying the abundances of the different light chemical elements — hydrogen, deuterium, helium, and lithium — in the universe today. According to the hot big bang model, these elements were created in the first few minutes after the big bang. For the first second after the bang, the temperature was so hot that even atomic nuclei could not exist. But as the universe cooled, protons and neutrons were able to stick together to form atomic nuclei. By comparing the predictions of the abundances of the light chemical elements with astronomical measurements of primordial gas, cosmologists have been able to develop an accurate picture of the state of the universe between one second and a few minutes after the bang. The success of the predictions shows that the laws governing the behavior of nuclei and elementary particles in nuclear reactors and accelerator laboratories on Earth apply equally well in the early universe. Hence, the history of the universe can be traced all the way back to the first second. That is why the one-second mark is set as the beginning of Act Two.

Ultimate Plastic™

The cosmic sphere is a very useful way of compiling astronomical observations of the region of the universe around us, but it has one major limitation: it ignores the fact that the universe is expanding. For example, the WMAP image painted on the outer layer appears to span an enormous area, a spherical surface 13.7 billion light-years in radius. However, at the time the radiation was emitted from the WMAP layer, the universe was a thousand-fold smaller than it is today. Thus, the WMAP layer was just 13.7 *million* light-years in radius at that time, only a quarter of the distance between the Milky Way and the nearest galaxy cluster today.

The expansion of the universe controls the temperature, density, composition, of the universe and the formation of astronomical structures. The realization that space can expand or contract traces back to Einstein's theory of gravity, known as the general theory of relativity. The central tenet of Einstein's theory is that space and time form an elastic substance called space-time that can stretch, contract, warp, or wiggle. The gravitational force is due to the warping effect that a massive object has on the space around it, analogous to the depression created when a bowling ball is placed on a mattress. When other objects travel through warped space, their paths are distorted, analogous to the way a marble rolling on the mattress will swerve when it gets near the depression created by the bowling ball. As John Wheeler of Princeton University, a leading exponent of general relativity, likes to put it, "Mass tells space-time how to curve; and space-time tells mass how to move."

In fact, according to Einstein's best known equation, $E = mc^2$, mass is just one form of energy. Wheeler's dictum remains true if the word "mass" is replaced everywhere with "energy," which can take any form whatsoever. (E stands for energy, m for mass and c for the speed of light.)

Now imagine that all of space is filled with a nearly uniform distribution of matter, radiation or other types of energy. Then, according to Einstein's theory, the entire universe can expand or contract, just like the overall stretching or shrinking of an elastic sheet. Ironically, Einstein himself resisted the idea of an expanding or contracting universe, even though it is a natural consequence of his own theory. For philosophical reasons, he strongly preferred a model in which the universe is static and eternal.

So committed was Einstein to his vision of a static universe that he introduced an extra form of energy specifically designed to oppose the gravitational attraction of matter. The new form of energy, which came to be known as the *cosmological constant*, has a repulsive gravitational effect, causing space to expand rather than contract. In his first model of the universe, Einstein finely adjusted the repulsive gravity of the cosmological constant to counter precisely the attractive gravity of matter. By setting the opposing influences in perfect balance, Einstein was able to construct a static model of the universe. However, this situation is unstable and contrived: unless the balance between forces is perfect, the universe either collapses or blows up.

The empirical proof that the universe is not static came ten years after Einstein's proposal. Edwin Hubble, for whom the space telescope is named, observed the motions of distant galaxies and found convincing evidence that they are spreading out and that the universe is expanding.

Soon after, Einstein abandoned his static universe model, and the cosmological constant along with it. Abandoning the cosmological constant seems to have been a mistake, for, as shall be explained, it plays a prominent role in current theories of the universe. To appreciate Hubble's evidence for cosmic expansion, consider first an imaginary pocket toy, similar to the types that appeared in advertisements in old comic books. The ad might read: "Ultimate Plastic™: Imagine holding a universe in the palm of your hand!"

