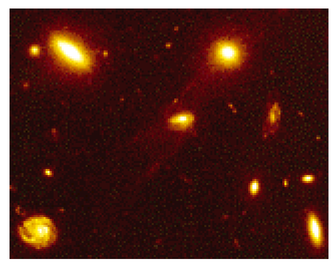
The Evolution of the Universe

Some 12 billion years ago the universe emerged from a hot, dense sea of matter and energy. As the cosmos expanded and cooled, it spawned galaxies, stars, planets and life

by P. James E. Peebles, David N. Schramm, Edwin L. Turner and Richard G. Kron

At a particular instant roughly 12 billion years ago, all the matter and energy we can observe, concentrated in a region smaller than a dime, began to expand and cool at an incredibly rapid rate. By the time the temperature had dropped to 100 million times that of the sun's core, the forces of nature assumed their present properties, and the elementary particles known as quarks roamed freely in a sea of energy. When the universe had expanded an additional 1,000 times, all the matter we can measure filled a region the size of the solar system.

At that time, the free quarks became confined in neutrons and protons. After the universe had grown by another factor of 1,000, protons and neutrons combined to form atomic nuclei, including most of the helium and deuterium present today. All of this occurred within the first minute of the expansion. Conditions were still too hot, however, for atomic nuclei to capture electrons. Neutral atoms appeared in abundance only after the expansion had continued for 300,000 years and the universe was 1,000 times smaller than it is now. The neutral atoms then began to coalesce into gas clouds, which later evolved into stars. By the time the universe had expanded to one fifth its present size, the stars had formed groups recognizable as young galaxies. When the universe was half its present size, nuclear reactions in stars had produced most of the heavy elements from which terrestrial planets were made. Our solar system is relatively young: it formed five billion years ago, when the universe was two thirds its present size. Over time the formation of stars has consumed the supply of gas in galaxies, and hence the population of stars is waning. Fifteen billion years from now stars like our sun will be relatively rare, making the universe a far less hospitable place for observers like us.



GALAXY CLUSTER

Our understanding of the genesis and evolution of the universe is one of the great achievements of 20th-century science. This knowledge comes from decades of innovative experiments and theories. Modern telescopes on the ground and in space detect the light from galaxies billions of light-years away, showing us what the universe looked like when it was young. Particle accelerators probe the basic physics of the high-energy environment of the early universe. Satellites detect the cosmic background radiation left over from the early stages of expansion, providing an image of the universe on the largest scales we can observe.

Our best efforts to explain this wealth of data are embodied in a theory known as the standard cosmological model or the big bang cosmology. The major claim of the theory is that in the large-scale average, the universe is expanding in a nearly homogeneous way from a dense early state. At present, there are no fundamental challenges to the big bang theory, although there are certainly unresolved issues within the theory itself. Astronomers are not sure, for example, how the galaxies were formed, but there is no reason to think the process did not occur within the framework of the big bang. Indeed, the predictions of the theory have survived all tests to date.

Yet the big bang model goes only so far, and many fundamental mysteries remain. What was the universe like before it was expanding? (No observation we have made allows us to look back beyond the moment at which the expansion began.) What will happen in the distant future, when the last of the stars exhaust the supply of nuclear fuel? No one knows the answers yet.

Our universe may be viewed in many lights--by mystics, theologians, philosophers or scientists. In science we adopt the plodding route: we accept only what is tested by experiment or observation. Albert Einstein gave us the now well-tested and accepted general theory of relativity, which establishes the relations between mass, energy, space and time. Einstein showed that a homogeneous distribution of matter in space fits nicely with his theory. He assumed without discussion that the universe is static, unchanging in the large-scale average [see "How Cosmology Became a Science," by Stephen G. Brush; *Scientific American*, August 1992].

In 1922 the Russian theorist Alexander A. Friedmann realized that Einstein's universe is unstable; the slightest perturbation would cause it to expand or contract. At that time, Vesto M. Slipher of Lowell Observatory was collecting the first evidence that galaxies are actually moving apart. Then, in 1929, the eminent astronomer Edwin P. Hubble showed that the rate a galaxy is moving away from us is roughly proportional to its distance from us.

The existence of an expanding universe implies that the cosmos has evolved from a dense concentration of matter into the present broadly spread distribution of galaxies. Fred Hoyle, an English cosmologist, was the first to call this process the big bang. Hoyle intended to disparage the theory, but the name was so catchy it gained popularity. It is somewhat misleading, however, to describe the expansion as some type of explosion of matter away from some particular point in space.

That is not the picture at all: in Einstein's universe the concept of space and the distribution of matter are intimately linked; the observed expansion of the system of galaxies reveals the unfolding of space itself. An essential feature of the theory is that the average density in space declines as the universe expands; the distribution of matter forms no observable edge. In an explosion the fastest particles move out into empty space, but in the big bang cosmology, particles uniformly fill all space. The expansion of the universe has had little influence on the size of galaxies or even clusters of galaxies that are bound by gravity; space is simply opening up between them. In this sense, the expansion is similar to a rising loaf of raisin bread. The dough is analogous to space, and the raisins, to clusters of galaxies. As the dough expands, the raisins move apart. Moreover, the speed with which any two raisins move apart is directly and positively related to the amount of dough separating them.

The evidence for the expansion of the universe has been accumulating for some 60 years. The first important clue is the redshift. A galaxy emits or absorbs some wavelengths of light more strongly than others. If the galaxy is moving away from us, these emission and absorption features are shifted to longer wavelengths--that is, they become redder as the recession velocity increases.

Hubble's Law

Hubble's measurements indicated that the redshift of a distant galaxy is greater than that of one closer to Earth. This relation, now known as Hubble's law, is just what one would expect in a uniformly expanding universe. Hubble's law says the recession velocity of a galaxy is equal to its distance multiplied by a quantity called Hubble's constant. The redshift effect in nearby galaxies is relatively subtle, requiring good instrumentation to detect it. In contrast, the redshift of very distant objects--radio galaxies and quasars--is an awesome phenomenon; some appear to be moving away at greater than 90 percent of the speed of light.

Hubble contributed to another crucial part of the picture. He counted the number of visible galaxies in different directions in the sky and found that they appear to be rather uniformly distributed. The value of Hubble's constant seemed to be the same in all directions, a necessary consequence of uniform expansion. Modern surveys confirm the fundamental tenet that the universe is homogeneous on large scales. Although maps of the distribution of the nearby galaxies display clumpiness, deeper surveys reveal considerable uniformity.

The Milky Way, for instance, resides in a knot of two dozen galaxies; these in turn are part of a complex of galaxies that protrudes from the so-called local supercluster. The hierarchy of clustering has been traced up to dimensions of about 500 million light-years. The fluctuations in the average density of matter diminish as the scale of the structure being investigated increases. In maps that cover distances that reach close to the observable limit, the average density of matter changes by less than a tenth of a percent.

MULTIPLE IMAGES

To test Hubble's law, astronomers need to measure distances to galaxies. One method for gauging distance is to observe the apparent brightness of a galaxy. If one galaxy is four times fainter than an otherwise comparable galaxy, then it can be estimated to be twice as far away. This expectation has now been tested over the whole of the visible range of distances.

