Cosmology: A Research Briefing

Panel on Cosmology

Board on Physics and Astronomy
Commission on Physical Sciences, Mathematics, and Applications
National Research Council

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Front Cover: The anisotropy of the temperature of the cosmic microwave background radiation, as mapped by the Differential Microwave Radiometer on NASA's Cosmic Background Explorer satellite. Red shades represent hotter fluctuations, and blue and black shades represent cooler fluctuations. (Courtesy of the COBE team and NASA.)

Back Cover: Looking back in time with NASA's Hubble Space Telescope (HST). The HST's Wide-Field Planetary Camera (WFPC2) captured this image of galaxies as they were billions of years ago. Many objects are irregular and ill-formed compared to nearby galaxies, showing the evolution of forms of galaxies between the distant past and times closer to the present. The size of the image is 75 arc seconds, and the total exposure time is 15 hours. (Courtesy of Edward Groth, Jerome Kristian, and members of the WFPC2 team.)

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PANEL ON COSMOLOGY

MARC DAVIS, University of California at Berkeley, *Chair*
BLAS CABRERA, Stanford University
SANDRA M. FABER, University of California, Santa Cruz
MARGARET GELLER, Harvard-Smithsonian Center for Astrophysics
JACQUELINE N. HEWITT, Massachusetts Institute of Technology
RICHARD KRON, Yerkes Observatory, University of Chicago
PHILIP M. LUBIN, University of California, Santa Barbara
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BOARD ON PHYSICS AND ASTRONOMY

Preface

The Board on Physics and Astronomy (BPA) is reassessing the areas of physics that were examined by the Physics Survey Committee in its report, *Physics Through the 1990s* (National Academy Press, Washington, D.C., 1986). One of the eight volumes of the report, *Gravitation, Cosmology, and Cosmic-Ray Physics*, was the subject of a National Research Council program initiation meeting that I chaired in 1992. At that meeting, the need for reassessments in the areas of cosmology, neutrino astrophysics, and cosmic-ray physics was identified.

The Panel on Cosmology, along with the Committee on Cosmic-Ray Physics and the Panel on Neutrino Astrophysics, is part of this updating effort. Because of the connection to astrophysics and astronomy, the BPA has coordinated with the Committee on Astronomy and Astrophysics (CAA) in the conduct of this study. The panel is chaired by Marc Davis, who also chairs the CAA.

The research briefing format is intended to provide advice to program managers and policy makers on the opportunities for scientific advances in a frontier field. The field of cosmology is an exciting frontier where astronomy, nuclear physics, and particle physics meet, and where we may be able to discover how the universe came to be as it is today.

David Schramm
Chair
Board on Physics and Astronomy

CONTENTS

I. OVERVIEW

We are the first generation of human beings to glimpse the full sweep of cosmic history, from the universe's fiery origin in the Big Bang to the silent, stately flight of galaxies through the intergalactic night. Humankind continues its own journey into the future with a new depth of understanding and appreciation for the forces that shape our destiny.

What Is Cosmology?

Cosmologists work to understand how the universe came into being, why it looks as it does now, and what the future holds. They make astronomical observations that probe billions of years into the past, to the edge of the knowable universe. They seek the bases of scientific understanding, using the tools of modern physics, and fashion theories that provide unified and testable models of the evolution of the universe from its creation to the present, and into the future.

What's All the Excitement About?

For 70 years, astronomers have known that the universe is expanding, that galaxies (gigantic collections of billions of stars) appear to be flying away from one another. Measurements of the speed and distance of other galaxies show that the more distant a galaxy is from the Milky Way (our galaxy), the faster it recedes. This phenomenon is called the Hubble expansion. Working backwards from their data, astronomers infer that the universe must have been created at a definite time, between 8 billion and 15 billion years ago.

In its early stages, the universe must have been enormously dense and hot—so hot that at one point it consisted mostly of radiation. As the universe expanded, it cooled. This idea is called the hot Big Bang model. For decades it remained untested and controversial.

Over the last three decades, new technologies and ideas have driven cosmology forward at a rapidly increasing pace. Once a science of data-starved speculation, cosmology is now a full-blown race between theory and observations—the hallmark of a vigorous physical science. This race began in earnest in 1964, when scientists at Bell Laboratories, while attempting to understand radio antenna noise, discovered that some of that noise was a signal received from all directions in outer space. It was soon realized that this signal might be the cooled-down remnant of the radiation predicted by the Big Bang model. Cosmology finally had an observational foothold—a measurable remnant of the early universe, a probe to test the various cosmological models. The radiation was dubbed the cosmic microwave background radiation (CMBR). In 1990, early data from the Cosmic Background Explorer (COBE, pronounced ko-bee) satellite showed that the CMBR had precisely the profile of intensity versus frequency to be consistent with the hot Big Bang model of the universe (see Figure 1).

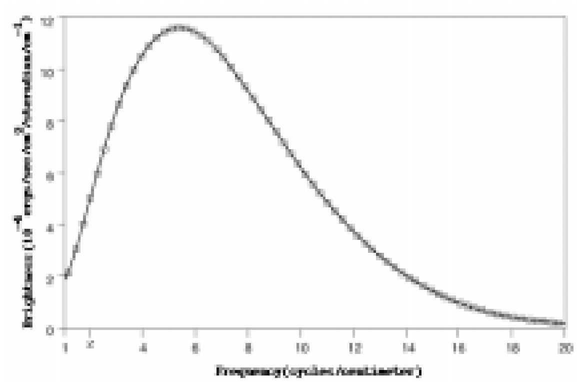


Figure 1. The measurement by the COBE satellite of the intensity versus frequency from the CMBR. (Courtesy of the COBE Science Working Group, NASA Goddard Space Flight Center.)

In 1992, the COBE satellite produced another remarkable discovery. Data from a second experiment aboard the satellite showed slight variations of the CMBR intensity with direction in the sky. The search for these variations had spanned 25 years. This discovery caused great excitement among cosmologists, because lumps in the CMBR are believed to be the ancestors of lumps of matter in our universe today. Making large surveys of the sky, astronomers are now able to locate the positions of thousands of galaxies in space and have found to their surprise that galaxies are far from uniformly distributed. Enormous sheets of galaxies enclose huge empty voids and form a structure that resembles a sponge or soap foam. Similarly, large-scale studies of galaxy motions show that huge regions of the universe are involved in high-speed bulk motion relative to the CMBR. The complexity and enormous scale of structure in the universe surprised cosmologists. But an elegant theory has been proposed to explain the formation of the recently discovered large-scale structure. In this theory, puny irregularities in the CMBR, similar to those detected by the COBE satellite, are amplified over the eons by gravitational forces to become the lumps and sheets of matter astronomers see in the universe today. As this theory is tested by new data, new ideas, and new calculations, cosmologists may at long last understand, in broad outline, the mechanism for structure formation in the universe.

The details of the statistical properties of the structure expected in the universe are dependent on the type and quantity of "dark matter" that dominates the universe. Cosmologists look forward to another exciting discovery—the identification of this mysterious dark matter. Over the decades, astronomers have gathered evidence of unseen mass binding together galaxies and clusters of galaxies, but the nature of the dark matter still remains a mystery. Is it something that we already know about, like the stuff that makes up our Earth and Sun? Or has nature concealed some completely new kind of matter from our earthbound physics experiments? Theoretical particle physics offers many exotic candidates, raising the possibility of not only discovering a major component of the universe but triggering a new era in particle physics as well. The search is on, in physics laboratories and at telescopes. A recent development is the search for dark matter by using its ability to bend light from distant stars or galaxies (gravitational lensing). Dark matter in clusters of galaxies and in the halo of our own galaxy is being studied with this elegant new technique.

A dream of cosmologists is to be able to make detailed studies of galaxies at great distances and early times. What did galaxies look like soon after formation? How do they evolve? When did they form? With the Hubble Space Telescope (HST) and giant (8- to 10-meter) new ground-based optical telescopes just commissioned and being built, the astronomical exploration of deep space (astronomers say "high redshift") starts now. The repaired Hubble and the new Keck telescope have racked up major discoveries in their first few months of operation, leaving no doubt that a new era is beginning for observational cosmology.

But what about even earlier, simpler cosmic times, before the galaxies formed? The CMBR can bring us news from a time when the universe was only 150,000 years old, or 0.001 percent of its current age. To find out what happened at even earlier times cosmologists must rely more on theoretical calculations, based on the physics we have learned on Earth. Our current understanding of conditions in the universe penetrates to remarkably early times, because theoretical predictions of early events have measurable consequences today. For example, nuclear reactions predicted to occur when the universe was only about a minute old should have produced helium, deuterium, and other light elements. The predicted abundances agree exquisitely with currently measured abundances of these elements! On less firm ground, but even more amazing, is the idea that the same CMBR lumps that acted as seeds for the formation of the large-scale structure can be traced back to quantum fluctuations occurring in the first billion billion billion billionth of a second after the Big Bang! If confirmed by measurements now under way, this knowledge will stand among the major triumphs of human ingenuity and imagination.

These are some of the current research frontiers that challenge and excite cosmologists. The main body of this report discusses current work on these issues in more depth. But before that, it describes some of the key questions that cosmologists are trying to answer. These give a broader perspective on the long-range goals of cosmology research.

The Cosmic Questions

If you are unfamiliar with the basic ideas of the Big Bang model, this might be a good time to read the sidebars—"The Cosmic Picture" (p. 5) and "The Early Universe" (p. 8). They outline the various epochs of the evolving universe and put the following discussion into a larger context.

Spanning enormous ranges of time, space, radiation wavelength, matter density, and temperature, cosmology research (like most science) must be subdivided in order to match the scales of human activity and instrumentation. Individual researchers may work in a relatively small area of the subject, yet each has in sight a set of large questions that his or her results might address. It is the need to find answers to questions like the ones below that motivates the cosmologist.

- *When did the universe start and how will it end?* The universe is expanding; galaxies are moving apart. Imagine this process in reverse, like a movie run backwards. The universe would appear to collapse. So there must have been a time in the past when the universe was concentrated to high density. This moment is the origin of the universe, the Big Bang. Measurements indicate that the universe is between 8 billion and 15 billion years old, only a few times the age of Earth; intense research is under way to increase the accuracy of this number. As for the end of the universe, there are two possibilities: the present expansion may go on forever, or the universe may stop expanding and come to a smooth halt, followed by collapse. Determining which will happen is harder than measuring the age, but there are two ways to do it: (1) by measuring the average mass density of the universe and finding out whether there is enough gravitational force to stop the current expansion (i.e., whether the receding galaxies have "escape velocity"), or (2) by observing the expansion velocities of galaxies at greater distances and earlier times to measure the rate at which the universe is slowing down. Both methods are being aggressively pursued, and answers are possible before the end of this decade.

- *What is the dark matter and what is its cosmological role?* Astronomers have been able to demonstrate that most of the matter in the universe cannot be observed directly. Dark matter does not shine like a star, and so astronomers cannot see it. But it must be present, because astronomers can observe its effect on other matter that can be seen. The obvious candidate for this dark matter would be ordinary matter in the form of old, burned-out stars or stars that are too small to shine ("Jupiters"). But this idea seems to be ruled out by calculations of the synthesis of light elements (for example, helium), which occurred when the universe was between 1 and 100 seconds old. As noted above, these calculations predict abundances that are in good agreement with the measured abundances of light elements. The agreement holds, however, only on the assumption that the amount of ordinary matter present today is small, less than 20 percent of the amount of dark matter deduced from gravitational effects observed in today's universe. Something other than ordinary matter must be present, something quite exotic and revolutionary—new elementary particles, perhaps, that fit into an attractive theoretical scheme of things but have not yet been detected on Earth. The dominant form of matter in our universe is unknown to us!

- *How did the large-scale structure of matter form, and how large is it?* When averaged over very large scales, the CMBR shows that the universe is quite smooth (homogeneous). However, surveys of galaxies out to just 5 percent of the distance represented by the CMBR show the universe to be clumpy and uneven (see Figure 2). How much farther must astronomers go to find smoothness, on average? Assuming that the homogeneous scale is finally found, what accounts for the complex structure graded from smooth to rough, and how did the universe evolve to this state? Cosmologists must rely heavily on special instrumentation to make very large sky surveys (encompassing a million galaxies!) to obtain the data to test

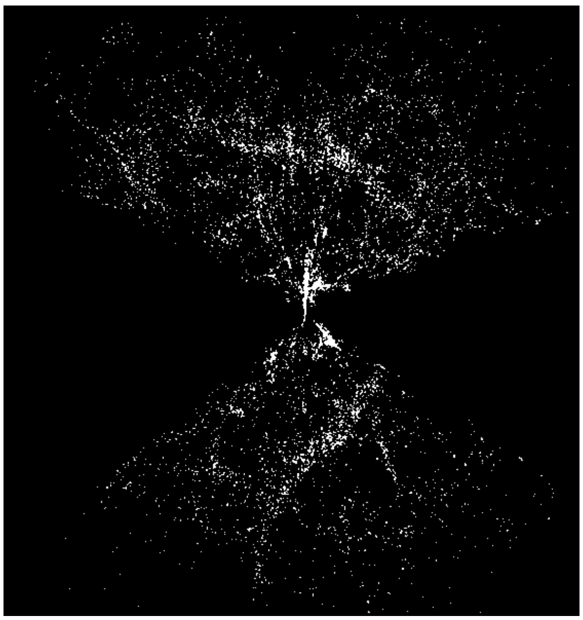


Figure 2. Data from surveys of galaxies show the universe to be clumpy and uneven. The voids and "walls" that form the large-scale structure are mapped here by 11,000 galaxies. Our galaxy, the Milky Way, is at the center of the figure. The outer radius is at a distance of approximately 450 million light-years. Obscuration by the plane of the Milky Way is responsible for the missing pie-shaped sectors. North is at the top. (Courtesy of Smithsonian Astrophysical Observatory, 1993. Northern data—Margaret Geller and John Huchra, southern data—Luiz da Costa et al.)

theoretical predictions. Those predictions are based on the idea that feeble variations ("bumps") in the CMBR show us the seeds of the structure-formation process. Important data on the bumps will come from new CMBR maps showing even finer details than those revealed by the COBE satellite. Understanding the connections between CMBR bumps and the large-scale structure seen now will challenge observers and theorists for some time to come.

- *What can we learn about physical laws from relics of the Big Bang?* When the universe was only about a minute old, the density and temperature were just right to quickly generate most of the helium and all of the deuterium present in the universe today. The remarkable thing is that our physics seems to work in a time and place so distant from us, a striking confirmation that physics as we know it can be used to study the early universe, and vice versa. There are other ways to improve our understanding of physics using other relics of the Big Bang. A current example is the effort of elementary-particle physicists to understand the observed ratio (with a value of 10^{10}) of photons from the CMBR to hydrogen atoms in the universe. The answer may be found in elementary-particle theory.