The toy comes as a cube the size of a sugar lump, with handles at each corner for you and some friends to stretch apart. Pull on the corners and the cube grows in size. Keep pulling and you can make the cube as big as a room. Inside the plastic, the makers have sprinkled tiny models of galaxies that you can see spreading apart from one another as the cube expands. The model galaxies are made of a hard material so that they do not expand when the cube is stretched — only the space between them does. This was Hubble's mental image of a chunk of the expanding universe.

None of the galaxies is special: if you could shrink yourself and perch on any one of them, you would see all the other galaxies moving away from you. Furthermore, each time the sides of the cube double in length, all distances double. Suppose the doubling takes place in one second. Then a galaxy that starts out 2 meters away from you winds up 4 meters away. So, it has moved 2 meters in 1 second, or, equivalently, it has receded at an average speed of 2 meters per second. A galaxy that is initially 3 meters away will be 6 meters away after one second, so it has receded faster than the first at an average speed of 3 meters per second. A galaxy that is initially 5 meters away has receded with an average speed of 5 meters per second. In other words, the farther away a galaxy is, the faster it recedes.

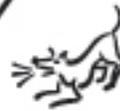
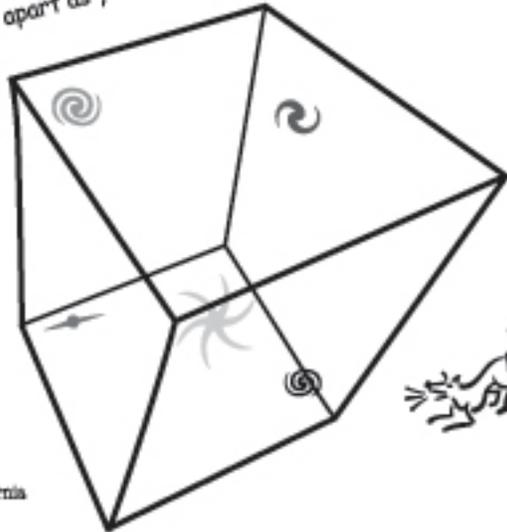


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Not only was Hubble's conclusion important, but the methods he used are still applied today, with various improvements, to measure cosmic distances. To determine the distance to galaxies, Hubble relied on the fact that nearly all galaxies contain pulsating stars known as Cepheids, whose brightness varies with time according to a regular, repeating rhythm. In 1912, Henrietta Leavitt, working at the Harvard Observatory, observed many Cepheids in the Milky Way and showed that those pulsating with the same rhythm emit the same amount of light. A decade later, using the 100-inch Hooker telescope at the Mount Wilson Observatory, the most powerful telescope on Earth at the time, Hubble managed to observe Cepheids in other galaxies. By comparing their apparent brightness to that of Cepheids in the Milky Way pulsating at the same rate, Hubble could estimate how far away their host galaxies must be.

In order to determine how fast each galaxy is moving toward or away from us, Hubble also measured the colors emitted by the Cepheids. Each star emits particular colors, depending on the composition of its atmosphere. For example, all stars contain hot hydrogen gas, which gives off light with a specific pattern of colors. If the star is stationary with respect to the Earth, the colors observed are the same as those of hot hydrogen gas measured in the laboratory. If the star is moving away from the Earth, though, each successive crest in the light wave has to travel a greater distance to reach the Earth, and, hence, the apparent wavelength is longer than it would be if the star were at rest. A longer wavelength of light corresponds to a redder hue. Therefore, the greater the speed at which the star recedes from the Earth, the greater is the redshift. If the star is instead moving toward the Earth, the pattern of colors is shifted toward bluer hues. Astronomers refer to the color changes as redshifts and blueshifts.

If the universe were static, as Einstein had first expected, Hubble might have found the motion of galaxies to be random, just like the molecules of air in motion all around us. Instead, he found something remarkable: except for the nearest neighbor galaxies, *all the other galaxies are running away*. When he plotted the speed versus the distance for each galaxy in his study, the graphs showed a straight line: the speed at which a galaxy recedes is directly proportional to its distance from the Earth, just like the model galaxies in Ultimate Plastic™. Here was a strong indication that space is uniformly stretching, just like the plastic in the imaginary toy. The slope of the straight line in his plot is called the Hubble parameter. It is a measure of the rate of expansion of the universe.