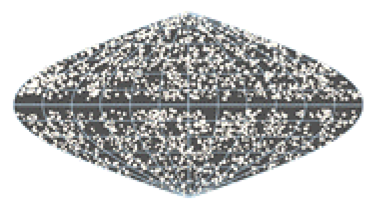
Some critics of the theory have pointed out that a galaxy that appears to be smaller and fainter might not actually be more distant. Fortunately, there is a direct indication that objects whose redshifts are larger really are more distant. The evidence comes from observations of an effect known as gravitational lensing [see illustration on opposite page]. An object as massive and compact as a galaxy can act as a crude lens, producing a distorted, magnified image (or even many images) of any background radiation source that lies behind it. Such an object does so by bending the paths of light rays and other electromagnetic radiation. So if a galaxy sits in the line of sight between Earth and some distant object, it will bend the light rays from the object so that they are observable [see "Gravitational Lenses," by Edwin L. Turner; Scientific American, July 1988]. During the past decade, astronomers have discovered about two dozen gravitational lenses. The object behind the lens is always found to have a higher redshift than the lens itself, confirming the qualitative prediction of Hubble's law.

Hubble's law has great significance not only because it describes the expansion of the universe but also because it can be used to calculate the age of the cosmos. To be precise, the time elapsed since the big bang is a function of the present value of Hubble's constant and its rate of change. Astronomers have determined the approximate rate of the expansion, but no one has yet been able to measure the second value precisely.

Still, one can estimate this quantity from knowledge of the universe's average density. One expects that because gravity exerts a force that opposes expansion, galaxies would tend to move apart more slowly now than they did in the past. The rate of change in expansion is thus related to the gravitational pull of the universe set by its average density. If the density is that of just the visible material in and around galaxies, the age of the universe probably lies between 10 and 15 billion years. (The range allows for the uncertainty in the rate of expansion.)

Yet many researchers believe the density is greater than this minimum value. So-called dark matter would make up the difference. A strongly defended argument holds that the universe is just dense enough that in the remote future the expansion will slow almost to zero. Under this assumption, the age of the universe decreases to the range of seven to 13 billion years.

To improve these estimates, many astronomers are involved in intensive research to measure both the distances to galaxies and the density of the universe. Estimates of the expansion time provide an important test for the big bang model of the universe. If the theory is correct, everything in the visible universe should be younger than the expansion time computed from Hubble's law.



HOMOGENEOUS DISTRIBUTION

These two timescales do appear to be in at least rough concordance. For example, the oldest stars in the disk of the Milky Way galaxy are about nine billion years old--an estimate derived from the rate of cooling of white dwarf stars. The stars in the halo of the Milky Way are somewhat older, about 12 billion years--a value derived from the rate of nuclear fuel consumption in the cores of these stars. The ages of the oldest known chemical elements are also approximately 12 billion years--a number that comes from radioactive dating techniques. Workers in laboratories have derived these age estimates from atomic and nuclear physics. It is noteworthy that their results agree, at least approximately, with the age that astronomers have derived by measuring cosmic expansion.

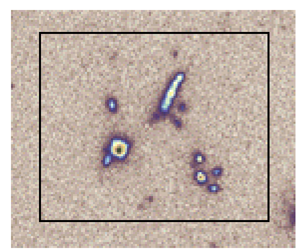
Another theory, the steady-state theory, also succeeds in accounting for the expansion and homogeneity of the universe. In 1946 three physicists in England--Hoyle, Hermann Bondi and Thomas Gold--proposed such a cosmology. In their theory the universe is forever expanding, and matter is created spontaneously to fill the voids. As this material accumulates, they suggested, it forms new stars to replace the old. This steady-state hypothesis predicts that ensembles of galaxies close to us should look statistically the same as those far away. The big bang cosmology makes a different prediction: if galaxies were all formed long ago, distant galaxies should look younger than those nearby because light from them requires a longer time to reach us. Such galaxies should contain more short-lived stars and more gas out of which future generations of stars will form.

Testing the Steady-State Hypothesis

The test is simple conceptually, but it took decades for astronomers to develop detectors sensitive enough to study distant galaxies in detail. When astronomers examine nearby galaxies that are powerful emitters of radio wavelengths, they see, at optical wavelengths, relatively round systems of stars. Distant radio galaxies, on the other hand, appear to have elongated and sometimes irregular structures. Moreover, in most distant radio galaxies, unlike the ones nearby, the distribution of light tends to be aligned with the pattern of the radio emission.

Likewise, when astronomers study the population of massive, dense clusters of galaxies, they find differences between those that are close and those far away. Distant clusters contain bluish galaxies that show evidence of ongoing star formation. Similar clusters that are nearby contain reddish galaxies in which active star formation ceased long ago. Observations made with the Hubble Space Telescope confirm that at least some of the enhanced star formation in these younger clusters may be the result of collisions between their member galaxies, a process that is much rarer in the present epoch.

So if galaxies are all moving away from one another and are evolving from earlier forms, it seems logical that they were once crowded together in some dense sea of matter and energy. Indeed, in 1927, before much was known about distant galaxies, a Belgian cosmologist and priest, Georges Lema”tre, proposed that the expansion of the universe might be traced to an exceedingly dense state he called the primeval "super-atom." It might even be possible, he thought, to detect remnant radiation from the primeval atom. But what would this radiation signature look like?



DISTANT GALAXIES

When the universe was very young and hot, radiation could not travel very far without being absorbed and emitted by some particle. This continuous exchange of energy maintained a state of thermal equilibrium; any particular region was unlikely to be much hotter or cooler than the average. When matter and energy settle to such a state, the result is a so-called thermal spectrum, where the intensity of radiation at each wavelength is a definite function of the temperature. Hence, radiation originating in the hot big bang is recognizable by its spectrum.

In fact, this thermal cosmic background radiation has been detected. While working on the development of radar in the 1940s, Robert H. Dicke, then at the Massachusetts Institute of Technology, invented the microwave radiometer--a device capable of detecting low levels of radiation. In the 1960s Bell Laboratories used a radiometer in a telescope that would track the early communications satellites Echo-1 and Telstar. The engineer who built this instrument found that it was detecting unexpected radiation. Arno A. Penzias and Robert W. Wilson identified the signal as the cosmic background radiation. It is interesting that Penzias and Wilson were led to this idea by the news that Dicke had suggested that one ought to use a radiometer to search for the cosmic background.

Astronomers have studied this radiation in great detail using the Cosmic Background Explorer (COBE) satellite and a number of rocket-launched, balloon-borne and ground-based experiments. The cosmic background radiation has two distinctive properties. First, it is nearly the same in all directions. (As the COBE team, led by John Mather of the National Aeronautics and Space Administration Goddard Space Flight Center, showed in 1992, the variation is just one part per 100,000.) The interpretation is that the radiation uniformly fills space, as predicted in the big bang cosmology.

Second, the spectrum is very close to that of an object in thermal equilibrium at 2.726 kelvins above absolute zero. To be sure, the cosmic background radiation was produced when the universe was far hotter than 2.726 kelvins, yet researchers anticipated correctly that the apparent temperature of the radiation would be low. In the 1930s Richard C. Tolman of the California Institute of Technology showed that the temperature of the cosmic background would diminish because of the universe's expansion.

