by MICHAEL S. TURNER

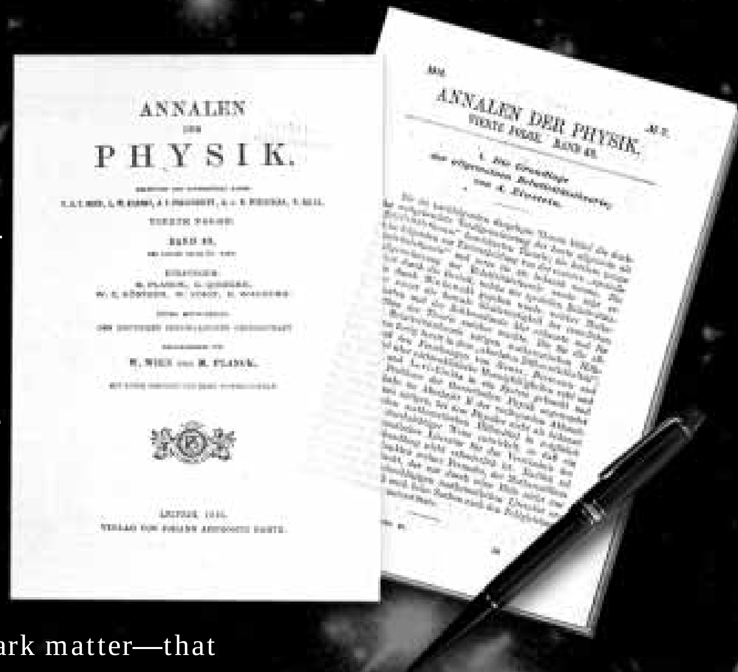
INNER SPACE & OUTER SPACE

Cosmology is in the midst of a Golden Age triggered in part by ideas about the earliest moments of the Universe based upon the unification of the forces and particles of Nature.

COSMOLOGISTS TACKLE the big questions. What is the size and shape of the Universe? What is it made of? How did it all begin? How will it all end? Not surprisingly, progress has come in fits and starts. Sometimes it is a key event that advances our understanding. For example, Edwin Hubble's discovery of the expansion of the Universe in 1929 was the first indication that it began from a Big Bang, and Arno Penzias and Robert Wilson's happening upon the microwave echo of the big bang in 1964 established that the beginning was very hot and dense. Other times conceptual breakthroughs have advanced cosmology, such as Albert Einstein's introduction of the General Theory of Relativity in 1916 which allowed the first mathematical description of the Universe, and George Gamow's late 1940s suggestion that the early Universe was a nuclear furnace that "cooked" the periodic table of elements, which was the first application of physics to the study of its origin and evolution.

Golden ages usually come at the conjunction of conceptual and observational advances. Cosmology is in the midst of such an age today. The conceptual breakthrough came in the 1980s with the realization that unified particle theories have important consequences for the earliest moments and may be

Computer event simulation courtesy David Brown, University of Louisville



crucial to answering some of the most pressing questions in cosmology. And furthermore, particle accelerators are a new kind of telescope that allow the recreation of the earliest moments in the collisions of very high-energy particles. The inner space/outer space connection has led to a remarkable extension of the Big Bang model which, if correct, will extend our understanding of the Universe to within 10^{-32} sec of the beginning. This paradigm, known as inflation and cold dark matter, holds that the bulk of the matter in the Universe exists in the form of slowly moving elementary particles—cold dark matter—that remain from the earliest moments and that all the structures we see in the Universe—galaxies, clusters of galaxies, superclusters, voids, great walls and so on—grew from quantum mechanical fluctuations occurring on the subatomic scales.

On the observational side, we are in the midst of a technological revolution that can be traced back to the commissioning of the 200-inch Hale telescope on Mt. Palomar in 1948, which allowed cosmological pioneers Hubble, Milton Humason, and Allan Sandage to begin the serious study of the Universe. The introduction of charge-coupled devices in astronomy in the 1970s increased the light-gathering power of photon detectors a hundredfold, making the Hale the equivalent of a 2000-inch telescope. The increase in computer power over the past forty years by truly astronomical factors was equally crucial. New windows on the Universe were opened with space-based telescopes for the ultraviolet, infrared, X-ray, and gamma-ray bands as well as the first optical telescope above Earth's blurring atmosphere. Other new instruments were developed: long-baseline radio interferometers with milliarcsecond resolution, the 10-meter Keck telescopes with their advanced instruments, and sensitive receivers using high electron mobility transistors and bolometers to study the microwave remnant of the Big Bang.