Since Hubble, observers have been using light from other kinds of astronomical sources to judge the range and recessional speed of galaxies and to confirm the validity of Hubble's law at greater distances. Each type of source has some distinctive feature that makes it possible to determine its brightness despite the fact that it is very far away. Then, as in the case of the Cepheids, comparing its brightness with nearby sources of the same type makes it possible to judge its distance. A recently discovered example is the Type IA supernova, a white dwarf star that accretes matter from a second star in orbit around it and explodes once it reaches a critical mass. Type IA supernovae have the advantage that they are far brighter than Cepheids and so can be used to judge the distance of extremely remote galaxies. A combination of methods like this was essential, for example, in mapping the distribution of galaxies in the Sloan Digital Sky Survey.

In our toy, the plastic expands but the model galaxies do not. Similarly, the expansion of the universe stretches the distances between well-separated galaxies but not the galaxies themselves, nor their components, including stars, planets, and people. The latter are held together by forces strong enough to resist the expansion of the universe. For example, the human body is held together by chemical bonds that are far stronger than the cosmological stretching force.

Hubble's law — that the recession speed grows in direct proportion to distance — is now established for galaxies within a few billion light-years of the Earth. Beyond that, naive notions of speed and distance need to be revised, since the recession speed as estimated from Hubble's law rises toward the speed of light. In this situation, the laws of special relativity need to be carefully applied. Nevertheless, the notion of space as Ultimate Plastic™ continues to provide the right insight about the expansion of the universe, and its effect on light and other forms of radiation, no matter how distant the source is from us. *Each time the universe expands by a factor of two, the wavelength of light traveling through space also doubles.* For example, the universe has stretched by a factor of a thousand since light was emitted from the WMAP layer. Today, the cosmic background radiation has a wavelength of a few millimeters and a temperature of 2.7 degrees above absolute zero (i.e., minus 270 degrees Celsius). But at the time it was emitted, the wavelength of the radiation was a thousand times shorter – a few microns, the wavelength of infrared light.

The energy and temperature of radiation grows in inverse proportion to its wavelength. Hence, cosmologists infer that the temperature of the universe was nearly three thousand degrees, or half the surface temperature of the Sun, at the time when the cosmic background radiation was emitted. This is hot enough to boil neutral atoms into charged nuclei and electrons. As the universe is traced even further back in time, the wavelength of the radiation gets smaller and the temperature grows ever higher. From what is known about how matter and energy change their character as the temperature rises, cosmologists can pinpoint many of the key transformative moments in the history of the universe.

Friedmann and the Expansion of the Universe

The first idea that expansion (or contraction) of space is a natural outcome of Einstein's general relativity theory was formulated by Russian mathematical physicist Alexander Friedmann, working in St. Petersburg in 1922. Assuming a nearly uniform distribution of matter, and no cosmological constant, Friedmann showed that space could not stand still. It would have to expand or contract everywhere in the same way, just like the Ultimate Plastic™ toy. Friedmann showed that in this case, Einstein's famously complicated equations of general relativity can be reduced to a simple formula, known as the *Friedmann equation*, linking the Hubble parameter to the curvature of space and the energy density of the universe, that is, the energy per cubic centimeter of space.

The curvature of space measures the deviation from the normal rules of geometry everyone learns in high school, rules dating back to Euclid. According to Euclidean geometry, two parallel lines maintain the same separation all along their paths. Equivalently, one can imagine sending off two parallel laser beams in any direction in three-dimensional space, and the two will never cross or diverge. Cosmologists use the term *flat* to describe space with this property. But Einstein's theory of gravity does not require that space be flat. Space can have a positive curvature, so that it bends back on itself like the surface of a sphere. In a positively curved space, two initially parallel light beams approach and intersect, just as the lines of longitude on the surface of a globe meet at the north and south poles. Cosmologists often refer to this case as a *closed* universe. Conversely, if the curvature is negative, space opens outward and two parallel light beams diverge. This case is called an *open* universe. The curvature is an important factor in determining the long-term future of the universe. For example, if the universe contains only matter and radiation, an open or flat universe expands forever but a closed universe expands only for a finite time before contracting into a big crunch.