The cosmic background radiation provides direct evidence that the universe did expand from a dense, hot state, for this is the condition needed to produce the radiation. In the dense, hot early universe thermonuclear reactions produced elements heavier than hydrogen, including deuterium, helium and lithium. It is striking that the computed mix of the light elements agrees with the observed abundances. That is, all evidence indicates that the light elements were produced in the hot young universe, whereas the heavier elements appeared later, as products of the thermonuclear reactions that power stars.

The theory for the origin of the light elements emerged from the burst of research that followed the end of World War II. George Gamow and graduate student Ralph A. Alpher of George Washington University and Robert Herman of the Johns Hopkins University Applied Physics Laboratory and others used nuclear physics data from the war effort to predict what kind of nuclear processes might have occurred in the early universe and what elements might have been produced. Alpher and Herman also realized that a remnant of the original expansion would still be detectable in the existing universe.

Despite the fact that significant details of this pioneering work were in error, it forged a link between nuclear physics and cosmology. The workers demonstrated that the early universe could be viewed as a type of thermonuclear reactor. As a result, physicists have now precisely calculated the abundances of light elements produced in the big bang and how those quantities have changed because of subsequent events in the interstellar medium and nuclear processes in stars.

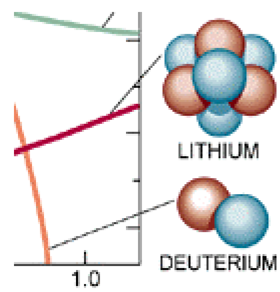
Putting the Puzzle Together

Our grasp of the conditions that prevailed in the early universe does not translate into a full understanding of how galaxies formed. Nevertheless, we do have quite a few pieces of the puzzle. Gravity causes the growth of density fluctuations in the distribution of matter, because it more strongly slows the expansion of denser regions, making them grow still denser. This process is observed in the growth of nearby clusters of galaxies, and the galaxies themselves were probably assembled by the same process on a smaller scale.

The growth of structure in the early universe was prevented by radiation pressure, but that changed when the universe had expanded to about 0.1 percent of its present size. At that point, the temperature was about 3,000 kelvins, cool enough to allow the ions and electrons to combine to form neutral hydrogen and helium. The neutral matter was able to slip through the radiation and to form gas clouds that could collapse into star clusters. Observations show that by the time the universe was one fifth its present size, matter had gathered into gas clouds large enough to be called young galaxies.

A pressing challenge now is to reconcile the apparent uniformity of the early universe with the lumpy distribution of galaxies in the present universe. Astronomers know that the density of the early universe did not vary by much, because they observe only slight irregularities in the cosmic background radiation. So far it has been easy to develop theories that are consistent with the available measurements, but more critical tests are in progress. In particular, different theories for galaxy formation predict quite different fluctuations in the cosmic background radiation on angular scales less than about one degree. Measurements of such tiny fluctuations have not yet been done, but they might be accomplished in the generation of experiments now under way. It will be exciting to learn whether any of the theories of galaxy formation now under consideration survive these tests.

The present-day universe has provided ample opportunity for the development of life as we know it--there are some 100 billion billion stars similar to the sun in the part of the universe we can observe. The big bang cosmology implies, however, that life is possible only for a bounded span of time: the universe was too hot in the distant past, and it has limited resources for the future. Most galaxies are still producing new stars, but many others have already exhausted their supply of gas. Thirty billion years from now, galaxies will be much darker and filled with dead or dying stars, so there will be far fewer planets capable of supporting life as it now exists.



DENSITY OF NEUTRONS AND PROTONS

The universe may expand forever, in which case all the galaxies and stars will eventually grow dark and cold. The alternative to this big chill is a big crunch. If the mass of the universe is large enough, gravity will eventually reverse the expansion, and all matter and energy will be reunited. During the next decade, as researchers improve techniques for measuring the mass of the universe, we may learn whether the present expansion is headed toward a big chill or a big crunch.

In the near future, we expect new experiments to provide a better understanding of the big bang. New measurements of the expansion rate and the ages of stars are beginning to confirm that the stars are indeed younger than the expanding universe. New telescopes such as the twin 10-meter Keck telescopes in Hawaii and the 2.5-meter Hubble Space Telescope, other new telescopes at the South Pole and new satellites looking at background radiation as well as new physics experiments searching for "dark matter" may allow us to see how the mass of the universe affects the curvature of space-time, which in turn influences our observations of distant galaxies.

We will also continue to study issues that the big bang cosmology does not address. We do not know why there was a big bang or what may have existed before. We do not know whether our universe has siblings--other expanding regions well removed from what we can observe. We do not understand why the fundamental constants of nature have the values they do. Advances in particle physics suggest some interesting ways these questions might be answered; the challenge is to find experimental tests of the ideas.

In following the debate on such matters of cosmology, one should bear in mind that all physical theories are approximations of reality that can fail if pushed too far. Physical science advances by incorporating earlier theories that are experimentally supported into larger, more encompassing frameworks. The big bang theory is supported by a wealth of evidence: it explains the cosmic background radiation, the abundances of light elements and the Hubble expansion. Thus, any new cosmology surely will include the big bang picture. Whatever developments the coming decades may bring, cosmology has moved from a branch of philosophy to a physical science where hypotheses meet the test of observation and experiment.

The Authors

EEBLES, DAVID N. SCHRAMM, EDWIN L. TURNER and RICHARD G. KRON have ied top honors for their work on the evolution of the universe. Peebles is professor of ceton University, where in 1958 he began an illustrious career in gravitational physics. time is spent with his three grandchildren. Turner is chair of astrophysical sciences at irector of the 3.5-meter ARC telescope in New Mexico. He has a personal, cultural and t in Japan. Since 1978 Kron has served on the faculty of the department of astronomy s at the University of Chicago, and he is also a member of the experimental astrophysics National Accelerator Laboratory. He enjoys observing distant galaxies almost as much kes Observatory near Lake Geneva, Wis. Schramm, who was Louis Block Distinguished or in the Physical Sciences and vice president for research at the University of Chicago, airplane accident while this special issue was being prepared for publication. This article on that appeared in *Scientific American* in October 1994.

This is an exciting time for cosmologists: findings are pouring in, ideas are bubbling up, and research to test those ideas is simmering away. But it is also a confusing time. All the ideas under discussion cannot possibly be right; they are not even consistent with one another. How is one to judge the progress? Here is how I go about it.

For all the talk of overturned theories, cosmologists have firmly established the foundations of our field. Over the past 70 years we have gathered abundant evidence that our universe is expanding and cooling. first, the light from distant galaxies is shifted toward the red, as it should be if space is expanding and galaxies are pulled away from one another. Second, a sea of thermal radiation fills space, as it should if space used to be denser and hotter. Third, the universe contains large amounts of deuterium and helium, as it should if temperatures were once much higher. Fourth, galaxies billions of years ago look distinctly younger, as they should if they are closer to the time when no galaxies existed. Finally, the curvature of spacetime seems to be related to the material content of the universe, as it should be if the universe is expanding according to the predictions of Einstein's gravity theory, the general theory of relativity.