- *Did the universe undergo inflation at a very early stage?* Despite many successes, the standard, simplest Big Bang model has serious problems. For example, large regions of the universe observed today (using the CMBR) were not in causal contact at the time the early universe was dense enough to settle down to a uniform temperature. That is, they were not close enough together to have ever exchanged light signals, or information of any sort. If the regions were never in causal contact, how did they manage to reach the same temperature, as indicated by the all-sky CMBR measurements? Also, why is the density of the universe so close (within a factor of 10) to the critical density required to stop the expansion? For the density of the universe to be so close to the critical density would seem to require extraordinary coincidences in the values of the cosmological constants in the initial universe. Such fine tuning of the initial values is necessary to achieve the delicate balance between the kinetic energy of expansion and the potential energy of

The Cosmic Picture

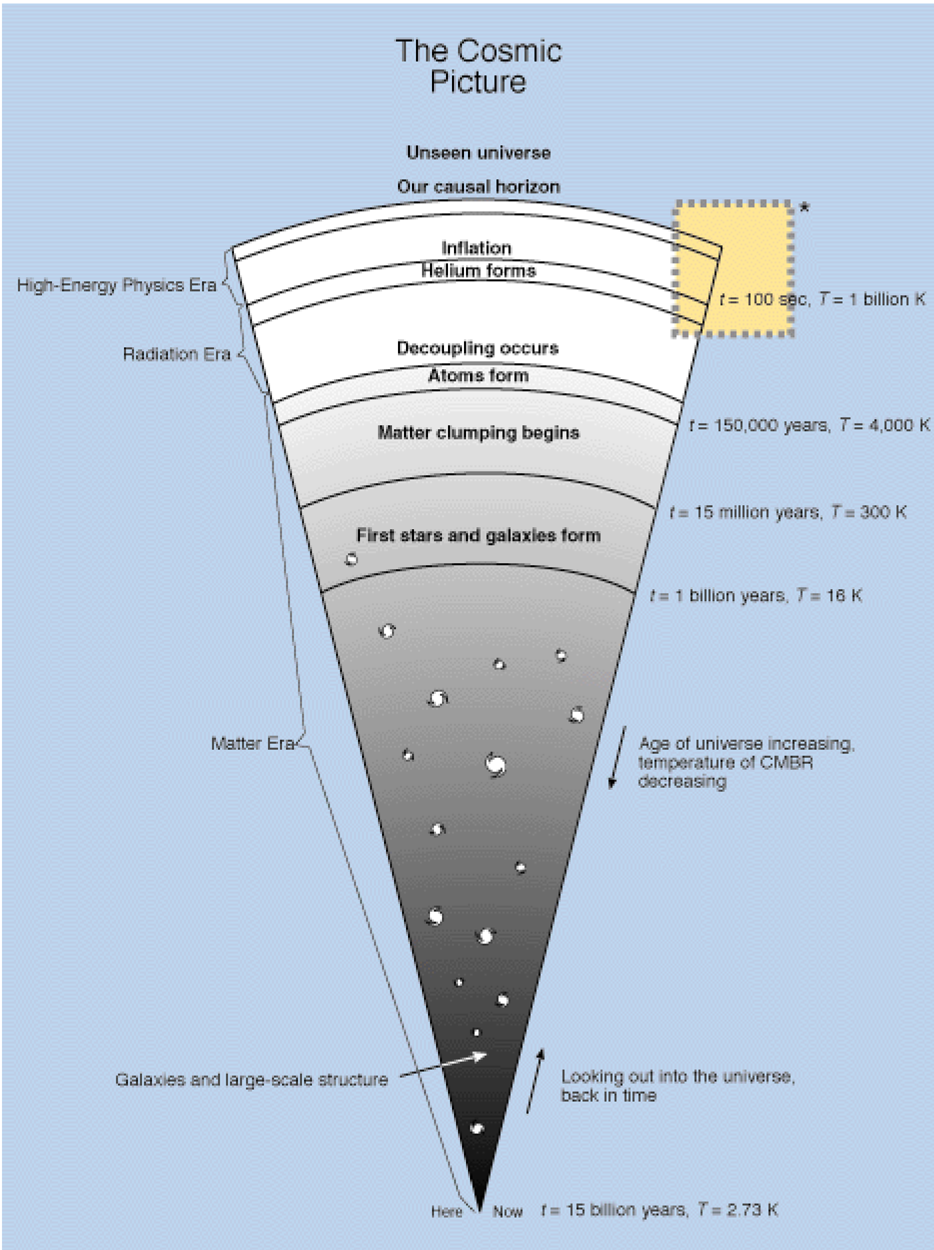
The pie-shaped figure on the next page shows a slice of the universe with the present-day Earth at the vertex, looking out and therefore looking back in time. Properties of the nearby universe can be measured directly by telescopes, and so the picture is more accurate near the vertex. Farther out, our knowledge is based less on direct observation and more on calculations and our knowledge of physics.

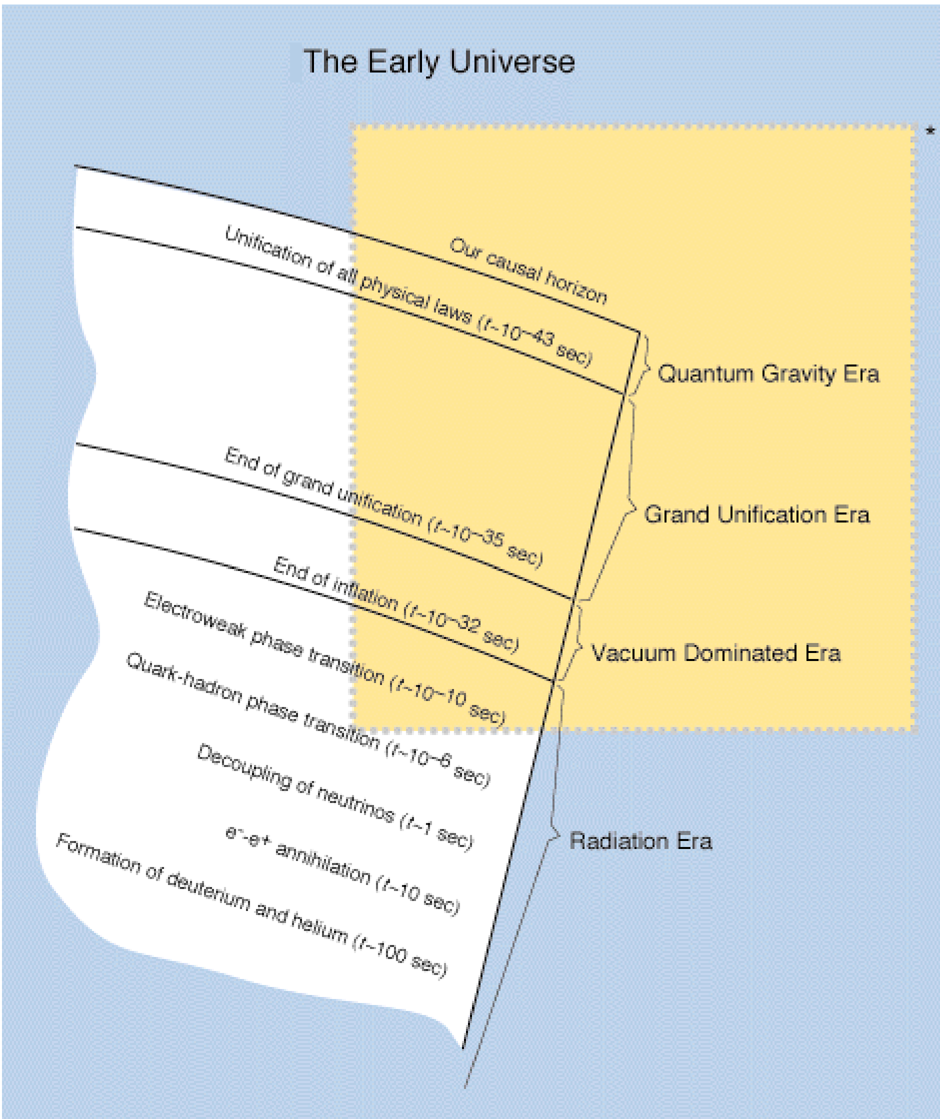
An important feature of the universe is that, as astronomers look at galaxies at greater and greater distances, they are seeing farther and farther back in time, because the speed of light is finite and it takes time for light to travel from a distant galaxy to us. Thus, astronomers see galaxies as they were in the past—the more distant the galaxy, the younger it was when the light left it, and thus the younger it appears. Labeled on the figure are the ages (measured from the Big Bang) of features as astronomers see them.

Our neighbors in the universe are other galaxies, each consisting of billions of stars. (The Milky Way Galaxy is relatively large, with about 100 billion stars.) Because many galaxies are "nearby" (the great Andromeda Galaxy is only 2 million light years away) and can be seen by the naked eye, they are relatively bright and easy to study. However, astronomers are eager to gather the vast amount of information available from more distant galaxies. This is the primary reason that astronomers want to build larger, more sensitive telescopes and detectors. By looking deeper and deeper into the universe, astronomers hope to witness the birth and aging processes of galaxies, and to study their distribution in space—the large-scale structure of the universe.

Going deeper into the universe, cosmologists imagine a period when stars and galaxies were forming for the first time. The age of the universe when stars and galaxies started to form is uncertain—somewhere between 15 million years and 1 billion years. The first stars and galaxies may have formed quickly, or the process may have been gradual. Cosmologists can only speculate because the data at this depth are so sparse. Paradoxically, cosmologists know more about the universe when it was only 150,000 years old. This early time is explored using the cosmic microwave background radiation (CMBR) that fills the universe. As the universe aged and expanded, the CMBR cooled, ultimately reaching its present temperature of $T = 2.73$ K (K = degrees kelvin above absolute zero). When the universe was 15 million years old, the CMBR had a temperature of about 300 K, which is close to room temperature (radiation temperatures are indicated at various times in the figure). An important epoch for the universe occurred when the temperature was about 4,000 K ($t \approx 150{,}000$ years). At higher temperatures (earlier times) atoms could not have existed because energetic collisions stripped electrons off the nuclei. All matter in the universe was electrically charged, and this charged matter interacted strongly with the CMBR. As the universe cooled below 4,000 K, atoms formed, the matter became neutral, and the radiation-matter interaction ceased to be cosmologically significant. Just slightly before this, gravitational clumping began to prevail over the dispersing tendency of radiation as the radiation cooled and weakened. Gravity pulled matter together to form the first stars, galaxies, and large-scale structure. The seeds for this structure can still be seen as tiny variations (anisotropy) in the intensity of the CMBR across the sky. These are vital clues to the structure formation process, coming from very early times.

Atoms formed during the epoch of photon decoupling, when the CMBR and matter first stopped interacting strongly. During this epoch, the universe was about a thousand times smaller, a billion times denser, and a thousand times hotter than it is now; it was filled with visible light instead of the microwaves astronomers detect now. (Neutral gas is essentially transparent to light.) Sitting in space during this epoch of the early universe would have been like sitting inside the Sun today—the light would have been blindingly bright in all directions.


The Cosmic Picture
Unseen universe
Our causal horizon
Inflation
Helium forms
High-Energy Physics Era
t = 100 sec, T = 1 billion K
Radiation Era
Decoupling occurs
Atoms form
t = 150,000 years, T = 4,000 K
Matter clumping begins
t = 15 million years, T = 300 K
First stars and galaxies form
t = 1 billion years, T = 16 K
Matter Era
Age of universe increasing, temperature of CMBR decreasing
Galaxies and large-scale structure
Looking out into the universe, back in time
Here
Now
t = 15 billion years, T = 2.73 K


The Early Universe
*
Our causal horizon
Unification of all physical laws (t~10−43 sec)
Quantum Gravity Era
End of grand unification (t~10−35 sec)
Grand Unification Era
End of inflation (t~10−32 sec)
Vacuum Dominated Era
Electroweak phase transition (t~10−10 sec)
Quark-hadron phase transition (t~10−6 sec)
Decoupling of neutrinos (t~1 sec)
e−-e+ annihilation (t~10 sec)
Formation of deuterium and helium (t~100 sec)
Radiation Era

The Early Universe

Before the epoch of photon decoupling, the CMBR was hotter yet, so hot that it constituted most of the energy in the universe at that time. Labeled the "radiation era" in the figure, this period can be studied by applying known laws of physics and by measuring the intensity of the CMBR at different wavelengths.

At $t = 1$ to 100 seconds after the Big Bang, something remarkable happened (as shown in the figure on p. 7). Calculations show that the temperature ($T = 1$ billion K) and density were just right for free protons and neutrons to combine via nuclear reactions, forming helium and other light elements. The calculations use data measured in high-energy and nuclear physics laboratories, and extrapolations of the density and temperature of the universe today. Accurate agreement between the predicted and the measured abundances of these elements is one of the great successes of the Big Bang model.

Going back to even earlier times tests particle physics theories at very high energies. Based on the best theories and observations of relics from this high-energy physics era, particle physicists have outlined a complex picture. The behavior of fundamental forces and elementary particles dominates the processes in this era of extremely high temperatures and densities. Forces merge and unify; particles appear and disappear. Perhaps the most exotic hypothesis posits inflation, a huge, sudden acceleration in the expansion of the universe, driven by a phase transition in a yet unknown field. Here cosmologists encounter the limits of present knowledge.

The edge of the accessible universe is the causal horizon, a spherical boundary centered on Earth with a radius of about 15 billion light-years (the speed of light × the age of the universe). Information from beyond the causal horizon cannot reach us because there has not been enough time since the Big Bang for any signal to travel so far, even at the speed of light. But as the universe gets older, the horizon moves out, bringing more of the unseen universe into view. What is the nature of the "stuff" beyond the horizon? Lacking information and an adequate physical theory of the Big Bang itself, cosmologists can only speculate. Observers on a galaxy a billion light-years away from the Earth could draw a similar causal horizon around themselves, but their horizon would include parts of the universe that astronomers on Earth would not be able to see. Given the assumption that observers see a similar universe regardless of where they are, the part that we call unseen must be similar to the part just inside our horizon. From this argument cosmologists conclude that the part of the universe we can see is embedded in a much larger universe of the same stuff, possibly extending to infinity, or possibly not.

The cosmological picture gets much fuzzier and more speculative as one tries to understand more distant, earlier conditions and events. But cosmology is a young science; most of our data and theories are less than 30 years old. It will be fascinating to see how this picture changes and gets filled in over the next three decades.

gravity and presents a problem for cosmologists. Theoretical physicists have proposed a brilliant solution to these and other cosmological puzzles. A concept called inflation proposes that the universe went through a huge, rapidly accelerating expansion at extremely early times (somewhere between 10^{-43} and 10^{-32} seconds). This proposal, which is based in elementary particle theory, solves the temperature uniformity problem by expanding a tiny uniform piece of the universe into a region much larger than the region astronomers can see today (see the sidebars). Inflation also adjusts the density to precisely the critical value needed to balance the expansion. Like all worthwhile scientific theories, the idea of inflation is testable. For example, it predicts a particular size distribution for the bumps in the CMBR. The initial results from the COBE satellite are encouraging, but a worldwide effort is under way to extend those results to smaller angles where unique signatures of the early universe may be found. The concepts of inflation and dark matter have revolutionized modern cosmology.

- *Do physics and cosmology offer a plausible description of creation?* As cosmologists and physicists push the boundary of our understanding of the universe ever closer to its beginning, one has to wonder whether the creation event itself is explainable by physics as we know it, or can ever know it. Though such a program still seems quite fantastic, not so long ago it seemed utterly unthinkable. A few theoretical physicists have started to work on the problem. One approach, still highly speculative, is to consider our entire universe as the result of a tiny quantum fluctuation in the vacuum. Under the right circumstances such a fluctuation could expand to scales unimaginably larger than the entire observable universe.