Because of the importance of the curvature, cosmologists tried for decades to determine whether the universe is flat, open, or closed. Finally, the WMAP measurements settled the issue, showing conclusively that the curvature is negligible and space is flat. But nothing in Einstein's general theory of relativity or Friedmann's analysis explains why there should be no curvature. Because the search for a natural explanation of this fundamental feature of the universe is one of the prime motivations for the inflationary and cyclic pictures, this issue will be revisited later in the book.

In a flat universe, Friedmann's relation becomes very simple: the expansion rate of the universe is proportional to square root of the energy density. The expansion of the universe in its turn determines how the temperature and energy density change. Appropriating Wheeler's phrase, one might say, "The energy density determines how fast space expands, and the expansion rate determines how fast the energy density falls."

All forms of energy must be counted, but each form of energy responds to the expansion differently. For matter, the energy density decreases because the volume grows and the matter spreads out more and more. For radiation, there is an additional effect: not only is the density of light waves diluted but, the expansion of the universe stretches the wavelength of each individual light wave, thereby depleting its energy. Thus the energy density of radiation falls even faster than the energy density of matter. For dark energy, the energy density remains nearly constant as the universe expands. Because of these differences, the relative proportions of radiation, matter, and dark energy change over time. At early times, radiation dominates the energy density of the universe. Later on, the density of radiation falls below that of matter. Finally, in the late universe, the dark energy dominates the density of the universe as both matter and radiation are diluted away. This explains why Act Two is divided into three scenes: the radiation-matter- and dark energy – dominated epochs.

The transition from radiation to matter dominance about 75,000 years after the big bang was a critically important event in cosmic history. Structure forms in the universe from

slight variations in density, such as those observed in the WMAP image, when matter clumps gravitationally around the regions with higher than average density. As long as radiation dominated the universe, though, the expansion rate was too rapid for structure to form. Only once matter came to dominate did the expansion slow enough to allow regions of higher density to draw together to form galaxies, within which stars and planets were born. The formation of the solar system and the Earth, therefore, depended crucially on this transition from radiation to matter domination.

The formation of the Earth also depended critically on the sequence of events that occurred during the radiation-dominated period that preceded matter dominance. Just a few seconds after the big bang, the temperature of the universe was a billion degrees, a hundred times hotter than the center of the Sun. This is the period discussed earlier when protons and neutrons first fused into helium and other nuclei, those fusion reactions marking the beginning of Act Two. Later on, the primordial helium underwent further fusion reactions in stars that produced carbon, oxygen and yet heavier elements. Most of the heavy elements that make up the Earth were formed in exploding stars called supernovae, and then scattered through space. Without the primordial helium emerging from the early universe, however, there would not have been enough heavier elements to form the iron cores of terrestrial planets, like the Earth, or the molecules on which life depends.

Naturally, cosmologists would like to extrapolate further back in time to discover how the matter and radiation themselves originated, but this is problematic. Extrapolated backward just one second before the start of Act Two, the Friedmann relation implies that the scale of the universe shrinks to zero and the energy density and temperature grow to be infinite. This is the moment known as the big bang, also referred to as the *initial singularity*. Mathematicians use the term “singularity” to indicate that equations are failing. The big bang is referred to as the initial singularity because Einstein’s equations of general relativity break down when the temperature and energy density become infinite, as Einstein himself recognized, and their description of the expansion of the universe ceases to be valid.