That the universe is expanding and cooling is the essence of the big bang theory. You will notice I have said nothing about an "explosion"--the big bang theory describes how our universe is evolving, not how it began.

I compare the process of establishing such compelling results, in cosmology or any other science, to the assembly of a framework. We seek to reinforce each piece of evidence by adding cross bracing from diverse measurements. Our framework for the expansion of the universe is braced tightly enough to be solid. The big bang theory is no longer seriously questioned; it fits together too well. Even the most radical alternative--the latest incarnation of the steady state theory--does not dispute that the universe is expanding and cooling. You still hear differences of opinion in cosmology, to be sure, but they concern additions to the solid part.

For example, we do not know what the universe was doing before it was expanding. A leading theory, inflation, is an attractive addition to the framework, but it lacks cross bracing. That is precisely what cosmologists are now seeking. If measurements in progress agree with the unique signatures of inflation, then we will count them as a persuasive argument for this theory. But until that time, I would not settle any bets on whether inflation really happened. I am not criticizing the theory; I simply mean that this is brave, pioneering work still to be tested.

REPORT CARD FOR MAJOR THEORIES

More solid is the evidence that most of the mass of the universe consists of dark matter clumped around the outer parts of galaxies. We also have a reasonable case for Einstein's infamous cosmological constant or something similar; it would be the agent of the acceleration that the universe now seems to be undergoing. A decade ago cosmologists generally welcomed dark matter as an elegant way to account for the motions of stars and gas within galaxies. Most researchers, however, had a real distaste for the cosmological constant. Now the majority accept it, or its allied concept, quintessence. Particle physicists have come to welcome the challenge that the cosmological constant poses for quantum theory. This shift in opinion is not a reflection of some inherent weakness; rather it shows the subject in a healthy state of chaos around a slowly growing fixed framework. We are students of nature, and we adjust our concepts as the lessons continue.

The lessons, in this case, include the signs that cosmic expansion is accelerating: the brightness of supernovae near and far; the ages of the oldest stars; the bending of light around distant masses; and the fluctuations of the temperature of the thermal radiation across the sky. The evidence is impressive, but I am still uneasy about details of the case for the cosmological constant, including possible contradictions with the evolution of galaxies and their spatial distribution. The theory of the accelerating universe is a work in progress. I admire the architecture, but I would not want to move in just yet.

How might one judge reports in the media on the progress of cosmology? I feel uneasy about articles based on an interview with just one person. Research is a complex and messy business. Even the most experienced scientist finds it hard to keep everything in perspective. How do I know that this individual has managed it well? An entire community of scientists can head off in the wrong direction, too, but it happens less often. That is why I feel better when I can see that the journalist has consulted a cross section of the community and has found agreement that a certain result is worth considering. The result becomes more interesting when others reproduce it. It starts to become convincing when independent lines of evidence point to the same conclusion. To my mind, the best media reports on science describe not only the latest discoveries and ideas but also the essential, if

sometimes tedious, process of testing and installing the cross bracing.
Over time, inflation, quintessence and other concepts now under debate either will be solidly integrated into the central framework or will be abandoned and replaced by something better. In a sense, we are working ourselves out of a job. But the universe is a complicated place, to put it mildly, and it is silly to think we will run out of productive lines of research anytime soon. Confusion is a sign that we are doing something right: it is the fertile commotion of a construction site.

Further Information:

THE EVOLUTION OF THE UNIVERSE. P. James E. Peebles, David N. Schramm, Edwin L. Turner and Richard G. Kron in Scientific American, Vol. 271, No. 4, pages 52–57; October 1994.
THE INFLATIONARY UNIVERSE: THE QUEST FOR A NEW THEORY OF COSMIC ORIGINS. Alan H. Guth. Perseus Press, 1997.
BEFORE THE BEGINNING: OUR UNIVERSE AND OTHERS. Martin Rees. Perseus Press, 1998.
THE ACCELERATING UNIVERSE: INFINITE EXPANSION, THE COSMOLOGICAL CONSTANT, AND THE BEAUTY OF THE COSMOS. Mario Livio and Allan Sandage. John Wiley & Sons, 2000.
Concluding Remarks on New Cosmological Data and the Values of the Fundamental Parameters. P. James E. Peebles in IAU Symposium 201: New Cosmological Data and the Values of the Fundamental Parameters, edited by A. N. Lasenby, A. W. Jones and A. Wilkinson; August 2000. Preprint available at http://xxx.lanl.gov/abs/astro-ph/0011252 on the World Wide Web.

The Author

P. JAMES E. PEEBLES is one of the world's most distinguished cosmologists, a key player in the early analysis of the cosmic microwave background radiation and the bulk composition of the universe. He has received some of the highest awards in astronomy, including the 1982 Heineman Prize, the 1993 Henry Norris Russell Lectureship of the American Astronomical Society and the 1995 Bruce Medal of the Astronomical Society of the Pacific. Peebles is currently an emeritus professor at Princeton University.

The Evolution of the Universe Some 12 billion years ago the universe emerged from a hot, dense sea of matter and energy. As the cosmos expanded and cooled, it spawned galaxies, stars, planets and life

by P. James E. Peebles, David N. Schramm, Edwin L. Turner and Richard G. Kron

SUBTOPICS: Hubble's Law Testing the Steady-State Hypothesis

Putting the Puzzle Together

ILLUSTRATIONS: Galaxy Cluster

Multiple Images

Homogeneous Distribution

Distant Galaxies

Density of Neutrons and Protons

------------------- Table of Contents At a particular instant roughly 12 billion years ago, all the matter and energy we can observe, concentrated in a region smaller than a dime, began to expand and cool at an incredibly rapid rate. By the time the temperature had dropped to 100 million times that of the sun's core, the forces of nature assumed their present properties, and the elementary particles known as quarks roamed freely in a sea of energy. When the universe had expanded an additional 1,000 times, all the matter we can measure filled a region the size of the solar system.

GALAXY CLUSTER At that time, the free quarks became confined in neutrons and protons. After the universe had grown by another factor of 1,000, protons and neutrons combined to form atomic nuclei, including most of the helium and deuterium present today. All of this occurred within the first minute of the expansion. Conditions were still too hot, however, for atomic nuclei to capture electrons. Neutral atoms appeared in abundance only after the expansion had continued for 300,000 years and the universe was 1,000 times smaller than it is now. The neutral atoms then began to coalesce into gas clouds, which later evolved into stars. By the time the universe had expanded to one fifth its present size, the stars had formed groups recognizable as young galaxies. When the universe was half its present size, nuclear reactions in stars had produced most of the heavy elements from which terrestrial planets were made. Our solar system is relatively young: it formed five billion years ago, when the universe was two thirds its present size. Over time the formation of stars has consumed the supply of gas in galaxies, and hence the population of stars is waning. Fifteen billion years from now stars like our sun will be relatively rare, making the universe a far less hospitable place for observers like us.