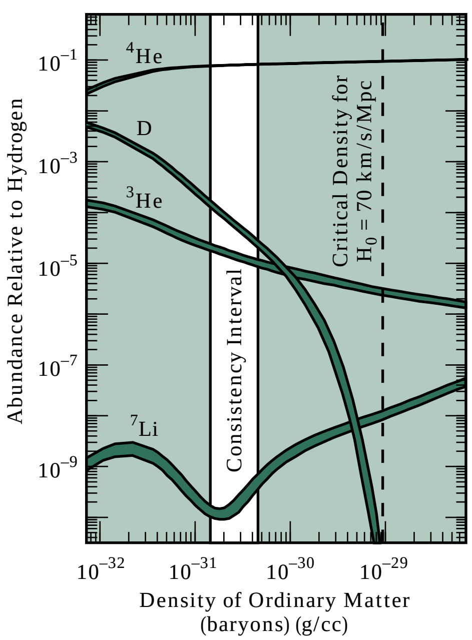
This issue of the *Beam Line* illustrates well the close relationship between particle physics and cosmology that has developed over the past two decades. All the articles relate to testing inflation and cold dark matter. Many of the protagonists (and authors) started their

The main ring of the world's most powerful accelerator, Fermilab's Tevatron. Collisions recreate conditions that last existed 10^{-12} seconds after the Big Bang. (Courtesy Fermilab Visual Media Services)

careers as high-energy physicists. Alan Guth, author of the article on inflation and inventor of inflation, was trained as a high-energy theorist and was a SLAC visitor when he did his seminal work. Indeed, much of inflationary cosmology was developed by high-energy theorists who have become part-time or full-time cosmologists like Guth and I (my graduate career began at SLAC). The article on the search for axions—one of the leading candidates for the constituents of cold dark matter—is written by two experimentalists, Leslie Rosenberg and Karl van Bibber, who began their careers in high-energy and medium-energy physics respectively. The "Fate of the Universe" which describes the quest to measure its geometry and is written by Gerson Goldhaber, known for his role in the discovery of charm, and his wife Judith. "Pi on the Sky," written by Heidi Newberg, is about mapping the large-scale structure of the Universe by determining the three-dimensional positions of a million galaxies. One of the major partners in this collaborative effort, known officially as the Sloan Digital Sky Survey or SDSS, is the Fermi National Accelerator Laboratory in Illinois. While the article which concerns the study of the origin and evolution of galaxies by bringing to bear two of the most powerful astronomical instruments—the Hubble Space Telescope and the twin Keck 10-meter telescopes—is written by two astronomers, Andrew Phillips and Nicole Vogt, one of the key participants in this project is high-energy theorist turned astronomer and former SLAC graduate student Professor Joel Primack of the University of California, Santa Cruz. Finally, Virginia Trimble, a frequent *Beam Line* contributor and bicoastal astronomer, has contributed an overview of the Universe, from the smallest to the biggest and the shortest to the longest, to put cosmology into its proper perspective.

TALL SHOULDERS

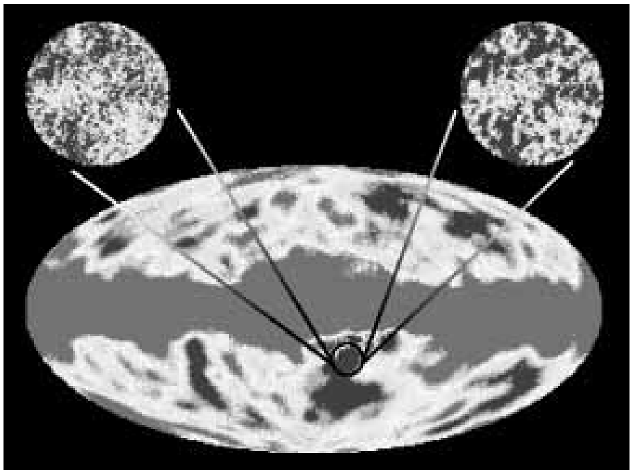
THE HOT BIG-BANG (standard) cosmology will likely be viewed as one of the intellectual triumphs of the twentieth century. It provides a tested account of the Universe from a fraction of a second after the beginning until the present 10 to 15 billion years later, as well as a firm base for speculations about much earlier times. According to this cosmology, the Universe began as a hot, very dense formless soup of the fundamental particles—quarks, leptons, gauge bosons, and possibly other elementary particles. As it expanded and cooled, layer upon layer of structure built up. At around 10^{-5} sec, neutrons and protons formed from quarks. In a series of well understood nuclear reactions that took place between a fraction of a second and several hundred seconds, the nuclei of the light elements D, ^{3}He, ^{4}He and ^{7}Li were formed. (The elements beyond ^{7}Li were formed much later by nuclear reactions within stars.) By a few hundred thousand years the Universe had cooled sufficiently so that atoms could form from the nuclei and free electrons present. Over the next 10 to 15 billion years all the cosmic structure seen today, from individual stars to superclusters and great walls, developed through the attractive action of gravity.