When equations develop singularities, physicists normally interpret it to mean that equations are being extended into a regime where they can no longer be trusted and that the laws of physics they were using must be replaced by improved ones capable of making sense of the situation. For example, the flow of air around the wing of an airplane can usually be accurately modeled by treating air as a smooth fluid. But if the plane exceeds the speed of sound, a shock wave forms and the fluid equations predict that the flow develops singularities, with the density of the air becoming infinite at some locations. In this situation, the equations can no longer be used. The remedy is an improved theory of shocks in which the air is described more precisely as a collection of molecules bouncing off one another. String and M theory, described later in this book, are improvements of Einstein’s theory of gravity that represent space-time in terms of new, more fundamental microscopic entities. Most cosmologists hope that such an improved description of gravity will ultimately tackle the problem of the cosmic

singularity, and some positive indications of this will be explained in subsequent chapters.

Today, many cosmologists interpret the singularity in Friedmann's equation as signifying the beginning of space and time, and most textbooks reinforce present this notion as certain. However, this is an assumption, not a proven fact. The cyclic model of the universe challenges this point of view, suggesting that the big bang was not the beginning of time but was rather a violent transition between two stages of cosmic evolution, with a "before" and an "after." In fact, according to the cyclic model, the big bang in our past was caused by a strange substance that is now starting to take over the universe and that will eventually lead to the next big bang in our future, and the one after that.

The strange substance is one of two shady characters that astronomers have had to introduce in order to make sense of Act Two. The original hot big bang model developed in the first half of the twentieth century included only ordinary atomic matter and radiation. As it turned out, two additional components were initially missed by astronomers but were lurking in the background all along, exerting a profound, controlling influence on everything which we now see, on everything that has transpired in Act Two and on everything that will happen in Act Three.

Two Shady Characters

The two new characters neither emit nor absorb light, so they are hard to find. Their composition is unknown. They have never been produced in a laboratory. They are not composed of protons, neutrons, or electrons, or any of the many more exotic elementary particles that have so far been produced in the high energy collisions that take place in particle accelerators. Where they came from or what they will do in the future is a mystery. But what is certain is that, together, they account for 95 percent of the energy in the universe today.

The two components are called *dark matter* and *dark energy*, rather unimaginative names for the two most surprising and enigmatic constituents of the universe. The nomenclature is actually confusing because it suggests that the two are related, whereas the only thing they have in common is that they do not absorb or scatter light. Their physical properties are completely different. And their roles in this history of the universe are completely different. Dark matter dominated the past; dark energy will shape the future.

Dark matter was discovered in the 1930s by Fritz Zwicky, an astronomer at the California Institute of Technology, who was trying to understand the rapid motion of galaxies within galaxy clusters. In a cluster, the galaxies are held together by gravity and orbit about one another. Zwicky found that he could explain the high orbital speeds of the galaxies only if the clusters contain a lot more matter than is present in visible stars and gas. He proposed that most of the mass of a galaxy cluster consists of some form of nonluminous matter (sometimes called the *missing matter*). Four decades later, theorists showed that individual spiral galaxies, including the Milky Way, must be embedded in a large cloud of dark matter in order for their stars to remain confined to thin disks. This prediction

was subsequently confirmed by astronomical observations tracking the rapid motion of gas at the outer edge of neighboring galaxies.