Our understanding of the genesis and evolution of the universe is one of the great achievements of 20th-century science. This knowledge comes from decades of innovative experiments and theories. Modern telescopes on the ground and in space detect the light from galaxies billions of light-years away, showing us what the universe looked like when it was young. Particle accelerators probe the basic physics of the high-energy environment of the early universe. Satellites detect the cosmic background radiation left over from the early stages of expansion, providing an image of the universe on the largest scales we can observe.

Our best efforts to explain this wealth of data are embodied in a theory known as the standard cosmological model or the big bang cosmology. The major claim of the theory is that in the large-scale average, the universe is expanding in a nearly homogeneous way from a dense early state. At present, there are no fundamental challenges to the big bang theory, although there are certainly unresolved issues within the theory itself. Astronomers are not sure, for example, how the galaxies were formed, but there is no reason to think the process did not occur within the framework of the big bang. Indeed, the predictions of the theory have survived all tests to date.

Yet the big bang model goes only so far, and many fundamental mysteries remain. What was the universe like before it was expanding? (No observation we have made allows us to look back beyond the moment at which the expansion began.) What will happen in the distant future, when the last of the stars exhaust the supply of nuclear fuel? No one knows the answers yet.

Our universe may be viewed in many lights--by mystics, theologians, philosophers or scientists. In science we adopt the plodding route: we accept only what is tested by experiment or observation. Albert Einstein gave us the now well-tested and accepted general theory of relativity, which establishes the relations between mass, energy, space and time. Einstein showed that a homogeneous distribution of matter in space fits nicely with his theory. He assumed without discussion that the universe is static, unchanging in the large-scale average [see "How Cosmology Became a Science," by Stephen G. Brush; Scientific American, August 1992].

In 1922 the Russian theorist Alexander A. Friedmann realized that Einstein's universe is unstable; the slightest perturbation would cause it to expand or contract. At that time, Vesto M. Slipher of Lowell Observatory was collecting the first evidence that galaxies are actually moving apart. Then, in 1929, the eminent astronomer Edwin P. Hubble showed that the rate a galaxy is moving away from us is roughly proportional to its distance from us.

The existence of an expanding universe implies that the cosmos has evolved from a dense concentration of matter into the present broadly spread distribution of galaxies. Fred Hoyle, an English cosmologist, was the first to call this process the big bang. Hoyle intended to disparage the theory, but the name was so catchy it gained popularity. It is somewhat misleading, however, to describe the expansion as some type of explosion of matter away from some particular point in space.

That is not the picture at all: in Einstein's universe the concept of space and the distribution of matter are intimately linked; the observed expansion of the system of galaxies reveals the unfolding of space itself. An essential feature of the theory is that the average density in space declines as the universe expands; the distribution of matter forms no observable edge. In an explosion the fastest particles move out into empty space, but in the big bang cosmology, particles uniformly fill all space. The expansion of the universe has had little influence on the size of galaxies or even clusters of galaxies that are bound by gravity; space is simply opening up between them. In this sense, the expansion is similar to a rising loaf of raisin bread. The dough is analogous to space, and the raisins, to clusters of galaxies. As the dough expands, the raisins move apart. Moreover, the speed with which any two raisins move apart is directly and positively related to the amount of dough separating them.

The evidence for the expansion of the universe has been accumulating for some 60 years. The first important clue is the redshift. A galaxy emits or absorbs some wavelengths of light more strongly than others. If the galaxy is moving away from us, these emission and absorption features are shifted to longer wavelengths--that is, they become redder as the recession velocity increases.

Hubble's Law

Hubble's measurements indicated that the redshift of a distant galaxy is greater than that of one closer to Earth. This relation, now known as Hubble's law, is just what one would expect in a uniformly expanding universe. Hubble's law says the recession velocity of a galaxy is equal to its distance multiplied by a quantity called Hubble's constant. The redshift effect in nearby galaxies is relatively subtle, requiring good instrumentation to detect it. In contrast, the redshift of very distant objects--radio galaxies and quasars--is an awesome phenomenon; some appear to be moving away at greater than 90 percent of the speed of light.

Hubble contributed to another crucial part of the picture. He counted the number of visible galaxies in different directions in the sky and found that they appear to be rather uniformly distributed. The value of Hubble's constant seemed to be the same in all directions, a necessary consequence of uniform expansion. Modern surveys confirm the fundamental tenet that the universe is homogeneous on large scales. Although maps of the distribution of the nearby galaxies display clumpiness, deeper surveys reveal considerable uniformity.

The Milky Way, for instance, resides in a knot of two dozen galaxies; these in turn are part of a complex of galaxies that protrudes from the so-called local supercluster. The hierarchy of clustering has been traced up to dimensions of about 500 million light-years. The fluctuations in the average density of matter diminish as the scale of the structure being investigated increases. In maps that cover distances that reach close to the observable limit, the average density of matter changes by less than a tenth of a percent.

MULTIPLE IMAGES To test Hubble's law, astronomers need to measure distances to galaxies. One method for gauging distance is to observe the apparent brightness of a galaxy. If one galaxy is four times fainter than an otherwise comparable galaxy, then it can be estimated to be twice as far away. This expectation has now been tested over the whole of the visible range of distances.

Some critics of the theory have pointed out that a galaxy that appears to be smaller and fainter might not actually be more distant. Fortunately, there is a direct indication that objects whose redshifts are larger really are more distant. The evidence comes from observations of an effect known as gravitational lensing [see illustration on opposite page]. An object as massive and compact as a galaxy can act as a crude lens, producing a distorted, magnified image (or even many images) of any background radiation source that lies behind it. Such an object does so by bending the paths of light rays and other electromagnetic radiation. So if a galaxy sits in the line of sight between Earth and some distant object, it will bend the light rays from the object so that they are observable [see "Gravitational Lenses," by

Edwin L. Turner; Scientific American, July 1988]. During the past decade, astronomers have discovered about two dozen gravitational lenses. The object behind the lens is always found to have a higher redshift than the lens itself, confirming the qualitative prediction of Hubble's law.

Hubble's law has great significance not only because it describes the expansion of the universe but also because it can be used to calculate the age of the cosmos. To be precise, the time elapsed since the big bang is a function of the present value of Hubble's constant and its rate of change. Astronomers have determined the approximate rate of the expansion, but no one has yet been able to measure the second value precisely.

Still, one can estimate this quantity from knowledge of the universe's average density. One expects that because gravity exerts a force that opposes expansion, galaxies would tend to move apart more slowly now than they did in the past. The rate of change in expansion is thus related to the gravitational pull of the universe set by its average density. If the density is that of just the visible material in and around galaxies, the age of the universe probably lies between 10 and 15 billion years. (The range allows for the uncertainty in the rate of expansion.)

Yet many researchers believe the density is greater than this minimum value. So-called dark matter would make up the difference. A strongly defended argument holds that the universe is just dense enough that in the remote future the expansion will slow almost to zero. Under this assumption, the age of the universe decreases to the range of seven to 13 billion years.

To improve these estimates, many astronomers are involved in intensive research to measure both the distances to galaxies and the density of the universe. Estimates of the expansion time provide an important test for the big bang model of the universe. If the theory is correct, everything in the visible universe should be younger than the expansion time computed from Hubble's law.