Big-bang production of the light elements depends upon the density of ordinary matter and agrees with the measured abundances for densities indicated by the white band, which falls far short of the critical density. (Courtesy Kenneth Nollett)

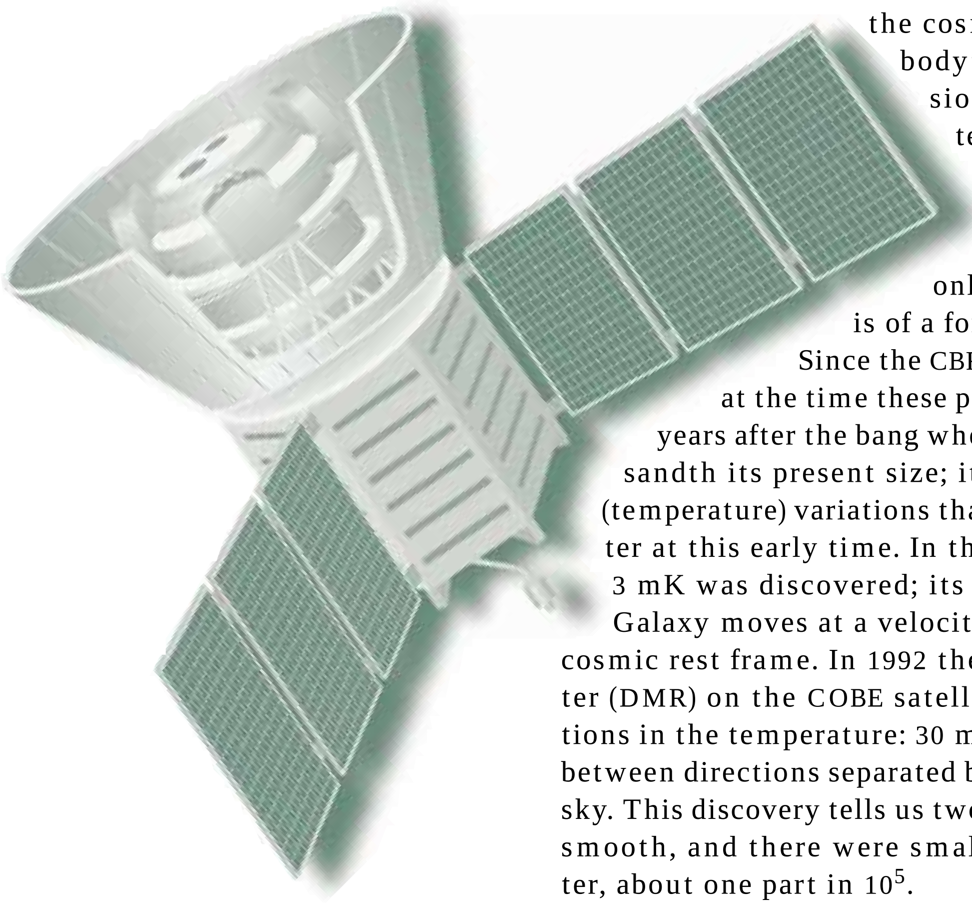
There is a wealth of observational data that support the standard cosmology; four observations provide the cornerstones. They are the expansion of the Universe; the microwave echo of the Big Bang (known as the cosmic background radiation or CBR); the abundance of D, ^{3}He, and ^{4}He and ^{7}Li; and the tiny variations (about one part in 10^5) in the intensity of the CBR between different directions on the sky.

Hubble presented the first evidence for a linear relation between the distances and the velocities of galaxies. Now known as Hubble's Law, this relation is well established (see sidebar on page 30). The notorious proportionality constant—Hubble's constant or H_0, whose reciprocal sets the time back to the bang—is finally being pinned down to a precision of around 10 percent, thanks to observations being made by the Hubble Space Telescope and clever techniques that exploit X-ray and microwave observations. Hubble's



COBE DMR map of the CBR (bright band across middle is emission from our own galaxy). The two blow-ups show a simulation of the fine detail that exists within the COBE 7° beam which the MAP and Planck satellites should reveal. The difference between an open universe model (Ω = 0.1) on the left and a flat universe model (Ω = 1) on the right is very striking. (Courtesy Martin White)

Law supports the idea of an expanding universe and provides the fundamental means of determining distances to galaxies: the measured redshift times c/H_0 is the distance to the galaxy.