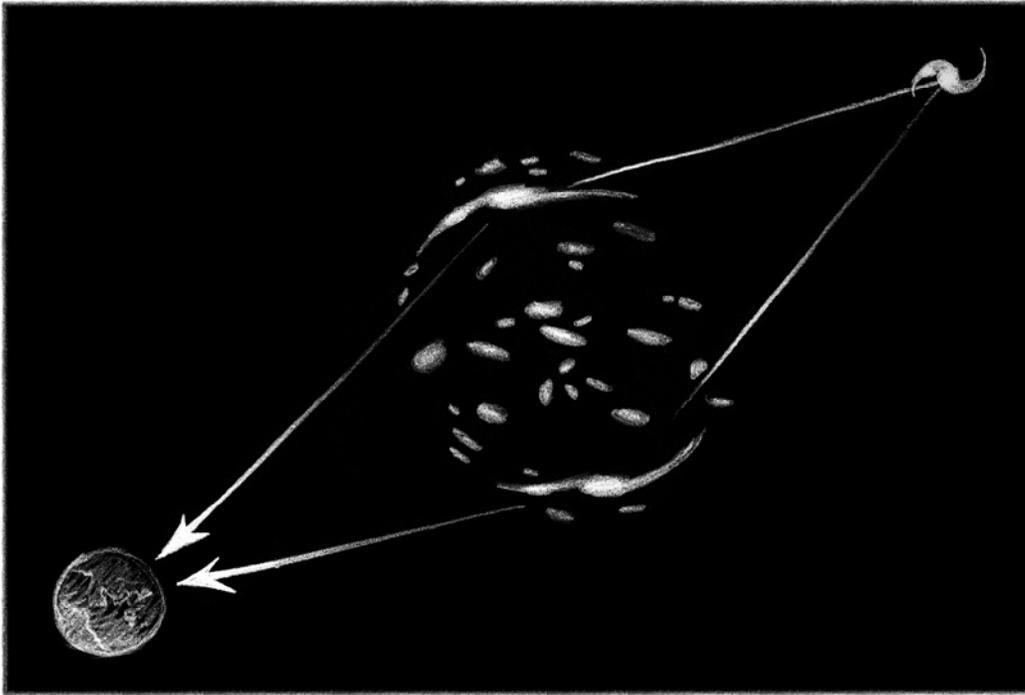


Fig. 2.7

In the 1980s, astronomers first began to “see” the dark matter in galaxy clusters by observing how its gravitational field bends the paths of light rays passing through it, an effect called *gravitational lensing*. To understand how one can “see” dark matter this way, just think about water in a drinking glass. Water is completely transparent to light, but one can tell that it is in the glass because it bends light rays passing through it and distorts the image of whatever is behind it. Likewise, even though the dark matter in a cluster of galaxies is completely transparent, it will, because of its gravity, bend the light passing through it from a distant galaxy on its way to the Earth. Clumps of dark matter can behave as gravitational lenses, each forming a separate image of the distant galaxy behind. In a telescope image, the highly distorted, lensed images of the distant galaxies appear in the same view as the images of the nearby cluster galaxies, giving the false impression that they lie at the same distance. By analyzing the shape and light pattern of the various sources, astronomers can clearly discriminate between the two. Then, by modeling the pattern of lensed images and the bending of light, astronomers can reconstruct the distribution of dark matter in the galaxy cluster. In this way, they can effectively “see” the dark matter through its light-bending effect.

Over the last few decades, cosmologists have come to understand that the presence of dark matter was essential to the formation of all of the structures making up the universe. For a few hundred thousand years after the big bang, when the universe was still filled with hot plasma, the intense pressure of the radiation prevented the ordinary matter composed of atomic nuclei and electrons from clumping together. Because dark matter is not affected by radiation, it was free to condense into concentrated dark matter clouds,

long before the ordinary matter could start to cluster. When the hot plasma cooled enough for the electrons and nuclei to combine into neutral atoms, ordinary matter was set free from the radiation. By this time, the clouds of dark matter were already in place and concentrated enough to attract the ordinary matter to their cores, where galaxies, stars, and planets then formed. If not for this assist by dark matter, galaxies would be much rarer than they are: in most of space, the dark energy would have taken over and diluted the matter away before it could ever clump. And without galaxies, there would be no stars and planets. Therefore, all of us owe our very existence to dark matter, even though its composition is not yet known.

Most physicists think that dark matter consists of an ocean of elementary particles that are electrically neutral, so that they interact very weakly with ordinary matter and do not scatter or absorb light. This would explain why the particles are not noticed even though the Earth is constantly moving through a sea of dark matter as it orbits the Sun. One way to try to detect the dark matter is to construct instruments that are sensitive enough to directly detect the dark matter particles flowing through the Earth. By placing these detectors in deep mines where they are shielded from ordinary cosmic rays, physicists hope to find a few rare events in which a dark matter particle bounces off an atomic nucleus and leaves a trail of light and ionized particles. As of 2007, many experiments are under way, but no confirmed detection has been made.