Clearly, these questions are at the heart of humankind's quest to understand our place in the cosmos. They involve some of the most fundamental unanswered questions of physical science. But why, in a time of great national needs and budget deficits, should the U.S. taxpayer support such seemingly impractical research as that described above?

Why Do Research in Cosmology?

In fact, far from being impractical, cosmological research produces important benefits for the nation and the world. First, it has unique technical spinoffs. Forefront research in cosmology drives developments in instrumentation for the collection, manipulation, and detection of radiation at radio, infrared, visible, ultraviolet, x-ray, and γ-ray wavelengths. The understanding and application of such types of radiation are the foundation for many important technologies, such as radar, communications, remote sensing, optics, medical radiology, and many more. Modern astronomical instruments are usually one-of-a-kind developments pioneered by teams of specialists who set out to achieve the best possible performance from their instrumentation. Instrument teams involve astronomers, physicists, and engineers from observatories, universities, and industry. This process produces a high return in new ideas, devices, and methods in the general areas of radiation technology. Some of these projects are models for effective technology transfer.

Another technical driver in cosmology is large-scale computing. Theorists push the state of the art by demanding the largest, fastest machines to run programs that model the universe. Such computer programs, or codes, model the evolution of systems of millions of gravitationally interacting particles. Codes for following the hydrodynamics of galaxy formation are the among the largest such codes in existence. Computers are severely taxed by the gigabytes of data streaming in from modern astronomical sensors. Indeed, large cosmological projects are now driving innovative hardware and software developments. For example, a new sky survey joins university astronomers with physicists at Fermi National Accelerator Laboratory, the latter contributing their special expertise in, and computer capability for, high-speed data processing.

A second benefit of cosmology is its unique ability to probe matter under extremes of density and temperature that can never be achieved in laboratories on Earth. The conditions in the early universe can be used to test physical theories against the measured results of nature's highest-energy experiment—the Big Bang. Pressures, temperatures, and densities in the early universe are extremes beyond our experience, but not beyond our imagination and physical theories.

A third reason to pursue cosmology is its tremendous intellectual appeal. Few areas of the human endeavor excite the human imagination as much as curiosity about the universe. How did it start? Why is it here? What is our role? How will it end? Throughout human history one finds this desire for knowledge about the heavens and human existence, and virtually all periods of enlightenment and progress have been times of rapid discovery in astronomy and physical science. Future generations will look back and evaluate our era's contributions similarly.

Finally, our cosmology—every culture's cosmology—serves as an ethical foundation stone, rarely acknowledged but vital to the long-term survival of our culture. Cosmological knowledge affects religious beliefs, ethical choices, and human behavior, which in turn have important long-term implications for humanity. For example, the notion of Earth as a limitless, indestructible home for humanity is vanishing as we realize that we live on a tiny spaceship of limited resources in a hostile environment. How can our species make the best of that? Cosmological time scales also offer a sobering perspective for viewing human behavior. Nature seems to be offering us millions, perhaps billions, of years of habitation on Earth. How can we increase the chances that humans can survive for a significant fraction of that time? Cosmology can turn humanity's thoughts outward and forward, to chart the backdrop against which the possible futures of our species can be measured. This is not irrelevant knowledge; it is vital.

Why Now?

Over the past three decades, cosmologists have built up a base of knowledge that can now be used to develop new ideas and better experiments for more exploration. Besides that knowledge base, a thriving science needs a technology base to open new possibilities in instrumentation and analysis, and it needs a dedicated, excited work force. But above all, a scientific revolution needs a subject rich in undiscovered knowledge.

These elements have just now come together for cosmology. A solid knowledge base has been developed, though it is meager compared to what is possible. The technology base is superb, and development is accelerating, especially in the areas of large telescopes and detectors with high sensitivity and resolution. The ability to get instruments into space, onto balloons, and to unique sites like mountain tops and the South Pole has proved to be a boon for observers. Over the last three decades, the evident possibilities of the field have attracted more and more young astronomers and physicists. There now is a new wave of well-trained young cosmologists, full of ideas and eager to push the field forward. If we recognize and exploit this unique opportunity, the early 21st century may witness a revolution in cosmology as exciting as the revolution in physics that took place in the early 20th century.

Summary

The past 30 years have seen seminal discoveries in cosmology. The Big Bang model is now established as the best description of the evolution of our universe. Observed remnants of its early stages of high density and high temperature offer persuasive evidence that cosmologists understand, in broad outline, the history of our evolving universe. Yet urgent questions remain. Cosmologists have vastly improved their overall understanding of the evolution of the universe and the formation of structure within it. However, the age of the universe and its ultimate destiny are still not known accurately. Cosmologists are uncertain of the timing of the epoch of galaxy formation and of the details of this complex process.

Many candidates for the ubiquitous dark matter have been proposed, but none has yet been observed.

Cosmology is one of the most exciting disciplines in all of physical science. The discoveries and insights of the last three decades have fueled interest and ideas, attracting outstanding young people to the field. The need for better data has driven major improvements in technology, especially detectors and telescopes, and the volume of new data has led cosmologists to press hard on the boundaries of computation. The combination of basic knowledge, highly motivated young scientists, and a growing technology base offers an unprecedented opportunity for further progress. The United States should continue to be a leader in this fast-moving, exciting area of science.

II. THE COSMIC MICROWAVE BACKGROUND RADIATION

What Is the Cosmic Microwave Background Radiation?

The cosmic microwave background radiation (CMBR), discovered in 1964, is a telltale remnant of the early universe. Its very existence is compelling evidence that the universe has evolved from an extraordinarily hot, compact beginning. To have produced radiation with the characteristics of the CMBR, the universe must at one time have been entirely different from what astronomers see today. No galaxies, stars, or planets existed: the universe was filled with elementary particles and radiation at extremely high energies.

The universe is between 8 billion and 15 billion years old. For all of that time, it has been expanding and the CMBR has been cooling. Currently, the radiation temperature is 2.73 K, which means that most of the CMBR exists now as radio energy in the microwave band. Man-made microwaves of the same sort link communication satellites to stations on Earth. But there are two major differences between satellite microwaves and the CMBR: First, the CMBR comes from all directions rather than from only one spot in the sky. Second, the CMBR has its power distributed over a wide range of microwave frequencies rather than concentrated at a single frequency, as is the case for a radio transmitter. To get accurate information about the early universe, cosmologists must measure the CMBR over a wide range of frequencies and across most of the sky.

From such measurements, cosmologists believe that the CMBR has been largely unchanged, except for cooling down, during the entire history of the universe. The complex evolution of matter in the universe—such as the formation of stars, galaxies, and large-scale structure—did not affect the CMBR. This radiation is a pristine cosmic remnant. It gives us a wonderful opportunity to look far back in time to study even fine details of the early universe. As cosmologists try to understand the origin and evolution of structure in the universe today, it is essential to know about physical conditions that existed long ago.

What Do We Learn by Measuring the Properties of the CMBR?

The spectrum

Since the discovery of the CMBR, cosmologists have made measurements of its intensity at different wavelengths—its spectrum. The Big Bang theory predicts that the remnant radiation will have a special kind of spectrum, a thermal spectrum. The thermal spectrum has a characteristic shape, and the wavelength corresponding to the "peak" depends on the temperature of the emitting body. The CMBR (at a temperature of 2.73 K) peaks at 2-mm wavelength; the Sun's thermal spectrum (6,000 K) peaks at a visible wavelength. Years of ground-based and balloon-based observations traced out a crude spectrum that tended to support the Big Bang theory. However, it became clear in the mid-1970s that truly decisive measurements of the CMBR needed to be done from space, above Earth's obscuring and bright (at these wavelengths) atmosphere. NASA's Cosmic Background Explorer (COBE) satellite, which was launched in November 1989, was specifically designed to make accurate measurements of the CMBR. The first scientific result from the COBE satellite was an exquisitely accurate measurement of the CMBR spectrum. The spectrum matched the thermal shape, just as the Big Bang theory had predicted. The data and the prediction are shown in Figure 1 (p. 1). This result provides strong support for the Big Bang theory.

The shape of the spectrum seen in Figure 1 has a distinguished history in physics for reasons not related to cosmology. Early in this century, Max Planck and others reluctantly introduced quantum physics to explain this same spectrum, emitted by all cavities at uniform temperature, regardless of the kind of material used to make the cavity. This same thermal spectrum now turns out to match the intensity profile of the universal CMBR—a curious connection between the smallest and the largest realms of physical theory. The simplest and most compelling explanation for the thermal shape of the CMBR is that the universe was all at the same temperature for some very early part of its early history. Space was uniformly filled with hot (but rapidly expanding and cooling) ionized gas and thermal radiation. The recognition that such an epoch existed in the early history of the universe is a cornerstone of modern cosmological models.

That a single experiment can have such profound implications is unusual. But the measurement was not easy. It required the use of a satellite to get the instrument above the atmosphere of Earth, and the entire instrument was cooled to a temperature of 1.5 K to reduce radiation from the instrument itself. The design, operation, and calibration of the COBE instrument all had their technological heritage in ground-based and balloon-based instruments, and the experience gained in these earlier experiments laid the foundation for the highly successful satellite measurement.

Theoretical modeling of the thermal history of the universe has developed concurrently with progress in the spectral measurements. The accurate fit of the measured CMBR spectrum to a thermal shape sets extremely tight bounds that limit the variety of hypothetical physical processes that could have taken place in the early universe. For example, energy-releasing processes that would have reheated the universe at critical epochs in its history can now be ruled out.

Cosmological theories based on the Big Bang unambiguously predict that the temperature of the universe will fall with time as the universe expands. Recent observations from the new Keck telescope have provided the first direct evidence that the CMBR temperature has indeed decreased over (relatively recent) cosmic time. Using the light from a distant, bright, quasi-stellar source, astronomers were able to measure the temperature of carbon atoms in an intergalactic cloud between Earth and the source. The shift of the spectral lines (redshift) of the cloud was also measured. The temperature of the cloud, which should have been the same as that of the CMBR, was found to be 7.6 K. This is exactly the value expected for the CMBR at that redshift.

Why are "bumps" in the CMBR so important?

The second important characteristic of the CMBR is the variation in intensity (or temperature) from place to place on the sky. Measurements of these variations, often called anisotropy measurements, tell us about tiny fluctuations in the uniformity of the early universe. Though small (1 part in 100,000), these fluctuations are believed to be the seeds of all complex structure in the universe today.

The main idea is that the universe as we see it today must somehow have evolved from the early stage of thermal uniformity implied by the CMBR spectrum measurements. Today, the universe is a rather lively place with everything from stars and planets to quasars, colliding galaxies, and black holes. A central unresolved question is, How did these structures form? One of the most appealing answers is also the simplest: objects formed because gravity pulled together matter that existed originally in slightly denser regions. Given enough time, the matter became compressed because, as more matter was pulled in, the gravitational forces grew even stronger until galaxies and other objects resulted. These objects resist further collapse because of their rotation and/or internal motions.

This idea, called gravitational instability, probably explains most of the objects that astronomers see in the sky today, but it requires small initial density fluctuations to start the process of collapse. Because the expansion of the universe greatly retards the formation of instabilities, the seeds of structure must already have existed at the time the CMBR last interacted with matter, 150,000 years after the Big Bang. Fluctuations that existed then are detectable by the CMBR anisotropy measurements as tiny variations (bumps) in radiation intensity across the sky.

Measurements of Anisotropy

Large-scale anisotropy

The theoretical details of the fluctuations and their consequences have been developed in the 30 years that cosmologists have known about the CMBR. Until 1992, no anisotropy (except for a separate effect due to the motion of our Solar System in the cosmos) had been detected in the CMBR, though many attempts had been made. Increased receiver sensitivity forced experimenters to develop increasingly sophisticated techniques to reduce systematic errors and the effects of noise from other sources of microwave radiation. As measurements became more sensitive and no anisotropy was found, the range of theoretical models that could fit the observations became smaller and smaller. As models were increasingly constrained, many cosmologists, especially the theorists making predictions, became increasingly nervous over the lack of detected fluctuations. So it was with great excitement that the COBE science team announced in 1992 that it had detected the long-sought bumps in the CMBR. The illustration on the cover of this report is the resulting COBE map of the intensity of microwave radiation arriving from various directions in the sky. The map contains some instrumental noise, but its lumps and bumps also show evidence for the beginnings of structure in the universe.

Like the measurement of the CMBR spectrum, the COBE detection of the CMBR anisotropy could not have occurred without the experience of earlier anisotropy experiments from the ground, from balloons, and from aircraft. As valuable experience was gained from the suborbital measurements, the technology and the experimenters' understanding of how to avoid contamination from many bright local sources both evolved. Balloons, rockets, and aircraft also provide important opportunities to follow up on satellite discoveries. Recently, data from an independent balloon experiment, using a frequency above that of the COBE's receivers, exhibited the same basic CMBR pattern as seen in the COBE data, thus confirming the satellite result. Low-cost balloon experiments have also enabled important first steps toward extending these results to smaller angular scales.

The detection of large-scale anisotropy has finally allowed the field of CMBR research to become established. Whereas previous noise-limited measurements could exclude but not support certain theories, the anisotropy measured by the COBE satellite is approximately at the level needed for the origin of structure as predicted by theories. In addition, the manner in which the strength of the anisotropy varies with the angular size of the bumps is consistent with Big Bang theory. Even the idea of an inflationary epoch in the early universe (see section V) seems to fit with the COBE result, although this characteristic of the CMBR fluctuations is not yet well determined. Within the past year, both theoretical thinking and experiment planning have undergone an important transformation because of the COBE detection. Almost all areas of cosmology have been affected, and many now take the magnitude of the COBE anisotropy signal as a reference point for new developments.

Medium-scale anisotropy

While the COBE anisotropy detection is extremely important, it was made at angular scales of more than 10 degrees on the sky, scales much larger than those actually involved in the formation of galaxies and clusters of galaxies. The best direct comparison between the primordial seeds and present day structures awaits the reliable detection and detailed mapping of CMBR anisotropy on smaller angular scales, comparable to the physical scale of superclusters of galaxies.

Medium-scale (0.5- to 10-degree) anisotropy measurements also probe important details of the decoupling process. Numerical calculations show that during the time that matter was combining into atoms and interacting with the CMBR for the last time, there were acoustic oscillations in the overdense bumps that should have left strong “fingerprints” in the CMBR anisotropy. Oscillations would amplify bumps to an extent that depended on the bump size and critical details of the cosmological model. The theory's prediction of peaks in the CMBR medium-scale anisotropy offers an intriguing and unexpected opportunity. If the profile of CMBR anisotropy versus bump size can be accurately measured, cosmologists may be able to measure three important cosmological parameters: Ω, the ratio of the mean mass density to that required to close the universe and eventually stop its expansion; Ω_B, the contribution to Ω from ordinary (baryonic) matter; and the expansion rate of the universe (the Hubble constant, H_0). Of course, the data may reveal something completely unexpected, a clue to unknown processes in the early universe. In either case, medium-scale anisotropy signals are bringing us detailed information about the conditions and dynamics that existed in the universe when it was only 150,000 years old—something quite unimaginable only a few years ago.

The opportunity to gain such important knowledge has recently focused a great deal of experimental and theoretical research on the issue of CMBR anisotropy on angular scales around 1 degree, at the low end of the medium scale. This scale corresponds to about 300 million light-years, which is smaller than the size of the region in the universe around us that has been well mapped in redshift surveys of thousands of galaxies. Experiments on this angular scale are relatively new compared to studies of the CMBR spectrum and the large-scale anisotropy measurements. The techniques and technology needed to overcome the new experimental challenges are just now beginning to be understood.