HOMOGENEOUS DISTRIBUTION These two timescales do appear to be in at least rough concordance. For example, the oldest stars in the disk of the Milky Way galaxy are about nine billion years old--an estimate derived from the rate of cooling of white dwarf stars. The stars in the halo of the Milky Way are somewhat older, about 12 billion years--a value derived from the rate of nuclear fuel consumption in the cores of these stars. The ages of the oldest known chemical elements are also approximately 12 billion years--a number that comes from radioactive dating techniques. Workers in laboratories have derived these age estimates from atomic and nuclear physics. It is noteworthy that their results agree, at least approximately, with the age that astronomers have derived by measuring cosmic expansion.

Another theory, the steady-state theory, also succeeds in accounting for the expansion and homogeneity of the universe. In 1946 three physicists in England--Hoyle, Hermann Bondi and Thomas Gold--proposed such a cosmology. In their theory the universe is forever expanding, and matter is created spontaneously to fill the voids. As this material accumulates, they suggested, it forms new stars to replace the old. This steady-state hypothesis predicts that ensembles of galaxies close to us should look statistically the same as those far away. The big bang cosmology makes a different prediction: if galaxies were all formed long ago, distant galaxies should look younger than those nearby because light from them requires a longer time to reach us. Such galaxies should contain more short-lived stars and more gas out of which future generations of stars will form.

Testing the Steady-State Hypothesis

The test is simple conceptually, but it took decades for astronomers to develop detectors sensitive enough to study distant galaxies in detail. When astronomers examine nearby galaxies that are powerful emitters of radio wavelengths, they see, at optical wavelengths, relatively round systems of stars. Distant radio galaxies, on the other hand, appear to have elongated and sometimes irregular structures. Moreover, in most distant radio galaxies, unlike the ones nearby, the distribution of light tends to be aligned with the pattern of the radio emission.

Likewise, when astronomers study the population of massive, dense clusters of galaxies, they find differences between those that are close and those far away. Distant clusters contain bluish galaxies that show evidence of ongoing star formation. Similar clusters that are nearby contain reddish galaxies in which active star formation ceased long ago. Observations made with the Hubble Space Telescope confirm that at least some of the enhanced star formation in these younger clusters may be the result of collisions between their member galaxies, a process that is much rarer in the present epoch.

So if galaxies are all moving away from one another and are evolving from earlier forms, it seems logical that they were once crowded together in some dense sea of matter and energy. Indeed, in 1927, before much was known about distant galaxies, a Belgian cosmologist and priest, Georges Lema”tre, proposed that the expansion of the universe might be traced to an exceedingly dense state he called the primeval "super-atom." It might even be possible, he thought, to detect remnant radiation from the primeval atom. But what would this radiation signature look like?

DISTANT GALAXIES When the universe was very young and hot, radiation could not travel very far without being absorbed and emitted by some particle. This continuous exchange of energy maintained a state of thermal equilibrium; any particular region was unlikely to be much hotter or cooler than the average. When matter and energy settle to such a state, the result is a so-called thermal spectrum, where the intensity of radiation at each wavelength is a definite function of the temperature. Hence, radiation originating in the hot big bang is recognizable by its spectrum.

In fact, this thermal cosmic background radiation has been detected. While working on the development of radar in the 1940s, Robert H. Dicke, then at the Massachusetts Institute of Technology, invented the microwave radiometer--a device capable of detecting low levels of radiation. In the 1960s Bell Laboratories used a radiometer in a telescope that would track the early communications satellites Echo-1 and Telstar. The engineer who built this instrument found that it was detecting unexpected radiation. Arno A. Penzias and Robert W. Wilson identified the signal as the cosmic background radiation. It is interesting that Penzias and Wilson were led to this idea by the news that Dicke had suggested that one ought to use a radiometer to search for the cosmic background.

Astronomers have studied this radiation in great detail using the Cosmic Background Explorer (COBE) satellite and a number of rocket-launched, balloon-borne and ground-based experiments. The cosmic background radiation has two distinctive properties. First, it is nearly the same in all directions. (As the COBE team, led by John Mather of the National Aeronautics and Space Administration Goddard Space Flight Center, showed in 1992, the variation is just one part per 100,000.) The interpretation is that the radiation uniformly fills space, as predicted in the big bang cosmology. Second, the spectrum is very close to that of an object in thermal equilibrium at 2.726 kelvins above absolute zero. To be sure, the cosmic background radiation was produced when the universe was far hotter than 2.726 kelvins, yet researchers anticipated correctly that the apparent temperature of the radiation would be low. In the 1930s Richard C. Tolman of the California Institute of Technology showed that the temperature of the cosmic background would diminish because of the universe's expansion.

The cosmic background radiation provides direct evidence that the universe did expand from a dense, hot state, for this is the condition needed to produce the radiation. In the dense, hot early universe thermonuclear reactions produced elements heavier than hydrogen, including deuterium, helium and lithium. It is striking that the computed mix of the light elements agrees with the observed abundances. That is, all evidence indicates that the light elements were produced in the hot young universe, whereas the heavier elements appeared later, as products of the thermonuclear reactions that power stars.

The theory for the origin of the light elements emerged from the burst of research that followed the end of World War II. George Gamow and graduate student Ralph A. Alpher of George Washington University and Robert Herman of the Johns Hopkins University Applied Physics Laboratory and others used nuclear physics data from the war effort to predict what kind of nuclear processes might have occurred in the early universe and what elements might have been produced. Alpher and Herman also realized that a remnant of the original expansion would still be detectable in the existing universe.

Despite the fact that significant details of this pioneering work were in error, it forged a link between nuclear physics and cosmology. The workers demonstrated that the early universe could be viewed as a type of thermonuclear reactor. As a result, physicists have now precisely calculated the abundances of light elements produced in the big bang and how those quantities have changed because of subsequent events in the interstellar medium and nuclear processes in stars.

Putting the Puzzle Together

Our grasp of the conditions that prevailed in the early universe does not translate into a full understanding of how galaxies formed. Nevertheless, we do have quite a few pieces of the puzzle. Gravity causes the growth of density fluctuations in the distribution of matter, because it more strongly slows the expansion of denser regions, making them grow still denser. This process is observed in the growth of nearby clusters of galaxies, and the galaxies themselves were probably assembled by the same process on a smaller scale.

The growth of structure in the early universe was prevented by radiation pressure, but that changed when the universe had expanded to about 0.1 percent of its present size. At that point, the temperature was about 3,000 kelvins, cool enough to allow the ions and electrons to combine to form neutral hydrogen and helium. The neutral matter was able to slip through the radiation and to form gas clouds that could collapse into star clusters. Observations show that by the time the universe was one fifth its present size, matter had gathered into gas clouds large enough to be called young galaxies.

A pressing challenge now is to reconcile the apparent uniformity of the early universe with the lumpy distribution of galaxies in the present universe. Astronomers know that the density of the early universe did not vary by much, because they observe only slight irregularities in the cosmic background radiation. So far it has been easy to develop theories that are consistent with the available measurements, but more critical tests are in progress. In particular, different theories for galaxy formation predict quite different fluctuations in the cosmic background radiation on angular scales less than about one degree. Measurements of such tiny fluctuations have not yet been done, but they might be accomplished in the generation of experiments now under way. It will be exciting to learn whether any of the theories of galaxy formation now under consideration survive these tests.