Another approach is to re-create the ultrahigh temperature and density of the early universe in a controlled laboratory setting to see if dark matter particles can be produced in these conditions. In the near future, this will be done at giant particle colliders like the Large Hadron Collider being built at the European Organization for Nuclear Research (CERN) in Geneva, Switzerland, and the International Linear Collider, which is currently being planned.

The reign of dark and ordinary matter lasted nearly 9 billion years, during which the first atoms, molecules, stars, and galaxies formed. Over that period, dark matter accounted for over 80 percent of the energy of the universe and ordinary matter accounted for the rest. Then, about 5 billion years ago, dark energy took over as the dominant form of energy in the universe.

Although it has nearly three times the density of dark matter today, dark energy has been much harder for astronomers to detect because it does not cluster under gravity and form distinguishable clumps. The only way to sense its presence is to measure its repulsive gravitational effect over very large regions of the universe. The first bits of evidence for dark energy were uncovered in the 1980s and early 1990s, but there were also contrary indications. The situation became clear only in the mid-1990s, when all the leading astronomical indicators converged on the same result. Ground- and balloon-based cosmic background radiation measurements, the predecessors of WMAP, showed that the light coming from the WMAP layer has not been affected by space curvature: space is flat. But it was also known by then that the sum total of all the clustered matter, both ordinary matter and dark matter, accounts for less than half the energy density required to explain the expansion rate of the universe, according to Friedmann's equation. The

simplest explanation for the shortfall is that the universe is dominated by a form of energy that is transparent, so it is invisible, and smoothly distributed, so it is not counted in the census of clustered matter. To avoid clustering, this additional type of energy must be gravitationally self-repulsive, cosmologists reasoned, and therefore completely different from dark matter.

The idea that gravity can repel goes against what children are taught in school; one of the first principles of physics, dating back to Newton, is that gravity always attracts. What was less widely appreciated, until recently, is that in Einstein's theory of gravity this axiom applies only to some forms of energy, like ordinary matter and dark matter. Other forms of energy, like dark energy, *can* gravitationally repel.

The simplest and most famous example of dark energy is the cosmological constant, introduced by Einstein in 1917. You can think of it as the energy of the vacuum — that is, the energy remaining in empty space after particles and all forms of radiation have been removed. Vacuum energy is totally inert. It has the same density at every point of space and at every moment in time, no matter what is happening in the universe. When space stretches, the vacuum energy density is completely unchanged. Since the volume is increases, this means that the total vacuum energy increases as the universe expands. Furthermore, the repulsive gravitational effect of vacuum energy causes space to expand even faster, creating even more space and even more vacuum energy. The result is a runaway exponential expansion and a runaway production of vacuum energy.

To understand how this runaway process got started, consider the time when galaxies were first forming and the dark energy density was much smaller than the matter density. As the universe expanded, the galaxies spread out and their density decreased, but the concentration of vacuum energy did not. Inevitably, the density of matter fell below the vacuum density. At that point the gravitational repulsion of the dark energy took hold, speeding up the expansion. Based on observations, the speedup occurred about 5 billion years ago. According to Friedmann's equation, from now on the universe will double in size every 10 billion years, placing us in an epoch of exponential growth. Gravity will continue to power this growth forever, unless the dark energy changes to another form. As described in the next chapter, such a change does indeed occur in the cyclic model.

In 1998, two groups of astronomers conducted a survey of very distant Type IA supernovae, the exploding stars described above, and compared their recessional speeds to those of nearby ones. The distant supernovae emitted their light many billions of years ago, so their recessional speeds could be used to determine the expansion rate of the universe in the remote past. Similarly, the recessional speeds of the nearby supernovae were used to determine the present expansion rate. By comparing the two expansion rates, these astronomers confirmed that the expansion is accelerating, confirming the earlier conclusion that the universe is now dominated by dark energy today. Follow-up supernovae surveys, the WMAP results, and other independent checks have provided overwhelming evidence that a dark energy–dominated epoch is well under way.