Unaware of Gamow's prediction of a microwave afterglow of the Big Bang, Penzias and Wilson discovered this radiation serendipitiously. The Far Infrared Absolute Spectrophotometer on the COBE satellite, launched in 1989, has shown that the cosmic background radiation is "black body" radiation to extraordinary precision, better than 0.01 percent, with a temperature of 2.7277±0.002K. (All objects emit radiation characteristic of their temperature; for a featureless black body the spectrum only depends upon the temperature and is of a form first described by Planck.)

Since the CBR provides a snapshot of the Universe at the time these photons last scattered, around 300,000 years after the bang when the Universe was about one thousandth its present size; it has been scrutinized for intensity (temperature) variations that can reveal the distribution of matter at this early time. In the 1970s a dipolar variation of about 3 mK was discovered; its simplest interpretation is that our Galaxy moves at a velocity of 620 km/sec with respect to the cosmic rest frame. In 1992 the Differential Microwave Radiometer (DMR) on the COBE satellite discovered much smaller variations in the temperature: 30 microKelvin temperature differences between directions separated by angles of around 10 degrees on the sky. This discovery tells us two things: the early Universe was very smooth, and there were small variations in the density of matter, about one part in 10^5.

The tiny variations in the CBR temperature validate a key element of the Big Bang theory, the idea that all the structure we see arose from small variations in the matter density which grew under the influence of gravity over the past ten billion or so years. Further, they allow us to begin to quantify the nature of the primeval lumpiness and test ideas (including Guth's and mine) about their origin.

Finally, the abundance pattern of the light elements D, ^{3}He, ^{4}He and ^{7}Li seen in the most primitive samples of the cosmos conform to the predictions of "big-bang nucleosynthesis." This tests the Big Bang theory to within a fraction of a second of the beginning, and provides two bonuses: the yields of these elements depend upon the mass density contributed by ordinary matter (baryons) and the number of light neutrino species. Since the early 1980s it has been known that this agreement holds only if the number of neutrino species is less than four and the baryon density is between about 1 percent and 10 percent of the critical density. The "cosmological prediction" of the number of neutrino species made by David Schramm and his collaborators was confirmed in 1989 by precision measurements of the properties of the *Z* boson with the SLC at SLAC and with LEP at CERN, the European particle physics laboratory. This determination of the baryon density is the linchpin in the argument that most of the mass in the Universe exists in the form of elementary particles left over from earliest moments.

The hot big-bang cosmology is not complete, nor is it likely to be the whole story. There are important properties of the Universe yet to be determined: the precise value of the expansion rate and time back to the bang, the fraction of the critical density contributed by matter, the geometric shape of the Universe (flat, curved like the surface of a ball, or curved like the surface of a saddle), the value of Einstein's cosmological constant, a better understanding of how galaxies form and evolve, a more precise description of the large-scale distribution of matter, and the nature of the ubiquitous dark matter. (While the total amount of matter is not known precisely, only a small fraction of it exists in the form of stars and similar "visible" matter.) And, fundamental questions remain unanswered. Why is the Universe made of matter and not equal amounts of matter and antimatter? What is the origin of the matter lumpiness that seeded all structure in the Universe? Why was the early Universe so smooth? What went bang?

Thanks to the current explosion in observational cosmology, we are rapidly closing in on many of the first set of questions. The measurements being made can strengthen the case for the standard cosmology as well as help to test ideas put forth to extend it. And, of course, they could bring some surprises. The second set of questions points to the existence of a grander theory, which is where the inner space/outer space connection comes in.