DENSITY OF NEUTRONS AND PROTONS The present-day universe has provided ample opportunity for the development of life as we know it--there are some 100 billion billion stars similar to the sun in the part of the universe we can observe. The big bang cosmology implies, however, that life is possible only for a bounded span of time: the universe was too hot in the distant past, and it has limited resources for the future. Most galaxies are still producing new stars, but many others have already exhausted their supply of gas. Thirty billion years from now, galaxies will be much darker and filled with dead or dying stars, so there will be far fewer planets capable of supporting life as it now exists.

The universe may expand forever, in which case all the galaxies and stars will eventually grow dark and cold. The alternative to this big chill is a big crunch. If the mass of the universe is large enough, gravity will eventually reverse the expansion, and all matter and energy will be reunited. During the next decade, as researchers improve techniques for measuring the mass of the universe, we may learn whether the present expansion is headed toward a big chill or a big crunch.

In the near future, we expect new experiments to provide a better understanding of the big bang. New measurements of the expansion rate and the ages of stars are beginning to confirm that the stars are indeed younger than the expanding universe. New telescopes such as the twin 10-meter Keck telescopes in Hawaii and the 2.5-meter Hubble Space Telescope, other new telescopes at the South Pole and new satellites looking at background radiation as well as new physics experiments searching for "dark matter" may allow us to see how the mass of the universe affects the curvature of space-time, which in turn influences our observations of distant galaxies.

We will also continue to study issues that the big bang cosmology does not address. We do not know why there was a big bang or what may have existed before. We do not know whether our universe has siblings--other expanding regions well removed from what we can observe. We do not understand why the fundamental constants of nature have the values they do. Advances in particle physics suggest some interesting ways these questions might be answered; the challenge is to find experimental tests of the ideas.

In following the debate on such matters of cosmology, one should bear in mind that all physical theories are approximations of reality that can fail if pushed too far. Physical science advances by incorporating earlier theories that are experimentally supported into larger, more encompassing frameworks. The big bang theory is supported by a wealth of evidence: it explains the cosmic background radiation, the abundances of light elements and the Hubble expansion. Thus, any new cosmology surely will include the big bang picture. Whatever developments the coming decades may bring, cosmology has moved from a branch of philosophy to a physical science where hypotheses meet the test of observation and experiment.

-- The Authors P. JAMES E. PEEBLES, DAVID N. SCHRAMM, EDWIN L. TURNER and RICHARD G. KRON have individually earned top honors for their work on the evolution of the universe. Peebles is professor of physics at Princeton University, where in 1958 he began an illustrious career in gravitational physics. Most of his free time is spent with his three grandchildren. Turner is chair of astrophysical sciences at Princeton and director of the 3.5-meter ARC telescope in New Mexico. He has a personal, cultural and religious interest in Japan. Since 1978 Kron has served on the faculty of the department of astronomy and astrophysics at the University of Chicago, and he is also a member of the experimental astrophysics group at Fermi National Accelerator Laboratory. He enjoys observing distant galaxies almost as much as directing Yerkes Observatory near Lake Geneva, Wis. Schramm, who was Louis Block Distinguished Service Professor in the Physical Sciences and vice president for research at the University of Chicago, died in a tragic airplane accident while this special issue was being prepared for publication. This article updates a version that appeared in Scientific American in October 1994.

COSMOLOGY_BACKGROUND RADIATION

Boomerang Effect

Balloon data confirm the big bang--and challenge it, too

Usually cosmology goes like this: new observations come in, scientists are baffled, models are upended. After the dust settles, however, patches are affixed and the prevailing theory emerges largely intact. But when the measurements by the Boomerang and Maxima telescopes came in, the sequence was reversed. Scientists were elated. "The Boomerang results fit the new cosmology like a glove," Michael S. Turner of the University of Chicago told a press conference in April. And then the dust settled, revealing that two pillars of big bang theory were squarely in conflict--a turn of events that could be nearly as monumental as the discovery of cosmic acceleration just over two years ago.

Both telescopes observed the cosmic microwave background radiation, the remnant glow of the big bang. Boomerang, lofted by balloon in December 1998 for 10 days over Antarctica, had the greater coverage--3 percent of the sky. Maxima, which flew above Texas for a night in August 1998, scrutinized a tenth the area but with higher resolution. The two instruments made the most precise maps yet of the glow on scales finer than about one degree, which corresponds to the size of the observable universe at the time the radiation is thought to have been released (about 300,000 years after the bang). On this scale and smaller, gravity and other forces would have had enough time to sculpt matter.

For those first 300,000 years, the photons of the background radiation were bound up in a broiling plasma. Because of random fluctuations generated by cosmic inflation in the first split second, some regions happened to be denser. Their gravity sucked in material, whereupon the pressure imparted by the photons pushed that material apart again. The ensuing battle between pressure and inertia caused the plasma to oscillate between compression and rarefaction--vibrations characteristic of sound waves. As the universe aged, coherent oscillations developed on ever larger scales, filling the heavens with a deepening roar. But when the plasma cooled and condensed into hydrogen gas, the photons went their separate ways, and the universe abruptly went silent. The fine detail in the background radiation is a snapshot of the sound waves at this instant. Areas of compression were slightly hotter, hence brighter; areas of rarefaction, cooler and darker.

From the Boomerang and Maxima data, cosmologists expected a profusion of large spots (oscillations that had most recently begun), spots half that size (oscillations that had gone on for longer), spots a third the size (longer still), and so on. On either a Fourier analysis or a histogram of spot sizes, this distribution would show up as a series of peaks, each of which corresponds to the spots of a given size [see illustration on opposite page]. The height of the peaks represents the maximum amount of compression (odd-numbered peaks) or of rarefaction (even-numbered peaks) in initially dense regions. Lo and behold, both telescopes saw the first peak--which not only confirms that sounds reverberated through the early universe, as the big bang theory predicts, but also shows that the sounds were generated from preexisting fluctuations, as only inflation can produce.

The next implication is for the geometry of the universe. If the rules of Euclidean trigonometry apply (as they do on a flat sheet of paper), the dominant spots should subtend 0.8 degree after accounting for cosmic expansion. If space is instead curved like a sphere, the spots will look larger; if it is curved like a saddle, they will look smaller. Boomerang measured an angle of 0.9 degree--close enough for the team, led by Paolo de Bernardis of the University of Rome and Andrew E. Lange of the California Institute of Technology, to declare in Nature that space is Euclidean. The Maxima team, in papers by Amadeo Balbi of Rome and Shaul Hanany of the University of Minnesota, reached the same conclusion, as did results from earlier telescopes, albeit with less precision. Yet follow-up studies soon showed that the lingering discrepancy, taken at face value, indicates that the universe is in fact spherical, with a density 10 percent greater than that required to make it flat. Such a gentle curvature seems awkward. Gravity quickly amplifies any deviations from exact flatness, so a slight sphericity today could only have arisen if the early universe was infinitesimally close to flat. Modified versions of inflation might explain this fine-tuning, but most cosmologists regard them as last resorts.