A current problem is to remove possible interference from weak radio sources and faint, diffuse emission from our own galaxy. To effect the separation, a wider range of frequencies and better sensitivity are being used. At angular scales around 1 degree, the greatest understanding of the structure-formation process would follow from detailed mapping of large regions of the sky; this poses difficult challenges for current experiments. Ground-based experiments must overcome fluctuations in atmospheric emission that are thousands of times larger than the expected CMBR anisotropy signal. Thus, experimenters are observing from sites with a cold, dry atmosphere like the South Pole, northern Canada, and mountain tops. Balloon experiments afford much smaller atmospheric fluctuations, but they are limited by the relatively short times available for observations. Long-duration balloon flights of many days are being planned to alleviate this problem, and they offer a powerful new opportunity to extend COBE results at relatively low cost. However, flight opportunities for long-duration balloons are currently scarce. Limited sky coverage and Earth's radiation environment are also problems for experimenters trying to map the CMBR anisotropy from ground-based and balloon-based platforms.

The situation for the measurement of medium-scale anisotropy is similar to that for measurement of the spectrum and large-scale anisotropy two decades ago. Data are beginning to indicate that something interesting is happening, but greater accuracy and broader sky coverage are needed to extract the important scientific results. Techniques for successful experiments are being developed using the experience gained with suborbital experiments, but Earth's environment poses major problems for experiments requiring high accuracy and large sky coverage. Research now under way will ultimately lead to the design of a satellite that can utilize the advantages of the space environment. Preliminary feasibility studies indicate that a midsize Explorer satellite in an orbit far from Earth is an attractive and relatively inexpensive possibility. A satellite experiment will permit the mapping of the CMBR sky pattern with sufficient detail and sensitivity to form an excellent picture of the early development of structure in the universe.

Small-scale anisotropy

Measurements of the CMBR anisotropy on angular scales smaller than about 0.5 degree must be made with relatively large ground-based telescopes (high angular resolution requires large antennas). The theoretical case is not yet as strong for small-scale measurements because such anisotropies are presumed to have been smeared out when matter and radiation interacted for the last time at the epoch of photon decoupling. However, variants of the

Big Bang theory, such as theories involving cosmic strings (discontinuities in the structure of space), predict that important clues to the universe's history might be embedded in the CMBR at these angular scales. A few experiments have been done from single large telescopes and from arrays of radio telescopes, such as the Very Large Array. Though sensitivities are comparable to the COBE detection level, only a small fraction of the sky has been scanned. Signals are detected, but they are thought to be due mostly to radio emission from galaxies, quasars, or other foreground radio sources. Because of the need for large instruments and the extreme care required for these measurements, progress on small-scale anisotropy is likely to be relatively slow. But it should be remembered that only a decade ago there was almost no interest in even medium-scale measurements. As understanding has grown, so also has the need for more diverse experimental data. And surely, as more data are analyzed, the simple models of structure formation must break down at some point. Improvements in small-scale measurements are one way to find such weaknesses in the models.

III. THE LARGE-SCALE STRUCTURE OF THE UNIVERSE

Galaxy Maps and Large-Scale Structure

What is large-scale structure, and why is it important?

Although the intensity of the CMBR is extremely uniform in all directions, with fluctuations measured at only 1 part in 10^5, the local distribution of galaxies is extremely irregular, with fluctuations in the density of galaxies per volume of space being well in excess of 100 percent. Maps of the distribution of galaxies in space reveal a remarkable pattern of thin, filamentary structures connecting small and large central concentrations of galaxies, punctuated by large, quasi-spherical voids. The example of the map shown in Figure 2 (p. 4) is the result of several years of painstaking spectroscopic observations with modest-size optical telescopes. The far-flung distribution of galaxies in the universe, the complex assemblage of clusters, filaments, and voids, is referred to as large-scale structure.

It is not surprising that galaxies are clustered. As explained above, the early universe contained small density irregularities, as measured by fluctuations in the CMBR, and the amplitude of these small bumps grew via their self-gravity to make the structure seen today. This condition of gravitational instability can amplify the initial density fluctuations of seeds on all scales. Galaxies and large-scale structure are all part of the same process; both are relics of the Big Bang.

Finding clumps of galaxies was thus expected, but their huge extent caught astronomers by surprise. Typical voids are 200 million light-years across, and one enormous curtain-like structure—the Great Wall—is draped across the universe in a span half a billion light-years across. Even this large size, however, is less than a tenth the scale measured by the COBE satellite discussed above. Altogether, the distances involved in the study of large-scale structure range over a factor of a million, from the size of galaxies to the CMBR anisotropy measured by the COBE satellite. This combination of observations gives us a powerful probe of Big Bang density fluctuations over a wide range of scales. The extent of early density fluctuations on different size scales and their subsequent growth under gravity are critical clues to the nature and amount of dark matter in the universe, as explained below.

Mapping the large-scale structure

Making maps of galaxies in three dimensions requires knowing how far away each galaxy is from Earth. One way to get this distance is to use Hubble's law for the expansion of the universe. Hubble discovered that the velocity at which two galaxies recede from each other is proportional to the distance between them. Inverting this relation yields an estimate of distance from observed velocity. The velocity with which a galaxy is receding from us is obtained by measuring the shift to redder colors of spectral features in its spectrum, a "redshift" analogous to the familiar Doppler shift in the frequency of sound waves from a receding source. The greater the redshift, the larger the velocity, and, by Hubble's law, the larger the distance.

We are truly living in the age of mapping the universe. The last decade has seen a revolution in the technology of light detectors that has made it possible to measure redshifts rapidly, even with modest-size telescopes. In 1976, there were only 2,700 galaxies with measured redshifts—now there are 100,000. By the year 2000 astronomers expect 1 million! This field of astronomy is still on a steep discovery curve.

The importance of uniform galaxy surveys

The first step in making a redshift survey is compiling a catalog of galaxy positions and brightnesses on the sky. Traditionally such catalogs have been based on photographic surveys taken in visible light. We are learning, though, that even small biases in the list of target galaxies may have a big effect on the final maps. Hence there is strong interest in new and better ways of finding galaxies. Three basic avenues are being explored. Deeper surveys of the whole sky in visible light are being conducted using highly sensitive detectors (called charge-coupled devices; CCDs) that can detect intrinsically faint galaxies, galaxies of low surface brightness, and distant galaxies. Near-infrared surveys of the sky at 2-micron wavelength will make it possible for the first time to observe the dip down near the plane of our galaxy, whose dust clouds obscure 35 percent of the sky in visible light. Finally, x-ray satellite surveys provide yet another means of mapping clusters of galaxies.

A fundamental question is whether one large section of the universe looks like another. In other words, how large do sections have to be before they begin to appear statistically uniform? Unfortunately, a single ground-based observatory sees only a portion of the sky. To achieve the high degree of uniformity needed over the whole sky requires careful surveys. There are three requirements: First, individual surveys must cover as much of the celestial sphere as possible. Second, surveys must be closely coordinated and well standardized so that they can be knitted together. Finally, homogeneous all-sky surveys need to be conducted by satellites above Earth, such as the Infrared Astronomy Satellite (IRAS), a joint mission of the United States, the United Kingdom, and The Netherlands that was flown in 1983.

A major goal for the next generation of surveys is to increase their range out to 3 billion light-years, roughly 20 percent of the radius of the visible universe. On such scales cosmologists would be probing structures that are the same size as the smallest structures in the COBE microwave map. The clustering behavior of galaxies over an extremely wide range of scales could be measured and compared directly to the CMBR anisotropy with no extrapolation. This would tell us how the density fluctuations have evolved from the epoch of CMBR emission (the epoch of photon decoupling) to the present. This information would yield essential clues to the amount and nature of dark matter in the universe.

Theory of large-scale structure

Statistical description and theoretical modeling of the observed galaxy distribution have been extremely productive over the past decade. Much of this modeling has been done with large computer simulations on the largest available supercomputers. This is a problem in the "grand challenge" class, with the goal of understanding in detail the formation of structure on both small and large scales. The models typically follow the evolution of a large patch of the universe. Calculations start with random initial fluctuations as statistically predicted for different cosmological parameters and different types of dark matter. The equations governing the gravitational coupling, as well as other physical processes, are then solved numerically by the computer. Starting from small amplitudes, the fluctuations become increasingly larger, as expected from the gravitational instability picture. The computational results can then be compared to the observed properties of large-scale structure in the universe. With careful analysis, such comparisons can set constraints on the amount and nature of dark matter. Some proposed dark-matter candidates have already been ruled out in this way. Figure 3 is a recent example of a numerical simulation, processed with similar selection criteria as for observational redshift surveys. The similarity in the voids and filaments shown in Figures 2 and 3 is striking.

Clusters of galaxies, with size on the order of 3 million light-years and mass of 10^{15} Suns, are central to our understanding of structure. Astronomers have recently discovered that galactic cores are dense enough to act as gravitational lenses (discussed in section IV in "Gravitational Lenses"), that most of the baryonic (ordinary) matter within them is in the form of hot gas, not galaxies, that dark matter constitutes approximately 80 percent of their total mass, and that they show a considerable amount of substructure when examined at high spatial resolution. The abundance of clusters and their detailed internal structure are predicted by models to be sensitive to assumptions about properties of the dark matter and the total amount of matter in the universe. Only the most powerful parallel supercomputers can adequately represent the gravitational and gas dynamical processes at sufficient resolution to model clusters.

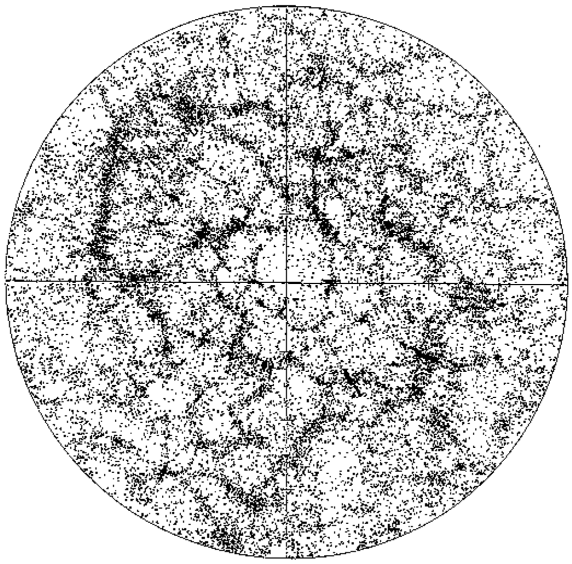


Figure 3. A simulated galaxy redshift survey based on a cosmological model dominated by cold dark matter and a nonzero cosmological constant. The observer is at the center of the circle, and the outer radius is at a distance of 600 million light-years. Compare to Figure 2. (Courtesy of Renyue Cen, Princeton University Observatory.)

An even more challenging problem is the question of how galaxies formed. For decades these fundamental building blocks of the universe were taken for granted, but now cosmologists realize that galaxy formation represents the smallest scale of the overall process of structure formation. Galaxy formation is fearsomely complicated because it involves the detailed physics of gas clouds, not just the simple pull of gravity. For example, in order to fall into a forming galaxy, gas has to cool first, which involves the emission of radiation. The cold gas then forms into stars. (Astronomers are not sure just how or how fast.) Dying stars in turn eject energy and gas back into the gas reservoir of the galaxy via supernova explosions. All the while, gas clouds are colliding and pushing one another around via shock waves and gas pressure. A galaxy is a complex system.

In the past few years computer advances have made possible the first attempts to calculate galaxy formation starting from expanding universe models and including the effects of gas. The results are encouraging, but much more computer power is needed to obtain accurate results. Fortunately, with the continuing development of ever-more-powerful computers and sophisticated gas-modeling techniques, one can reasonably hope that progress in this field will be rapid.

Cosmic Velocity Flows

What are cosmic flows, and why are they important?

Galaxy maps of the universe by themselves are unreliable tracers of the true density of matter because astronomers do not know precisely how or where galaxies formed. Perhaps matter did not “light up” equally in all places to make visible galaxies. Matter that did not form into galaxies may exist today but be invisible. Astronomers sum up this question by asking: Do galaxies fairly trace mass? This cannot be told from redshift maps alone.

Cosmic flows offer a way to answer this question because they are generated by the gravity of all matter, whether luminous or not. These flows are the irregularities in the Hubble expansion that are created (according to gravitational instability) as galaxies stream out of voids and fall onto clusters and superclusters. A map of cosmic flows can be used to generate a map of the mass density distribution that caused them, including any dark matter between the galaxies. Such a map is shown in the upper panel of Figure 4, along with a map of the directly observed galaxy distribution of the same region in the lower panel. The two roughly agree, suggesting that galaxies do trace mass, at least approximately. This result is important evidence that the gravitational instability picture is basically correct.

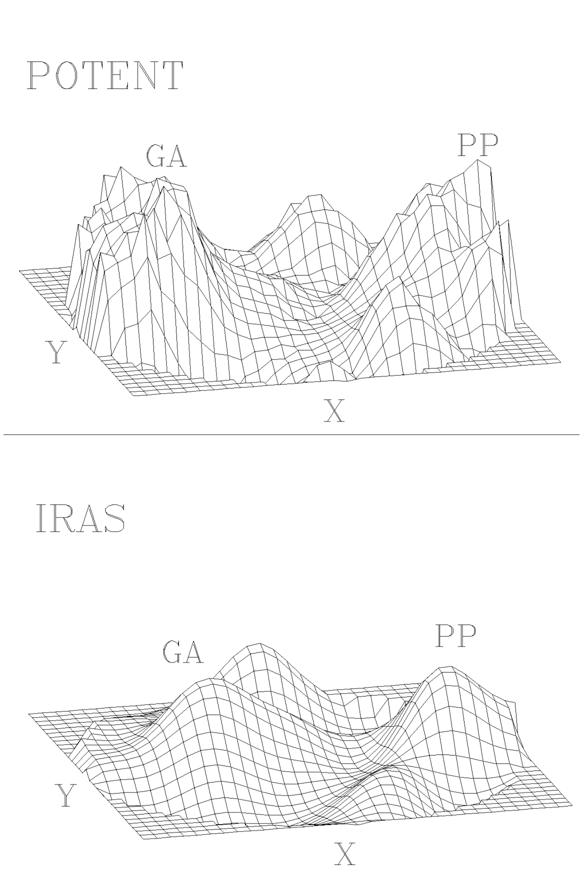


Figure 4. The density distribution of mass inferred from studies of large-scale flow using the POTENT method (upper panel) is compared with the density distribution of galaxies derived from the Infra-Red Astronomy Satellite (IRAS) redshift survey (lower panel). The two distributions have been smoothed and are shown in the supergalactic plane. The height in the plot is proportional to the density fluctuation about the mean density of the universe. The Local Group of galaxies is at the center, the Great Attractor (GA) on the left, the Perseus-Pisces (PP) supercluster on the right, and the Sculptor void in between. The similarity between the two density fields indicates that galaxies tend to trace mass and that the cosmological parameter Ω is of order unity. (Courtesy of Yair Sigad, Avishai Dekel, Michael A. Strauss, and Amos Yahil, submitted to the Astrophysical Journal in 1997, and Avishai Dekel, private communication.)