The discovery of dark energy stunned scientists worldwide. Overnight, the view of the universe and of its future changed. The conventional view was that everything in the universe attracts under gravity just as ordinary matter does. For seventy years, most cosmology textbooks took this for granted and ignored the possibility of gravitational repulsion. Authors claimed that the cosmic expansion rate is slowing and that the future of the universe depends only on whether the amount of matter is sufficient to stop the expansion and cause the universe to contract to a big crunch. Now it is clear that the textbooks were all wrong. Matter ruled the universe in the past, but a new age has begun in which the influence of matter on the evolution of the universe is becoming negligible and the fate of the universe rests instead on the nature of dark energy.

If the dark energy is due to a cosmological constant, the universe will expand exponentially forever. All of the galaxies seen today will be diluted away and space will approach a nearly perfect vacuum. However, this need not be the case. Physicists have identified several alternative kinds of dark energy that might allow the universe to avoid this dismal fate. One example, called *quintessence*, is also gravitationally self-repulsive, but its density decreases slowly with time. In this case, dark energy dissipates and gives way to a new kind of evolution. A specific kind of quintessence occurs in the cyclic model that enables the universe to recover from each period of accelerated expansion and begin a new cycle.

The Big Picture

The detailed reconstruction of the last 14 billion years of cosmic history, beginning one second after the big bang, has to be counted as one of the most extraordinary human achievements. Any credible account of the origin and future of the universe must be based on what has been learned thus far.

The most basic fact is that the universe evolves. Soon after the bang, the universe was very hot and dense. But it has now expanded into a cold, dilute state. It began almost uniform and structure-less and has become highly complex and elaborate. Over time, matter has been drawn together by gravity and other forces and has arranged itself in ever more complex structures: nuclei, atoms, molecules, minerals and life, planets, stars, galaxies, galaxy clusters, and superclusters. All of this complexity arose from almost undetectable non-uniformities in the distribution of energy that existed at the one - second mark.

The matter in the universe comes in two types: dark matter and ordinary matter. Both were present in the primordial plasma emerging from the bang. Dark matter played a vital role in forming galaxy halos, and still plays a dominant role in their structure. Ordinary matter fell into the cores of the dark matter halos to form stars, supernovae, and planets. The light chemical elements — hydrogen, deuterium, helium, and lithium — were made in the hot big bang by the fusion of primordial protons and neutrons as the universe cooled. Heavier elements, including carbon, oxygen and iron were made by the burning of helium in stars and supernovae.

On the largest length scale that can be observed, out to 13.7 billion light-years, the structure of the universe is stunningly simple. There is no detectable curvature of space, and matter and radiation are smoothly distributed. Perhaps even more remarkable, the laws of physics seem to be the same everywhere. The expansion of space and the clustering of matter under gravity are accurately governed by Einstein's theory of general relativity. The laws of quantum mechanics, which govern the structure of atoms and molecules, the laws of nuclear and statistical physics, which govern the burning of stars, the laws of light and electromagnetism and the laws of fluid dynamics, hold everywhere as well. The universe appears to be simple and comprehensible.

On smaller scales, gravity has worked its magic, taking the almost imperceptible nonuniformities that emerged from the bang and steadily drawing together islands of matter, dark and ordinary, which then collapsed into galaxies, stars and planets. Gravity governs the structure of stars, heating the gas to temperatures where hydrogen can burn into helium, and helium into heavier elements. Gravity holds planets in orbit around stars. Gravity drives the collapse of stars, leading to violent supernova explosions within which the heavier chemical elements are formed. And gravity produces the giant black holes found at the centers of most large galaxies, which swallow gas and stars and are responsible for the most violent and energetic phenomena in the universe.

The most puzzling discovery is that for the last 5 billion years, the formation of new structures in the universe has ceased and the universe has begun to become simple and uniform again. This strange turn of events is related to the fact that dark matter and ordinary matter, which are gravitationally attractive and can cluster into new structures, together account for less than a third of the total energy of the universe. The remainder is in dark energy, which is gravitationally repulsive and has begun to stretch the universe out and return it to a smooth, uniform state. At least at the moment, the tug-of-war between dark matter and dark energy appears to have been won by dark energy. Whether this situation is permanent is at the crux of the debate between the inflationary and the cyclic pictures of the universe.