A more palatable alternative is that the trigonometric calculation somehow did not properly account for cosmic expansion. This would happen if the radiation did not travel as far as assumed--that is, if it was released later in cosmic history, if the famous Hubble constant were larger (making the universe younger), if the universe contained more matter (holding back the expansion) or if the cosmological constant were smaller (taming cosmic acceleration). All these possibilities, however, seem to contradict other observations. A way to keep the peace is if the cosmological constant has not, in fact, been constant. Its inconstant cousin, known as quintessence, would impart a milder acceleration. As Paul J. Steinhardt of Princeton University has argued, quintessence would also explain why the first peak is lower than it should be. Something seems to have monkeyed with the radiation since its release, and quintessence would indirectly do exactly that.

The second big mystery in the data is even more dire: there is only the merest hint of a bulge where the second peak should be. That suggests that the primordial plasma contained surprisingly many subatomic particles, which would weigh down the rarefaction of the sound waves and suppress the even-numbered peaks. But accounting for those extra particles is no easy matter. According to Max Tegmark of the University of Pennsylvania and Matias Zaldarriaga of the Institute for Advanced Study in Princeton, N.J., the Boomerang results imply that subatomic particles account for 50 percent more mass than standard big bang theory predicts--a difference 23 times larger than the error bars of the theory. "There are no known ways to reconcile these measurements and predictions," says nucleosynthesis expert David R. Tytler of the University of California at San Diego. One mooted solution, a steeply "tilted" version of inflation that did not create fluctuations uniformly on all scales, also contradicts the data.

New information due out soon could resolve some of the problems: only part of the Boomerang and Maxima data has been analyzed, and both balloons will fly again this year in search of the decisive third peak, an inkling of which appeared in the Maxima observations. Several other experiments are planned, and the long-awaited Microwave Anisotropy Probe is now scheduled to launch next spring. That roar in the heavens may have been laughter at our cosmic confusion.

--George Musser

Chapter 10: The Expanding Universe

This chapter recounts several important historical threads in the development of modern cosmology. Controversy over the nature of "spiral nebulae" had persisted since the late 18th century, with one camp insisting they were external "universes," while their opponents were equally convinced that the spiral nebulae were localized clusters of stars within our Galaxy. An important early discovery was Shapley's determination of the size of the Milky Way Galaxy, and of our location within it. Shapley found the Milky Way to be much larger than previously believed, and on this basis he erroneously concluded that the spiral nebulae must be relatively nearby clusters. Shapley and Curtis participated in a famous debate in 1920 over the nature of the spiral nebulae, but insufficient data prevented a resolution of the puzzle. Finally, Hubble determined that the Andromeda Nebula (now known as the Andromeda Galaxy) was much too far to lie within the confines of the Milky Way; Hubble had discovered external galaxies. In the first quarter of the twentieth century, humanity's view of the cosmos leaped from a fairly limited realm of the Sun surrounded by an amorphous grouping of stars, to one in which the Milky Way is just a typical spiral galaxy in a vast universe filled with galaxies.

Not long after Hubble's discovery of external galaxies came his discovery of a linear relationship between their redshifts and their distances, a relationship known today as the Hubble Law. Determining the value of the constant of proportionality, the Hubble constant, remains an important research goal of modern astronomy. The Hubble "constant" is not really constant, because it can change with time, though at any given instant of cosmic time in a homogeneous, isotropic universe, it is the same at all spatial locations. The inverse of the Hubble constant, called the Hubble time, gives an estimate of the age of the universe.

The development of the theory of general relativity provided the framework in which Hubble's discovery could be understood. Einstein found that his equations would not admit a static, stable model of the universe, even with the addition of the "cosmological constant.". The timely discovery of the redshift-distance relationship provided evidence that the universe was *not* static, but was expanding. The Robertson-Walker metric is the most general metric for an isotropic, homogeneous universe that is also dynamic; i.e. it changes with time. An important parameter in this metric is the scale factor, the quantity which describes how lengths in the universe change with cosmic time. The scale factor wavelength of light as it traverses the universe.

Measuring Hubble's constant requires accurate distances to increasingly remote galaxies. One of the best distance measures is the Cepheid variable star. The HST has now been able to detect Cepheid variable stars in the galaxy M100 in the Virgo galaxy cluster. Several Cepheids have been found such as this one. These new data give us a distance to M100 of 17 Mpc and is consistent with a rather large Hubble constant of about 80 km/sec/Mpc.

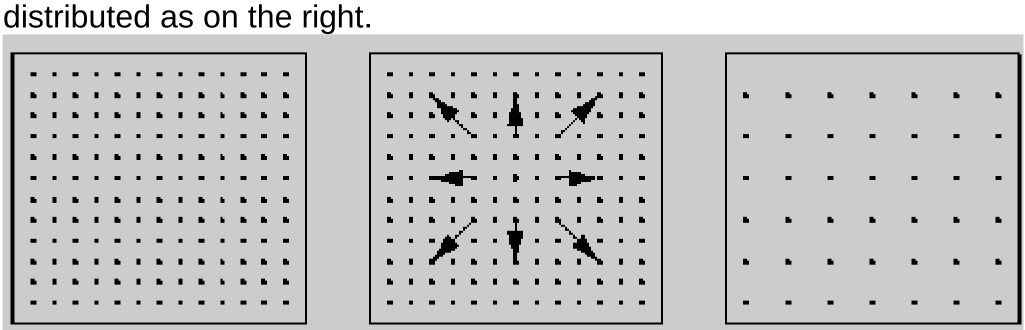
There are several important concepts and ideas in this Chapter.

- The definition of redshift.
- The distance ladder

- The Hubble law
- Einstein's cosmological constant
- Robertson-Walker metric and the scale factor
- Hubble constant, Hubble time, Hubble sphere
- Cosmic redshift

Edwin Hubble

How does cosmological redshift relate to the scale factor? What do graphs of scale factor R versus t mean? How is the Hubble constant term H related to the scale factor? What does "expanding space" mean?
What does a Hubble flow do to the spatial distribution of galaxies? Consider the following image. On the left we have a bunch of galaxies, uniformly distributed. In the center we pick out a galaxy and show the Hubble flow. After some amount of time, expansion leaves the galaxies distributed as on the right.



Location in the expanding universe does not matter. Expansion is uniform and looks the same everywhere. Each galaxy sees the other galaxies moving away in accordance with the Hubble law. Another example is provided by these figures showing the expansion of a 2D sphere.

The major difficulty is reconciling the observation that the universe is expanding, and that it is expanding away from us according to the Hubble law, but we are not at the "center" of the universe. Indeed, there is *no* center. People sometimes ask, if there is an expansion doesn't there have to be a center of the expansion? No. Space is expanding (or stretching out, if you will) *everywhere*, not expanding away from some point.

Questions and Answers related to Chapter 10.

An additional internet source on galaxies can be found at the Galaxy Primer page.
Here is a paper about the history of the Curtis-Shapley Debate which took place in 1920. This paper was written in conjunction with a National Academy anniversary debate on the nature of the gamma ray burst sources.
On-line biographies of: Edwin Hubble
For more information, try working through the lab Determining the Extragalactic Distance Scale available from Northwestern University.