Because cosmic flows can measure the clustering of matter on even very large scales, they are the best indicator of the absolute level of density fluctuations in the universe today. This indicator of density fluctuations can be compared to the strength of CMBR fluctuations on larger scales at earlier times. Close to Earth, within 250 million light-years where flows are well measured, flow velocities have approximately the magnitude predicted if standard dark-matter theories employ the COBE measurements. This local agreement suggests that our basic model for structure formation, spanning many decades of length scale and depending on details of the nature of dark matter, is approximately correct.

By measuring the size of the flow motions around particular clumps of galaxies, astronomers can estimate the total amount of matter in each one. If galaxies trace the distribution of matter, or even if not, as long as their distribution is biased in a consistent and predictable way, astronomers can generalize from the galaxy masses to estimate the total matter density in the universe. In short, astronomers can "weigh the universe" and measure the elusive parameter Ω the ratio of the mean mass density to that required to close the universe and eventually stop its expansion.

Our present knowledge of galaxy formation and biasing is still poor. Nevertheless, cosmologists can draw two conclusions. First, measurements of cosmic flows on all scales are an important test of competing theories of structure formation. And second, the high values observed for cosmic velocity flows are the strongest indicator so far that Ω might actually be 1, a value favored by theoretical considerations, as explained below in section V.

Measuring cosmic flows

Since cosmic flow is a deviation from the Hubble-law motion of a galaxy, measuring it requires two types of observations: First, the observed redshift of the galaxy must be measured from its spectrum. Second, an independent estimate of the distance of the galaxy must be made, which is much more difficult. If a galaxy has no motion other than the Hubble flow, its redshift will correlate perfectly with its distance via Hubble's law. Any deviation outside of that due to errors in the estimated distance represents the cosmic flow.

Unfortunately, distances are hard to estimate, and errors can lead to spurious measurements of cosmic flows. The distance to galaxies is usually estimated by the Tully-Fisher relation, which states that big galaxies rotate faster than small ones. (Rotation speed can be measured from features in optical or radio spectra.) Rotation rate is thus a measure of true galaxy brightness, allowing one to deduce how far away a galaxy is based on its apparent brightness. The Tully-Fisher relation has an accuracy of about 15 percent. This translates to an error in flow motion of 600 km/s at a distance of 200 million light-years, and the error grows with distance. Even the largest cosmic motions are no bigger than this. By averaging together several galaxies in a group or cluster, the error can be reduced, but measuring flows is still only reliable out to about 400 million light-years using current methods.

Two conclusions follow. First, cosmic flow surveys are limited by distance errors to volumes that are much smaller than those sampled by redshift surveys. Second, distance measuring techniques with smaller errors are badly needed to increase the viable range of cosmic-flow surveys. At present, the catalog of flow motions contains about 3,000 galaxies out to a radius of 300 million light-years over the whole sky. This volume can be enlarged incrementally with current methods, but a major increase would require better measures of distance. More accurate distance measures would also allow us to study nearby motions more precisely, make better density maps, and derive a more precise measure of the mean mass density of the universe. An improvement in the accuracy of distance measurements by as little as 30 percent would be extremely important. Several approaches are under study, including improvements to the Tully-Fisher method as well as some entirely new methods.

Summary and Prospects for Large-Scale Structure

Cosmic flow measurements and redshift maps go hand in hand, since the structures they reveal arise from the same cause. Combining these two tools has already had a big impact on our view of structure in the universe. When combined with the COBE measurement of CMBR fluctuations, flow measurements and maps have quantified the fluctuation amplitudes on virtually all scales of interest. Estimates of mass on the scales of galaxy clusters and on smaller scales appear to suggest that the density of the universe is low, a factor of 10 less than required for closure of the universe ($\Omega \approx 0.1$). This result has been known for two decades and has not changed with recent data. On the other hand, the newer data on large-scale flows, which measure mass on scales 30 times larger than the older work, seem to suggest that the universe may contain sufficient density for closure ($\Omega \approx$ 0.5 to 1). This contradiction must be telling us something about the nature of the dark matter distribution. It appears as though the dark matter clusters only weakly with galaxies and groups of galaxies but clusters more strongly on the larger scales of superclusters. At present, it is not clear how these apparently contradictory observations can be reconciled. Whether any of the current models of large-scale structure can describe all the observations is an open question.

The field of large-scale structure is still growing rapidly from the infusion of new data, and even more ambitious surveys are now in the planning stages. Prospects also exist for improvement in the accuracy of the distance indicators for galaxies. With better data and theoretical tools, cosmologists have the prospect of solving several key cosmic mysteries: What is the nature of the dark matter and how dense is it? What is the average density of matter in the universe? Is it near the closure density, $\Omega = 1$, or is it much less than that, as some measurements seem to indicate? Where and how were galaxies formed?

IV. THE DISTANT UNIVERSE

Measuring the Cosmological Parameters

We have known since the late 1920s that the universe is expanding. Quantifying the expansion is done conventionally in terms of two numbers. H_0, the Hubble constant, measures the current expansion rate of the universe, and q_0 is the rate at which the expansion is slowing, or decelerating, because of the self-gravitational pull of all the matter in the universe. The standard cosmological solutions of Einstein's equations of general relativity are specified by H_0 and q_0. H_0^{-1}, the inverse of the Hubble constant, is a measure of the current age of the universe, while q_0 is a measure of how long the universe will continue to expand.

Two additional quantities that affect the expansion are the cosmological constant, Λ, the vacuum energy density of the universe, and Ω, the ratio of the total mass/energy density in the universe to the critical density, which is required to just bring the expansion to a halt in the infinite future. Consider first the case where $\Lambda = 0$. If $\Omega < 1$, the self-gravity of the universe is insufficient ever to stop its expansion (an "open" universe). If $\Omega > 1$, the expansion will eventually stop and the universe will collapse (a "closed" universe).

The Λ term represents a strange phenomenon. As noted, it measures the energy density of a vacuum, which remains constant as the universe expands, unlike ordinary matter and radiation whose densities decrease with expansion. A non-zero vacuum energy density would mean that energy is present in an empty universe even in the absence of particles or radiation. Though it seems odd, such a possibility is consistent with Einstein's theory of gravitation. The key point about Λ is that such energy generates gravity even without normal matter or radiation—hence, gravity from a vacuum. Because of this phenomenon, and because Λ remains constant as the universe expands (a vacuum cannot be diluted), the existence of non-zero Λ radically changes the dynamics of the universe. This is the key concept that underlies inflation, which is discussed in section V. If there is currently no vacuum energy density in the universe, then $\Lambda = 0$ and $q_0 = \Omega/2$; most cosmologists believe that Λ is 0, but understanding why it is so small is a profound question of fundamental physics.

The Hubble constant, H_0

The Hubble constant measures how fast the universe is expanding today. In addition, the age of the universe can be expressed as approximately $(2/3)H_0^{-1}$ (the precise value depends on Ω and Λ). The accurate determination of H_0 has occupied astronomers for several decades, and the scientific motivation for finding an accurate value of this critical constant has become ever stronger. Another key use of H_0 is to estimate the physical distance and size of objects that have measurable redshifts. For example, the size of the largest structures in the universe is related to the distance that light could have traveled in the time up to the epoch when matter began to dominate over radiation. The corresponding size scale today is an important relic of the Big Bang, but its value is proportional to H_0^{-2} and therefore suffers from the current uncertainty. An accurate measurement of H_0 is crucial for assessing whether the detailed models of the evolution of structure in the universe can be reconciled with a wide range of observations.

Current estimates of H_0 range between 45 km/s per megaparsec (a megaparsec is about 3 million light-years) and 90 km/s per megaparsec. A value near 45 to 50 is considered low and 80 to 90 is considered high. If $\Lambda = 0$ and $\Omega = 1$ (the theoretically preferred values for these parameters), then $H_0 = 50$ km/s per megaparsec means an age of 13.3 billion years, and $H_0 = 90$ km/s per megaparsec means 7.4 billion years. A fundamental reality check comes from requiring the oldest stars in our galaxy to be younger than the age of the universe. This requirement, a logical necessity, sets an upper limit to H_0. Astronomers' best estimates of the age for such globular cluster stars are near 15 billion years, in conflict with the smaller value of the age of the universe estimated by high values of H_0.

Ground-based facilities and techniques have improved dramatically over the past three decades, yet H_0 still remains uncertain to almost a factor of two. The problem is that different techniques and different research groups get discrepant values for H_0. This is a sure sign that unknown systematic errors exist. Which value is correct? The successful repair of the Hubble Space Telescope (HST) has enabled that instrument to help resolve this long-standing issue. The HST observations employ a well-established astronomical technique that relies principally on using Cepheid variable stars in other galaxies as "standard candles" of known luminosity. The technique provides estimates of the distance to other galaxies. The distances, together with the recession velocities measured by the redshifts of their spectra, permit determination of the value of H_0. Recent results derived from HST observations yield a value of $H_0 = 80 \pm 17$ km/s per megaparsec, consistent with low values of the age—below 10 billion years. The resulting conflict with estimates for globular cluster ages may emerge as one of the most exciting cosmological questions of the next decade. Solving this problem could require major changes to stellar evolution theory, or even non-zero values for Λ.

The planned refurbishment of the HST with a new, advanced camera in 1999 should enable it to make an even more accurate calibration of the cosmic distance scale and a more definitive measurement of the Hubble constant. However, because of the critical conflict between the estimated ages, it is clearly vital to verify the HST value by alternative, independent means. These include methods based on the detailed study of supernova atmospheres, the attenuation of CMBR radiation as it passes through the hot gas within galaxy clusters (the Sunyaev-Zel'dovich effect), and the difference in arrival time between separate components of gravitationally lensed quasars (discussed below). All these approaches offer alternative measurements of H_0.

The deceleration parameter, q_0

Measuring q_0 directly requires measuring the change in the universal expansion rate over a large range of cosmic time. This is done using "global" cosmological tests extending over large enough distances that the travel time of light is an appreciable fraction of the age of the universe. The basic idea is that the size and appearance of a distant patch of the universe, as viewed from our vantage point, depends both on how the universe expands (its global geometry) and on the bending of light by the gravity of intervening matter.

Extensive efforts in the 1960s and 1970s to study the apparent luminosity or size of distant objects, such as very luminous galaxies, were based on the hope that these objects were constant in brightness. These efforts were mostly abandoned after it was learned that the intrinsic luminosity of these standards probably changed significantly with time because of galaxy evolution. Recent studies of the apparent size of features in distant radio galaxies might provide a new way to measure q_0. Direct counts of galaxies as a function of measured redshift can also be a powerful probe of the curvature of space—another name for q_0. This test was attempted in the last decade, but again yielded ambiguous conclusions. With improved modeling of the evolution of galaxies and a major effort to obtain spectra of a large sample of faint galaxies, this test might prove to be an effective way to measure both q_0 and Λ. Cosmological models with different values of q_0 and Λ predict different volumes of space for a given observed redshift, and the number of galaxies is a measure of the size of that volume. This volume evolution affects not only the number of quasars, supernovae, or galaxies at any redshift, but also the number of potential gravitational lenses (discussed below). Preliminary results from a study of quasar images with HST suggest that lensed quasars are relatively rare. Models with large Λ overpredict the number of observed gravitational lenses; therefore, Λ is not large.

The density parameter, Ω

Without going to cosmological distances, it is possible to measure the density parameter Ω, by means of so-called local tests. Many of the local tests "weigh" local structures by applying the virial theorem, which states that the kinetic energy of a self-gravitating system should be approximately equal to its potential energy. Since the motion of luminous galaxies must be observed to estimate the kinetic energy of the system, only the component of the mass density clustered with luminous galaxies can be examined in this fashion. As noted earlier, such measurements tend to give low values of Ω, around 0.1 to 0.2. However, as mentioned in the discussion of cosmic velocity flows in section III, there may be a component of dark matter clumped in sizes larger than clusters of galaxies but smaller than superclusters. Cosmic velocity flows may be detecting structures on this scale, giving values of Ω near 1. If there exists a perfectly smooth background of mass density unclustered with the galaxy distribution on any scale, it can be detected only by its effects on the curvature of space, in the global measurements of q_0.

Deep Imaging of Galaxies

Galaxies have been used as beacons to map the distribution of matter in the universe ever since they were recognized as independent systems of stars. As described above, the "local" distribution of galaxies shows a complicated network of structures. When averaged over the largest distances, many billions of light-years, the distribution of matter is expected to be more homogeneous. Current research programs on very distant galaxies have two distinct goals. The first is to use the number of visible galaxies as a measure of the surveyed volume. If galaxies were stationary and the geometry of space were determined by the rules of euclidean geometry, then the number of galaxies seen would be roughly proportional to the cube of the distance probed ($N \propto r^3$). When the effects of redshift and non-euclidean geometry are taken into account, the number of galaxies is expected to increase more slowly than r^3 at larger distances, as is indeed observed. (If these effects were not present, the night sky would not be dark! This is known as Olbers's paradox.) Questions about the geometry of the universe—is space positively or negatively curved, infinite or finite?—can be related by general relativity to the dynamics of the expansion (will the universe expand forever, or will it stop expanding and collapse in a Big Crunch?). Thus, measuring the curvature of the universe in the past can be used to predict the expansion of the universe in the future.

The second use of distant galaxies is to probe for signs of evolution of galaxies and of the clustering of galaxies in the universe over the billions of years during which their light has been traveling to us. The notion is that a galaxy seen at an earlier stage in its life should have more gas available out of which to form new stars, and consequently it should appear brighter and bluer (when adjusted for redshift) because of the presence of many massive, hot young stars. A trend to bluer colors in fainter galaxies has been detected, and its detailed interpretation is a subject of active current research.

Normal nearby galaxies emit most of their light at visible wavelengths, but the light received from the most distant galaxies is redshifted to infrared wavelengths. In the past decade, detectors with high sensitivity have been developed that are ideal for measuring weak infrared radiation, and the main technical problem that remains is the strong emission of infrared radiation from the atmosphere and from the telescope itself. This problem is analogous to local interference in the CMBR measurements, and the solution is similar: go where it's cold, to the South Pole or out in space. Plans are well advanced to deploy a telescope at the South Pole to make deep-sky surveys at near-infrared wavelengths. This approach is less expensive than building space observatories, but it has the disadvantage of being restricted by the atmosphere to a relatively narrow spectral range. This effort in Antarctica is complemented by planned space missions such as the Space Infrared Telescope Facility (SIRTF), which will provide much more extensive coverage of the spectrum and will cover the whole sky. Space experiments have in fact already provided important results. For example, the intensity of the total infrared radiation from the sky has been accurately measured by the Diffuse Infrared Background Experiment aboard the COBE satellite. Much of this radiation is from the Milky Way, and identifying the cosmological component is a difficult task.

In the future, a main goal will be to image distant galaxies at the highest possible angular resolution, both with the HST and with ground-based techniques. The development of adaptive optics technology, which sharpens the view of ground-based telescopes, and its application to distant galaxy research will open a powerful new channel of information about the distant universe. The angular size of a typical distant galaxy is about the same as the size of the blurring caused by looking through Earth's atmosphere; hence almost all of the detail is scrambled. Sharp images of distant galaxies are important because they are a test of evolutionary models. For example, it is becoming increasingly clear that an important process in the early evolution of galaxies involves galaxies merging together, or at least strongly interacting with each other. If this idea is correct, astronomers expect to see more multiple, merging, and disturbed galaxies at high redshifts, when the frequency of this activity was higher. The first deep images of the universe coming from HST seem to bear this out. The HST image on the back cover is typical in showing many disturbed and interacting objects among the smaller, and thus presumably more distant, objects.

Evolution of Large-Scale Structure Back in Time

Since density fluctuations tend to grow, the amplitude of the density variations associated with the large-scale structure must have been smaller when the universe was younger. The unique capability of large telescopes to look deep into space corresponds to being able to look back in time—cosmologists can map the distant universe and see the galaxy distribution as it was billions of years ago. By comparing different depths in space, cosmologists can in effect "make a movie" of the developing structure. Successive scenes in the movie are first galaxy formation, then cluster formation, and finally superclustering today. Present optical and x-ray data hint strongly that clustering in the universe continues to grow rapidly, but these observations are still primitive. The evolution of galaxies and large-scale structure is a sensitive probe of alternative models of structure formation, but one that has been little utilized to date. With the completion of giant new optical telescopes (such as the Keck (Figure 5), the Gemini, and other large telescopes under construction), as well as the refurbishment of the HST with a new, advanced camera, progress in this important field should accelerate.

Looking all the way back to a time when the universe was only a quarter of its present age requires maximum light-gathering power since very distant galaxies must be observed. There are several requirements for such studies—the largest possible optical-infrared telescopes with wide fields of view; spectrographs capable of measuring many galaxies simultaneously; the largest possible optical CCDs and infrared array detectors; and deep surveys in other wavelengths, including radio and x-ray regions.

Supernovae, Quasars, and Absorption Line Systems: Probes for Cosmology

In a closed cosmological model (e.g., $q_0 \geq 0.5$, $\Lambda = 0$), space is positively curved and finite. A two-dimensional analog is the curved and finite surface of a sphere. In an open model, space is negatively curved and infinite. A two-dimensional analog is a hyperboloid, which is shaped like a saddle. At a given redshift, sources of the same intrinsic luminosity appear to be larger and brighter in a closed universe than in an open universe, because of the focusing effects of the curvature and the more rapid deceleration. Astronomers endeavor to identify and employ classes of bright sources of known or calculable luminosity as "standard candles." By measuring the apparent luminosity at various redshifts of these sources, cosmologists can determine whether the universe is closed or open. Supernova explosions provide sources of this kind because their intrinsic brightness is governed by the physics of the explosion, of which there is good theoretical understanding.

Quasars are star-like objects with large redshifts and inferred luminosities that are often hundreds of times those of normal galaxies.

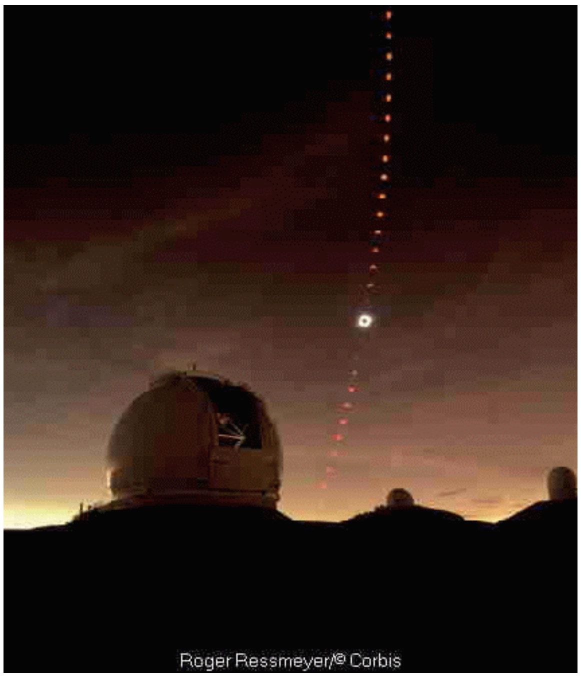


Figure 5. The first Keck telescope, atop Mauna Kea, Hawaii. This 10-m-diameter optical telescope is the first in a new generation and will be joined by the second Keck telescope.

They are thought to occur in the nuclei of galaxies, but the conditions required for a galaxy to harbor a quasar are not known. Quasars show strong evolution in the sense that they emitted much more energy at earlier cosmic epochs, but why this is so is also unknown. Moreover, the observed rapid variation in brightness of individual quasars is not understood. The task of understanding the nature and origin of quasars is still at the forefront of cosmological research.

Quasars can serve as background lamps against which absorption from intervening material can be detected spectroscopically. The material may be in the form of gas in galaxies (the galaxy itself may or may not be visible) or in the form of intergalactic clouds of gas that have never been processed through stars. The technique has exceptionally high sensitivity to small amounts of material, and so it provides a probe of the universe that is independent and complementary to that provided by visible galaxies. The change in the average number of absorbers as a function of redshift is an important diagnostic for understanding the evolution of these objects. Spectroscopic attributes of the absorbers can tell us about their physical properties as well as the intensity and spectrum of the intergalactic radiation falling on them.

These absorption studies have shown that the absorbing gas occurs in lumps, and that there is little neutral hydrogen in a smoothly distributed intergalactic medium. One explanation of this lack of neutral hydrogen is that, at some point, the entire universe was reionized—heated so hot that hydrogen atoms were broken up into their constituent protons and electrons. But if the universe was reionized, what were the heating agents and when did the reionization occur? On the other hand, if there was no epoch of reionization, what conditions yielded such high efficiency in clearing intergalactic space of neutral hydrogen? This field will be advanced with the further identification of close pairs of quasars to provide nearly coincident lines of sight, as well as the further identification of galaxies likely to be responsible for individual absorption systems. At present these absorption lines provide one of our only probes of nonluminous structure at high redshift. Continued theoretical as well as observational studies provide our best hope for an accurate picture of the intergalactic medium and its evolution.

Gravitational Lenses

What are gravitational lenses, and why are they important?

The gravitational lens is a relatively newly discovered phenomenon that is emerging as an important research tool in cosmology. Lensing can be produced when light propagating through the universe is deflected by the gravitational field of a massive object positioned near its path. Gravitational lensing effects are similar to those produced when a glass lens deflects the path of light rays in a camera, but the deflections are too small to be observed in a terrestrial laboratory. However, in 1979 the discovery of a double quasar, which was actually twin images of the same quasar, provided the first convincing demonstration that gravitational lensing produces observable effects in the cosmos.

Gravitational lensing has been observed in several forms. There are now approximately 20 known cases of strong lenses in which two or more images of a background source are produced by a foreground gravitational lens. This striking phenomenon is the most easily recognized, and early work in gravitational lensing concentrated on the study of strong lensing. Figure 6 shows an Einstein cross, a lens that produces four multiple images of a distant quasar with a central object. Another manifestation is weak lensing, in which background sources, though not multiply imaged, are visibly distorted by the presence of the intervening gravitational field (Figure 7). Changes in the gravitational field, produced for example by relative motion of the source and the lens, have been observed through the changes in the magnification of the source that produce variations in the source brightness. The multiple images found in strong lenses are associated with different propagation times from source to observer, and the resulting time delay between the arrival times of signals from each image has also been observed. In the best studied case, the measured time delay from one image to the other is approximately 1.5 years. Finally, the presence of a population of massive objects, such as galaxies, screening a population of background sources, such as quasars, produces lensing effects detectable through statistical analysis of the ellipticities of the lensed images.

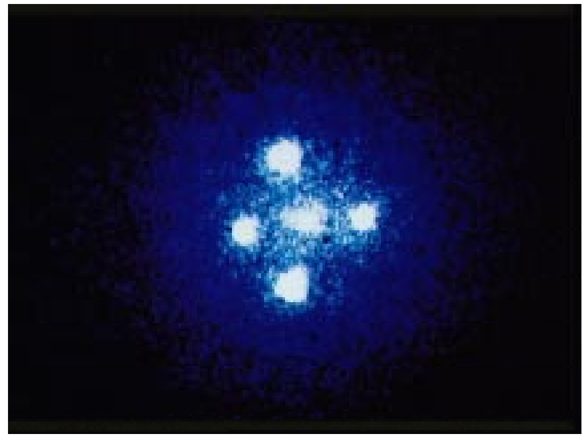


Figure 6. The image of an Einstein cross produced by a gravitational lens. A distant quasar is precisely aligned behind the foreground galaxy whose gravitational field deflects the light from the quasar into four distinct images. (Courtesy of the Space Telescope Science Institute.)

Gravitational lenses provide a unique opportunity to infer the properties of the space-time in which they are embedded, the mass distribution of the lens, and the detailed properties of the background source. These opportunities are being realized as instruments improve in angular resolution and sensitivity, as our data-handling capabilities grow, and as increased computational capacity can be applied to theoretical analyses of lenses.

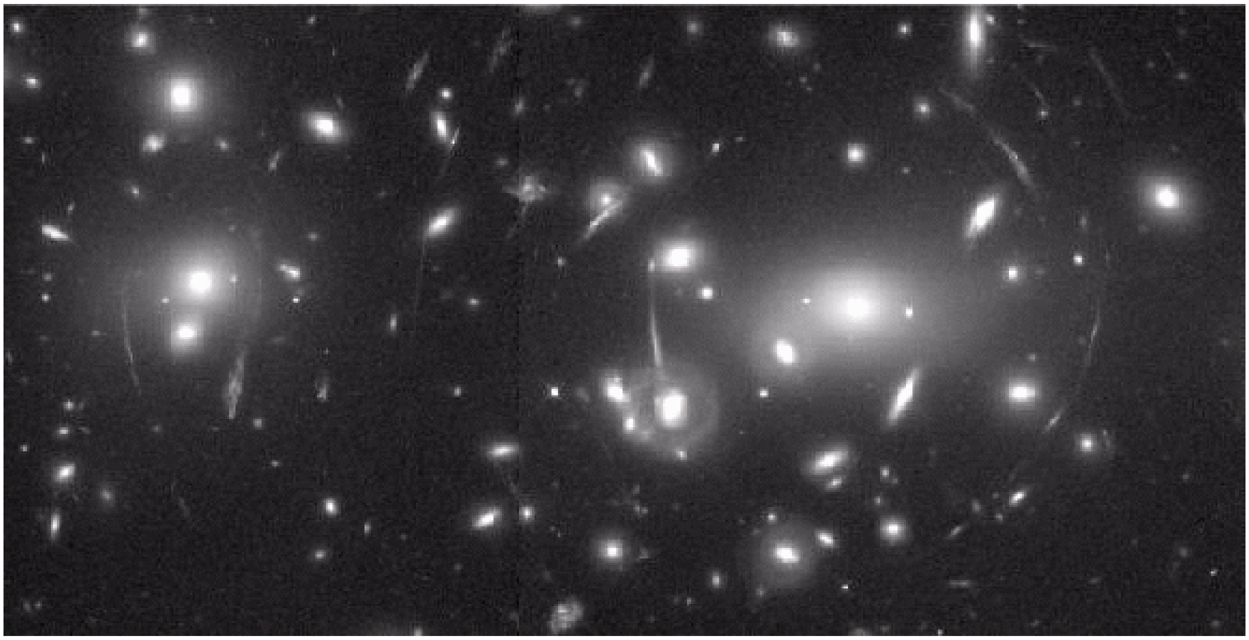


Figure 7. Gravitational lensing of distant background galaxies by the potential well of a foreground cluster of galaxies. The distinctive arcs are a result of strong lensing in which the images formed by the lens encircle the optical axis of the system. (Courtesy of Space Telescope Science Institute.)

Measuring cosmological parameters with gravitational lenses

Because the light rays in a gravitational lens system propagate across large distances, their interpretation is subject to assumptions about the cosmological model. Observations of gravitational lenses therefore provide a way to measure or constrain the cosmological parameters H_0, q_0, and Λ described above. The Hubble constant is most directly inferred through a measurement of the time delay in the arrival of signals from the multiple images of a strong gravitational lens. The success of this technique is predicated on a precise understanding of the distribution of the matter in the lens, which must be reconstructed purely from the properties of the images. The statistics of gravitational lenses provide a powerful technique for the determination of cosmological parameters. For example, the frequency of occurrence of gravitational lenses depends strongly on the geometry of the universe. A high-redshift quasar is twice as likely to be gravitationally lensed in a $q_0 = 0$ universe as in a $q_0 = 0.5$ universe. Similarly, a high-redshift quasar is about 15 times more likely to be strongly lensed in a flat universe if $\Lambda = 1$ than if $\Lambda = 0$. Current limits appear to preclude models in which the Λ term dominates the universe; improved constraints will be possible with improved imaging using the newly completed Very Long Baseline Array (VLBA), the HST, and ground-based optical telescopes equipped with adaptive optics systems.

Gravitational lensing, along with the spectroscopic absorption studies of intergalactic clouds, is one of the few techniques in cosmology in which our ability to detect the presence of matter does not require that the matter be luminous. Lensing can address the important issues of the nature and the distribution of dark matter on a wide range of scales. For example, the measurement of weak lensing, in which faint background galaxies would be expected to have correlated orientations due to the gravitational distortions induced by the foreground mass distribution, can be studied by careful analysis of high-quality images covering large fields of view. Recent theoretical analysis describes how this method can provide a solid measurement of the matter-clustering amplitude of the foreground mass distribution. Elongated images are more likely to occur near large concentrations of matter, such as clusters of galaxies, where several spectacular examples have already been observed (see Figure 7).

On small scales (stellar masses or smaller), the most effective technique is observation of microlensing, the variations in flux detected from a background source due to the focusing of rays caused by the passage of a massive object through the beam. By searching for microlensing events in the direction of nearby concentrations of stars, three separate research groups have found spectacular examples of large flux amplification (up to a factor of 14!). These events might imply that the dark matter comprising the halo of our galaxy is dominated by compact stars that were never sufficiently massive to ignite their nuclear furnaces and become luminous, or that there exist many more remnants of normal stars in an extended disk of our galaxy than had been anticipated. The time behavior of one well-documented microlensing event in the direction of the nearby Large Magellanic Cloud is shown in Figure 8.

The study of gravitational lensing has already provided important results in cosmology. Improved instrumentation and data-handling techniques are allowing astrophysicists to recognize and exploit subtle manifestations of gravitational lensing, as well as the striking examples of strong lensing. With the planned capabilities of future generations of instruments, and the growing interest in gravitational lensing as an observational tool, it is likely that this trend will continue.

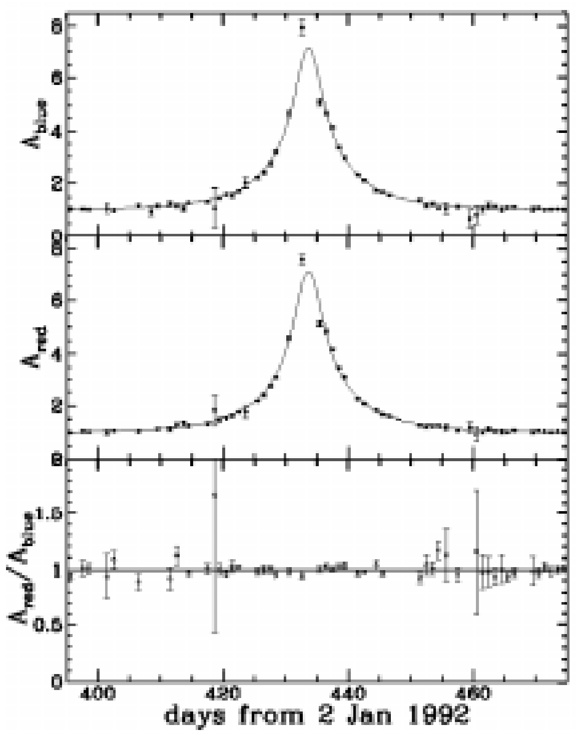


Figure 8. The first well-documented microlensing event, detected when a faint object of approximately 0.1 solar mass crossed very close to the line of sight between Earth and a star in the Large Magellanic Cloud (LMC). The gravitational lensing caused by the object has focused and intensified the light detected from an LMC star in the background, causing the peak in the brightness at both blue (A_{blue}) and red (A_{red}) wavelengths recorded as a function of time. (Courtesy of Charles Alcock for the MACHO Project.)

V. PHYSICS OF THE EARLY UNIVERSE

In contrast to the observational studies of the CMBR, galaxies, and large-scale structure, the field of the physics of the early universe involves concepts that are less familiar, more theoretical, and more daunting. A little background, supplementary to the sidebars, is helpful.

As described in the sidebars (pp. 5 and 8), the universe is cooling and decreasing in density as it expands. Since temperature is simply a measure of mean energy per particle, the energy available for particle interactions is also declining. If we imagine running the universe's clock backward toward zero, before the first 100 seconds, the CMBR would be blindingly hot and energetic, and more and more energetic events would become possible, including the creation of multitudes of elementary particles that are not stable at the present energy density of the universe.

An important concept of modern physics is the phase transition, the idea that the nature of the interactions of particles can change with available energy. The freezing and boiling of water are familiar examples of phase transitions. In the early universe, the nature of physical law itself is thought to have undergone a series of phase transitions, with enormous consequences for the physics of that era. The history of the early universe and the laws of physics are intimately intertwined—each one can be illuminated by studying the other. Moreover, energies in the Big Bang reached up to 10^{14} times higher than any conceivable terrestrial accelerator, and these energies probe realms that are inaccessible to our laboratory experiments. For this reason the Big Bang is sometimes called the "poor man's particle accelerator."

The aim of early-universe cosmology is to trace the successive transitions of forces and particles from the earliest, fiercely hot moments of the Big Bang to the epoch of atom formation at 4,000 K (see section II on the cosmic microwave background radiation). Along the way, at certain critical temperatures, precipitous changes in the state of the universe occurred. Some of these changes have observable consequences, called relics, that persist to this day and provide key tests of models. Some of these relics—the ratio of photons to atoms and the nature of the large-scale fluctuations in the matter distribution as detected by the COBE satellite and studies of large-scale structure—are discussed above. Other fundamental questions, such as why the universe is homogeneous on the largest scales, and what is the nature of dark matter, also appear to have their answers in the physics of the early universe.

The sidebar "The Early Universe" (p. 8) treats the first 100 seconds after the Big Bang. During this period, the universe was opaque to all forms of electromagnetic radiation, and so astronomers cannot make direct observations of the events at these early times. Nevertheless, important experimental and observational information can be obtained that leads to reasonable physical inferences about events and conditions during this period. Progress in the study of the early universe has been spectacular in recent years.

The earliest state of the universe that can be addressed by physical theories is called the quantum gravity era (see sidebar, "The Cosmic Picture," p. 5), because during that era the temperature and density of the universe were so high that gravity must be described by a quantum field theory of some kind. The four forces of nature (gravity, the weak force of radioactive decay, electromagnetism, and the strong nuclear force) were probably completely unified during this era, and space and time could not be differentiated. After this almost unimaginably remote epoch, the universe cooled sufficiently for gravity to be described by Einstein's general relativity theory, but the temperature was still sufficiently high that the other three forces of nature remained unified (the grand unification era). Many theorists believe the phase transition that marked the end of the grand unification era was followed by a period of inflation. (Inflation is discussed below.)

As time progressed and the universe cooled further, additional phase transitions occurred, such as the end of the symmetry between weak interactions and electromagnetic interactions and the transition from free quarks to quarks bound into hadrons. (Protons and neutrons are the most familiar example of hadrons.)

At very high temperatures quantum interactions create and destroy particles, leading to an equilibrium in the number density of each particle type. However, particle interaction rates depend on temperature, and as the universe cooled, interactions occurred less frequently. When an interaction rate became small relative to the expansion rate of the universe, the equilibrating process effectively ended. The abundances of the reacting particles were thereafter fixed. Although the expansion rate of the universe slowed as it became cooler and less dense, particle interaction rates decreased even more rapidly.

Although the abundance of atoms relative to photons is likely to be a relic from an earlier, hotter epoch whose physics is not yet well understood, the conditions that existed when the universe was 1 second old can now be explored in the high-energy physics laboratory. Cosmologists are therefore more confident in their modeling of the constituents and the physical processes at work. For example, by the time the universe was 1 second old, it had cooled and expanded to the point where neutrinos, whose weak interaction with other matter decreases as a function of temperature, effectively ceased interacting with matter. This change acted to stabilize the ratio of neutrons to protons. With further cooling, positrons (antielectrons) annihilated most of the electrons, and neutrons quickly attached to the protons, forming all the deuterium (an atomic nucleus consisting of one proton and one neutron) and most of the helium now present in the universe.

Thus, many interactions that were close to thermal equilibrium in the early universe later froze out at a predictable epoch, and left relics, some of which survive to the present day (see Table 1). One example is the abundance of primordial helium and deuterium, discussed in more detail below.

Primordial Nucleosynthesis and Dark Matter

Along with the Hubble expansion and the cosmic microwave background radiation, one of the pillars of the Big Bang theory is its successful prediction of the abundances of the light elements deuterium, helium, and lithium. The Big Bang theory says that when the universe was about 1 second old and had a temperature of 10^{10} K, nuclear processes should have started that eventually yielded certain well-specified abundances for these light elements (see Table 1). The abundances of these light elements have all been found to be in agreement with the predictions of Big Bang theory within the accuracy of the measurements. Even the abundance of lithium relative to hydrogen, predicted to be 1 part in 10 billion, matches the observations. Furthermore, the Big Bang theory predicts that the abundances will fit well only if there are no more than three families of neutrinos—a condition that was confirmed recently at the Large Electron-Positron (LEP) Collider in Geneva, Switzerland. Thus, the Big Bang theory's detailed predictions, even though they are based on the nature of the universe when it was only 1 second old, have been confirmed by observations and experiments.

The light elements shown in Table 1, with abundances ranging from about 23 percent for helium to 1 part in 10^{10} for lithium, all fit with the Big Bang theoretical predictions on one condition—that the one adjustable parameter of the theory, Ω_B (the ratio of the mean density of ordinary matter (baryons) to the critical density in the universe), has a value between 0.01 and 0.1. The nucleosynthesis calculations thus imply either that (1) the total density of the universe is much less than the critical density and it will never stop expanding, or (2) the dominant component of the universe is not ordinary (baryonic) matter.

Table 1. Observed Relic Values

Relic	When Measured	Observed Values
^{1}H (Hydrogen)	1960s	~76% by mass
^{2}H (Deuterium)	1970s	$>1.8 \times 10^{-5}$ relative to hydrogen
^{3}He (Helium-3)	1970s	$<6 \times 10^{-5}$ relative to hydrogen
^{4}He (Helium-4)	1960s	~23±1% by mass
^{7}Li (Lithium-7)	1980s	$1.5\pm0.5 \times 10^{-10}$ relative to hydrogen
Number of neutrino families	1990	$N_\nu = 2.99\pm0.02$

The value of Ω_B predicted by primordial nucleosynthesis can be compared to that observed in the universe. The mass density of luminous material in stars and galaxies is small, $\Omega_{visible} < 0.01$, while the hot gas in galaxy clusters, which astronomers can detect by its x-ray emission, contributes perhaps $\Omega_{gas} \sim 0.03$. The sum of these values lies in the range consistent with primordial nucleosynthesis. At the same time, dynamical models based on the relative motions of galaxies, and the way spiral galaxies rotate, argue that galaxies have more mass than is seen in their detected stars and gas. These dynamical arguments imply that each galaxy has an invisible halo of dark matter that is about 10 times the visible mass. Moreover, consideration of large-scale flows seems to indicate a still larger amount of dark matter on scales much larger than single galaxies. Perhaps there is even enough to be consistent with a total matter density of $\Omega \sim 1$, or at least $\Omega > \Omega_B$. This implies that there must exist some unknown form of matter that dominates the mass density of the universe—an awkward situation for cosmologists.

There are other theoretical reasons to expect that $\Omega = 1$, or in other words that the total mass density is exactly equal to the critical value that just closes the universe. Ω is an unstable quantity in an expanding universe. If Ω is below 1 it will rapidly become much less than 1 as expansion proceeds. Conversely, if Ω is greater than 1, it will grow to values much greater than 1. Only if $\Omega = 1$ does it stay at 1; all other values diverge to either zero or infinity. A finite, non-zero value of Ω today, other than $\Omega = 1$, implies that it must have been extremely close to 1 at the beginning of the universe. Cosmologists have puzzled over this fine-tuning problem for decades, but just in the past decade or so, considerations of the early universe have motivated a sensible resolution to this question—inflation.

Epoch of Inflation and Grand Unified Theories of Matter

After the Big Bang, the temperature of the early universe was so high that the four fundamental forces of nature are believed to have been merged. In the grand unification era that followed, the grand unified theory (GUT) predicts that all the forces except gravity were of equal strength. Modern theories of these forces involve a concept known as symmetry breaking, in which the lowest-energy state (the vacuum) is not symmetric at the low temperatures of the present universe. As time progressed, the temperature decreased, and the vacuum underwent a phase transition from a symmetric state of higher energy. The higher energy of the “false vacuum” can in principle act like a non-zero cosmological constant, $\Lambda \neq 0$, which, according to Einstein’s general relativity theory, can drive an extremely rapid, accelerating expansion of the universe. This expansion is called inflation (see “Measuring the

Cosmological Parameters" in section IV) and is supposed to have occurred in the first instants after the creation of the universe (see pp. 5-8). In a very short time (10^{-32} s), the early universe may have expanded by a greater factor than it has in the billions of years since. Thus, inflation is intimately connected with our understanding of elementary-particle physics.

Inflation beautifully explains three long-standing problems of cosmology. In the normal theory, regions of space separated by a distance greater than the distance light has traveled in the time since the Big Bang are effectively disconnected from each other. In traditional, non-inflationary models, there is no reason for such regions to be similar. For example, since disconnected regions can never have exchanged energy, why should they be at exactly the same temperature? Energy exchange between nearby regions could result in small patches with uniform temperature, but CMBR measurements tell us that large regions are nearly equal in temperature. Because inflation can quickly expand an extremely tiny volume into a vastly larger region of space, it would allow a small, uniform patch to expand to cover our entire observable universe, leading to a nearly uniform temperature for the CMBR.

At the same time, there must remain some minimum level of bumpiness even in the uniform patches, because quantum mechanics and the uncertainty principle require it. Inflation magnifies these tiny fluctuations into the CMBR anisotropy that astronomers see today and the large-scale structure of matter in the universe. Indeed, the variation in amplitude of fluctuations of different angular size is consistent with the expectations of the inflationary model. Inflation takes microscopic quantum noise and blows it up to create the seeds of galaxies and large-scale structure.

A third advantage of inflation is that it forces the spatial curvature of the universe to be negligibly small on a cosmological scale so that space is flat (i.e., euclidean geometry applies). This flatness is a direct consequence of the tremendous expansion expected during inflation. A small closed surface such as a balloon has an obvious curvature, but if expanded to the size of Earth, its curvature is much less apparent. The absence of curvature in an inflationary universe would imply that today, the density parameter Ω should be close to unity. Thus, an inflationary phase in the early universe naturally solves the fine-tuning problem mentioned above.

The panel emphasizes that inflation is an idea, not a complete or well-tested physical theory. In addition to the original version described here, many different variants have been presented, some with inflation occurring during the quantum gravity era, others with inflation occurring much later, each driven by different mechanisms. Although our understanding of particle physics is incomplete at these energies, and we have no understanding of the details of the inflationary epoch, inflation is an attractive concept because of its ability to resolve several long-standing cosmological conundrums. Many cosmologists are convinced that such an episode must have occurred.

Particle Theory and Dark Matter Candidates

Astronomers have found strong evidence for a major dark matter component of the universe; the visible matter does not add up to the total amount of matter measured by dynamical means. Could the dark matter be ordinary baryonic matter in a form that doesn't shine—perhaps brown dwarf stars, black holes, or hot intergalactic gas? Apparently not, according to the calculations of primordial nucleosynthesis, which work only if the density of baryons is less than 0.1 of the critical value ($\Omega_B < 0.1$). Thus the bulk of the dark matter must be composed of an unknown form of matter. What could it be? Particle physics has some candidates that are discussed below, and the astronomical behavior of dark matter offers some clues. Observations show that the dark matter is much less clumped than the visible matter. Therefore, the two kinds must interact only weakly, mainly via the gravitational force. Computer simulations of the formation of large-scale structure also provide valuable information about the behavior of the dark matter, which plays an important role in shaping the structure. These studies show that the non-baryonic dark matter candidates can be divided into two categories depending on the velocity with which the particles were moving when the universe became dominated by matter (see pp. 5-8). During this epoch, a rapidly moving particle (e.g., because its mass is small) is considered hot dark matter; a slowly moving particle is considered cold dark matter. Currently, the cold dark matter candidates, or a mixture of hot and cold, give the best agreement between computer simulation results and the observed large-scale structure.

Most cosmologists believe that the unknown matter needed to explain the "missing mass" exists in the form of some yet-undetected elementary particle—a particle that is fundamentally different from ordinary matter. Such a particle would be a relic of some process in the high-energy-physics era, but whether from the grand unification era or some later era is not known. Clearly, it is important to identify this non-baryonic dark matter, by direct searches and by accelerator experiments, with particle theory providing guidance to focus the experiments. Chief among the theoretical elementary-particle candidates for non-baryonic dark matter are weakly interacting massive particles (WIMPs), axions, and neutrinos with finite mass. Of these, only neutrinos are known to exist, but they are usually assumed to have zero mass. The experimental upper limit for the electron neutrino mass is about 7 electron-volts (eV; the mass of the electron is about 511,000 eV). A sea of primordial neutrinos with this mass would provide sufficient dark mass to make $\Omega = 1$. However, neutrino dark matter would be hot and so does not work well by itself in computer simulations of the observed large-scale structure. Another class of phenomena from particle physics, called cosmic strings or textures, can be added to act as seeds for cosmic structure, or some cold dark matter (e.g., axions) can be added to make the results look more like the observations.

The most likely dark matter candidates from particle theory are added to a mix of ordinary matter and thermal radiation in a gigantic computer model that simulates the complex physics of an expanding universe that contains collapsing clumps of matter. These simulations are complex and difficult to do. The goal is to find a set of parameters and values that produces a simulation with clumps that have a large-scale structure much like that seen by astronomers. Another approach to identifying the dark matter particles is to search for them directly with techniques drawn from experimental particle physics.

WIMPs

There are good theoretical and experimental reasons to suspect that a new symmetry exists in nature, known as supersymmetry, which might enable gravity to be unified with the weak, electromagnetic, and strong forces. If supersymmetry exists, then every fundamental particle of ordinary matter and radiation has a supersymmetric partner particle, as yet undetected. The lightest supersymmetric particle cannot decay (because there are no lighter particles to decay into) and would therefore have survived from the time of the early universe until now. Such a particle's interactions with ordinary matter would be very weak, and current accelerator experiments tell us that the mass of the lightest supersymmetric particle is greater than 20 GeV (billion electron-volts; the mass of the proton is about 1 GeV)—massive for an elementary particle. Thus WIMPs make an ideal candidate for non-baryonic dark matter in the universe. They are imagined to be only weakly associated with luminous matter, for example, forming a loosely bound halo around our galaxy and others.

Laboratory detectors are now under construction in several countries to look for a flux of WIMPs with mass in the range from 5 to 100 GeV. Early results from conventional detectors have already set useful limits on the flux of WIMPs, and new efforts are starting based on entirely new cryogenic detectors. If WIMPs form a halo around our galaxy, then they constantly bombard Earth, but only rarely would a WIMP interact with an atom. Searches for WIMPs are conducted by measuring the recoil energy expected from the occasional collision between a WIMP and the nucleus of an atom in the detector. The experiments are extraordinarily difficult because the expected event rate for WIMP interactions is very low, somewhere between 0.001 to 1 event per kilogram of detector per day. Furthermore, the energy deposited in the detector for each event is small. However, the biggest problem in these experiments is the confusion generated by similar signals coming from natural radioactivity and cosmic rays. The experiments are therefore conducted deep underground to greatly reduce the cosmic ray flux and use extremely pure materials to minimize radioactive contamination. Like all direct searches for dark matter, these are high-risk experiments because of their technological challenges and because of the absence of precise predictions for the mass and the behavior of the WIMP candidates. But they are also experiments with potentially huge payoffs—understanding the missing mass and opening a new chapter in particle physics.

Axions

The axion is an unusual particle whose existence has been postulated for reasons related to charge-parity (CP) conservation, a symmetry of the strong interaction in elementary-particle physics. If axions actually exist, they do not behave like most particles, which move independently and randomly with different directions and energies. Instead, axions are expected to move coherently, behaving more like a slowly moving sea of particles. Theory allows only a narrow range of possible masses for the axion, near 10^{-5} eV—the opposite extreme from the possible mass for WIMPs. Nevertheless, if the axion exists with this mass, its total cosmological mass density could still dominate the universe.

Dark matter axions could be detected based on the prediction that axions can change into photons in a strong magnetic field. If tuned to the proper frequency, a microwave cavity embedded in a strong magnetic field appears to spontaneously produce electromagnetic energy, or photons. Axion-induced oscillations would occur only in a narrow frequency range. By tuning the cavity to different frequencies a range of possible axion masses could be scanned. Two prototype detectors have been built, and results from these experiments are expected in the next few years. If the axion is detected, it will be a triumph of experimental ingenuity and the verification of a remarkable theoretical concept.

Neutrinos

In the early universe, neutrinos were as abundant as any other particle species. Although neutrinos ceased to interact significantly with other matter when the universe was only 1 second old, they have not disappeared, and today neutrinos are believed to make up a background sea of radiation similar to the CMBR. Because neutrinos are so abundant (100 per cubic centimeter, on average), they would dominate the mass density of the universe if they had even a little mass. Neutrino masses can be probed by accelerator experiments looking for one species of neutrino spontaneously changing into another species. The rate of transformation depends on the difference in mass between the species. Sensitive experiments of this sort are under way at the Fermi, Brookhaven, and Los Alamos national laboratories, and at CERN.

There is also an astrophysical method for measuring the masses of neutrinos. When a massive star explodes as a supernova, 99 percent of its energy is carried away by neutrinos. The neutrinos are predicted to be emitted in a brief, intense pulse. Measuring the amount that the pulse has spread out when it arrives at Earth allows estimation of limits on the masses of the neutrinos. This method was pioneered by two underground experiments that detected the neutrino pulse from the 1987 supernova in the Large Magellanic Cloud. A supernova in our own galaxy could provide enough data to make a much better measurement of neutrino mass if detectors were operating when it occurred. A future supernova closer to Earth might yield a sufficient flux of neutrinos of all species, so that estimates or improved limits on the masses of different species of neutrinos could be inferred. It is important that the detectors be ready when the next supernova in the Milky Way occurs, given that the previous one was recorded 400 years ago, and opportunities for observing such events occur only rarely.

Summary of the Study of the Early Universe

The success of the Big Bang theory of nucleosynthesis gives reason to hope that particle physicists and cosmologists can reach even farther back into the early universe with theories and experiments. The key tasks are to extend our knowledge of physics at the highest energies and to find self-consistent explanations of all of the phenomena astronomers see in the universe today. The abundances of the light elements, CMBR fluctuations, the composition and structure of matter, and the homogeneity and geometry of today's universe are examples of observable phenomena that have roots in the early universe. To study these and other relics of the Big Bang, astronomers and physicists use traditional optical and radio telescopes and particle accelerators. A wide variety of special-purpose instruments are also in use, such as underground dark matter detectors and small microwave radiometers on balloons and at the South Pole. The essential strategy comes mostly from theorists working at the boundary of particle physics, nuclear physics, and astrophysics—in the emerging field of particle astrophysics.

In the past decade much common ground has been found between the physics of the very small (elementary particles) and the physics of the very large (cosmology). The early universe offers the particle theorist the ultimate laboratory for testing exotic theories of unification and high-energy phenomena. The concepts of particle theory offer the cosmologist physical explanations for the origins of otherwise mysterious phenomena such as the fine-tuning problem ($\Omega \approx 1$), the source of the fluctuations that gave rise to large-scale structure in the universe, and the nature of the dark matter. Identification of the missing dark matter and the testing of the concept of inflation are the major challenges ahead.

VI. CONCLUSION

Cosmologists work to better understand the contents, structure, and evolution of the universe over vast stretches of space and time and over enormous ranges of density, temperature, and energy. Theorists, observers, and experimenters use a diverse assortment of techniques and instruments to answer questions of the most fundamental kind. Progress over the past three decades, but especially since the maturing of space science, has been astonishing. Recent observational results from the COBE satellite have revolutionized how cosmologists think about structure in the universe, and current efforts to map the fluctuations in the CMBR on smaller angular scales promise to show us details of the thermal history of the universe and to measure its fundamental parameters. Observations of large-scale structure in the universe as measured by the galaxy distribution have made dramatic progress in recent years, challenging all available theoretical models. Our knowledge of large-scale flows is still incomplete, but, when the work is finished, cosmologists will be much closer to understanding the role of dark matter in the universe. The new generation of giant telescopes such as the 10-m Keck are making remarkable observations, and the Keck, along with its newly constructed twin and the two 8-m Gemini telescopes, will enable study of the distant universe in ways never before conceivable. The HST has already made seminal contributions, including a measurement of the Hubble constant that gives the universe a surprisingly young age. We expect dramatic advances in our understanding of galaxy and large-scale structure evolution, as well as new tests of global curvature, to emerge from these studies in the coming decade. We still have no clear idea of the nature of the ubiquitous dark matter, but it is almost certainly a remnant of the early universe. Several experiments are under way to detect, or eliminate, candidates for this dark matter, and these will make substantial progress in the coming decade.

The problems of cosmology are particularly well posed, but many of the solutions have remained elusive for decades. At last, with the accelerating influx of new data from numerous advanced experimental and theoretical techniques, fundamental questions about the nature of our physical world are beginning to be answered. Cosmologists eagerly await the exciting new insights that will surely come in the next decade. If another briefing on cosmology is written 10 years from now, it will undoubtedly bear little resemblance to this one.

GLOSSARY

Λ: The cosmological constant, which measures the energy density of a vacuum.

Ω: The ratio of the average total density of matter to the critical density required to close the universe and eventually stop its expansion. Ω can be broken down into its components according to the type of matter involved.

Ω_B: The ratio of the mean density of baryons to the critical density required to close the universe.

Anisotropy: Variation with direction.

Axion: A hypothetical elementary particle whose existence might explain certain particle physics experiments. A candidate for cold dark matter.

Baryon: A massive, strongly interacting elementary particle, such as a proton or a neutron.

Baryonic matter: Ordinary matter as we know it consists largely of baryons, as opposed to hypothetical matter that might theoretically exist. Both kinds have mass, and either kind can be dark matter.

Big Bang theory: The theory that the universe began with all matter and energy concentrated to very high density and temperature some 15 billion years ago. The present universe expanded from that epoch and is still expanding. In the hot Big Bang theory, the ratio of photons to atoms is large, say $\sim 10^9$, as astronomers now observe.

Black hole: An object that has become so dense that, through the effects of general relativity, its contents are no longer accessible to the outside universe. No light from the surface can escape to the outside, hence the term "black."

Brown dwarf: A hypothetical star not sufficiently massive to ignite hydrogen burning, with mass less than 10 percent of the mass of the Sun.

CCD: Charge-coupled device. An electronic image detector used in modern video cameras and astronomical instruments.

CERN: The European Laboratory for Particle Physics.

Closed universe: A universe expanding slowly enough to be braked by gravity. In this case, $\Omega \geq 1$. If $\Omega > 1$ (above critical density), the universe will eventually recollapse. If $\Omega = 1$ (at critical density), the universe will expand forever, but ever more slowly.

Cluster: An assemblage of many galaxies.

CMBR: Cosmic microwave background radiation.

COBE: The Cosmic Background Explorer satellite.

Cosmic remnant: A product of a primordial physical process. The cosmic microwave background radiation is a cosmic remnant.

Cosmic velocity flow: Alterations in the regular movement of celestial objects away from each other caused by the gravitational attraction of other nearby objects. These flows give an indication of total mass, both luminous and nonluminous.

Cosmology: The study of the contents, structure, and evolution of the universe from the beginning of time to the infinite future.

CP: Charge-parity conservation. The symmetry of properties under a reflection in space and reversal of charge.

Critical density: The density of matter that would just halt the expansion of the universe. The dividing line between a collapsing and an ever-expanding universe.

Dark matter: Matter that does not emit enough light or other radiation to be observed directly. Most of the matter in the universe is believed to be of this type. Cold dark matter had a low velocity compared to the speed of light during the epoch of recombination. An example would be elementary particles with mass about equal to that of a proton or higher. Hot dark matter had a high velocity (near the speed of light) during the epoch of recombination. An example would be light elementary particles.

Epoch: A period characterized by the dominance of a particular physical process, such as the formation of the light elements from protons and neutrons.

Epoch of photon decoupling: See epoch of recombination.

Epoch of recombination: The time when electrons and nuclei were combining to form atoms and the universe was 1,600 times smaller than its present size. Also called the epoch of photon decoupling and the epoch of atom formation.

eV: An electron-volt, a measure of energy equal to that gained by an electron passing through a potential difference of 1 volt. Also a unit of particle mass. Electrons have a mass of about 0.511 MeV (million electron-volts); protons have a mass of about 938 GeV (billion electron-volts).

Flat universe: A universe where space is euclidean (zero curvature). If $\Lambda = 0$, a flat universe has $\Omega = 1$. If Λ is non-zero, then $\Lambda + \Omega = 1$.

Forces of nature: The four basic forces of physics: gravity, electromagnetism, and the weak and strong interactions.

Freeze-out: The disequilibrium by which relics are formed in the universe.

Galaxy: A large assemblage of stars. Our own galaxy, the Milky Way, contains 10^{11} stars.

Grand unification era: The era when the universe cooled sufficiently for gravity to be described by Einstein's general relativity theory, but where the temperature was still sufficiently high that the other remaining three forces of nature remained unified.

Grand unified theories: Theories that combine the strong, electromagnetic, and weak interactions into one unified theory.

Gravitational instability: The process whereby a small lump in an expanding universe can grow under gravity, pulling in surrounding matter and ultimately collapsing to form an object like a galaxy or cluster of galaxies.

Gravitational lens: A celestial object that distorts the image of another object behind it by virtue of the fact that its gravity affects the propagation of the light from the background object.

H_0: The Hubble constant. A measure of the expansion rate and age of the universe.

Hadron: A strongly interacting particle such as a proton or neutron.

Halo: The matter surrounding a galaxy.

Horizon: Edge of the portion of the universe visible to us. Light signals from beyond this point have not had time to reach Earth yet.

HST: Hubble Space Telescope.

Hubble's law: The principle that any two distant celestial objects (e.g., galaxies) move away from each other at a speed that is proportional to the distance between them, due to the homogenous expansion of space.

Inflation: A rapid expansion appearing as an early phase in some cosmological models, which solves several problems of cosmology.

Infrared: Light of wavelength longer than the reddest part of the visible spectrum.

Intergalactic medium: The material between galaxies.

Ionized: Under terrestrial conditions, most matter has an equal amount of positive and negative charge, so that its net charge is zero. At high temperatures, the charges separate in a process called ionization.

IRAS: The NASA, British, and Dutch Infrared Astronomy Satellite, which was flown in 1983.

Keck telescopes: The two new, state-of-the-art ground-based 10-meter optical telescopes located on Mauna Kea, Hawaii.

LEP: The Large Electron-Positron Collider. A particle accelerator at CERN.

Leptons: A class of elementary particles including electrons, muons, and tauons.

Microlensing: If a small, dark body is directly in the line of sight to a bright background star, the brightness of the background star may appear to increase because of bending of the light rays by the dark body.

Neutrinos: Very light (possibly massless) particles that are emitted in the process of radioactive decay. There are three species, associated with electrons, muons, and tau-leptons. They interact with ordinary matter through the weak force.

Nucleosynthesis: The process by which the elements are built up from protons and neutrons.

Open universe: A universe expanding faster than the retarding pull of gravity. It has less than critical density, $\Omega < 1$, and expands forever.

Planck time: The period of time immediately after the creation of the universe (10^{-43} s) during which quantum gravity is the principal phenomenon governing the evolution of the universe.

q_0: The deceleration rate for the expansion of the universe, which is related to the curvature of space.

Quarks: The elementary constituents of hadrons or baryons (such as protons and neutrons).

Quasar: An object with a large redshift and an inferred luminosity often hundreds of times that of a normal galaxy.

Redshift: The shifting of light toward the red end of the spectrum that occurs when the observed light source is receding from the observer.

SIRTF: Space Infrared Telescope Facility. A proposed orbiting infrared telescope.

Standard candle: A celestial object whose intrinsic brightness is known or can be estimated by some physical principle and whose observed brightness is therefore useful as a tool to measure distance.

Supersymmetry: A space-time symmetry that would imply the existence of partners to all elementary particles, with quantum spins of one-half a unit higher or lower. Often used in constructing theories that unify gravity with the three other forces.

Thermal spectrum: The characteristic distribution of radiation as a function of frequency that is emitted by a body at a well-defined temperature, also called a black-body spectrum.

Tully-Fisher relation: A method to determine galactic distances. Big, luminous galaxies rotate faster than small, faint ones. The connection between the two is given by the Tully-Fisher relation.

Unification: The concept that two or more forces that seem distinct in today's universe could, at higher energies (or temperature), merge to become one force.

Universe: All of space and time taken together.

VLA: The Very Large Array. An array of 27 radio telescopes in New Mexico, capable of adjustable spacing along a Y-shaped track, up to a radius of 27 km.

VLBA: Very Long Baseline Array. A newly completed radio interferometer operated by the National Radio Astronomy Observatory. Capable of producing images with angular resolution of one thousandth of a second of arc.

Weak interactions: The interactions of elementary particles that are responsible for radioactive decay.

WIMP: Weakly Interacting Massive Particle. A candidate for dark matter.

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