The LEP tunnel at CERN which houses the most powerful electron/positron collider and will eventually house the Large Hadron Collider, which will be able to recreate conditions that last existed 10^{-15} seconds after the Big Bang. (Courtesy CERN)

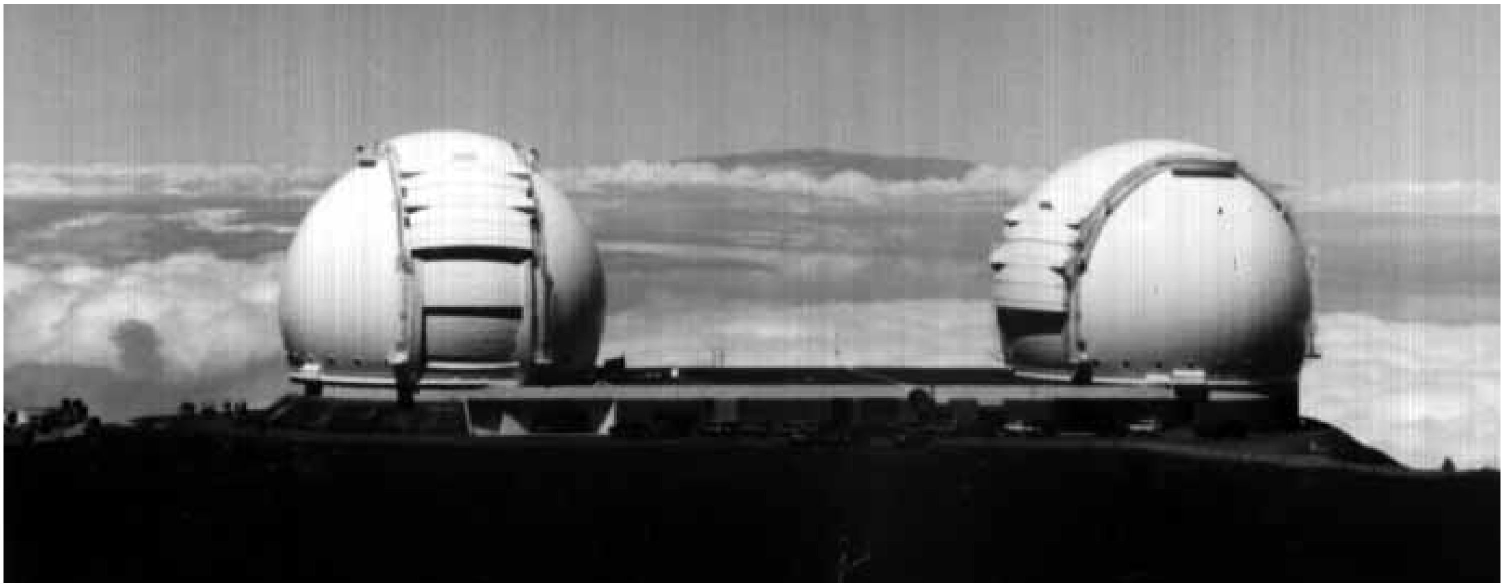
THE INNER SPACE/OUTER SPACE CONNECTION

IN ITS INFANCY THE UNIVERSE was a hot soup of the fundamental particles—quarks, leptons, and gauge bosons. The further back in time, the higher the temperature and energy per particle. Particle accelerators create a soup of high-energy quarks, leptons, and related particles when they collide protons and antiprotons, electrons and positrons, or positrons and protons. Therefore, like telescopes, they are cosmic time machines that allow cosmologists to explore the earliest moments. Conversely, the early Universe is a very powerful cosmic accelerator that allows particle physicists to probe deeper into inner space than they can with terrestrial accelerators.

The unification of the forces and particles of Nature is the holy grail of particle physics. There is a general belief and some evidence (for example, the unification of the weak and electromagnetic forces) that the full simplicity of Nature is only manifest at high energies and temperatures. This makes the early Universe a testing ground for the grandest ideas of particle physics, including unification of the strong, weak, and electromagnetic forces, supersymmetry, and superstrings. Conversely, the unification of the particles and forces certainly has consequences for the earliest evolution of the Universe.

The BaBar detector will be used to study the matter-antimatter asymmetry puzzle and could help cosmologists to understand better the origin of ordinary matter in the Universe.

The 1980s were the go-go days of early Universe cosmology. Many exciting ideas about the earliest moments based upon speculations about the unification of the forces were put forth. An attractive explanation for the origin of the asymmetry between matter and antimatter known as baryogenesis developed. Baryogenesis holds that a slight excess of matter—quarks and leptons—arose early on due to the same force that leads to the instability of the proton and the slight preference for matter in the laws of physics (CP violation). (See the article, "The Mystery of the Matter Asymmetry" by Eric Sather in the Spring/ Summer 1996 issue of the *Beam Line*, Vol. 26, No. 1.) After all the antimatter annihilated with matter (around 10^{-5} sec) only the matter we see today remained. The major scientific goal of the SLAC B Factory is a better understanding of CP



Paul J. Stomski, Jr.

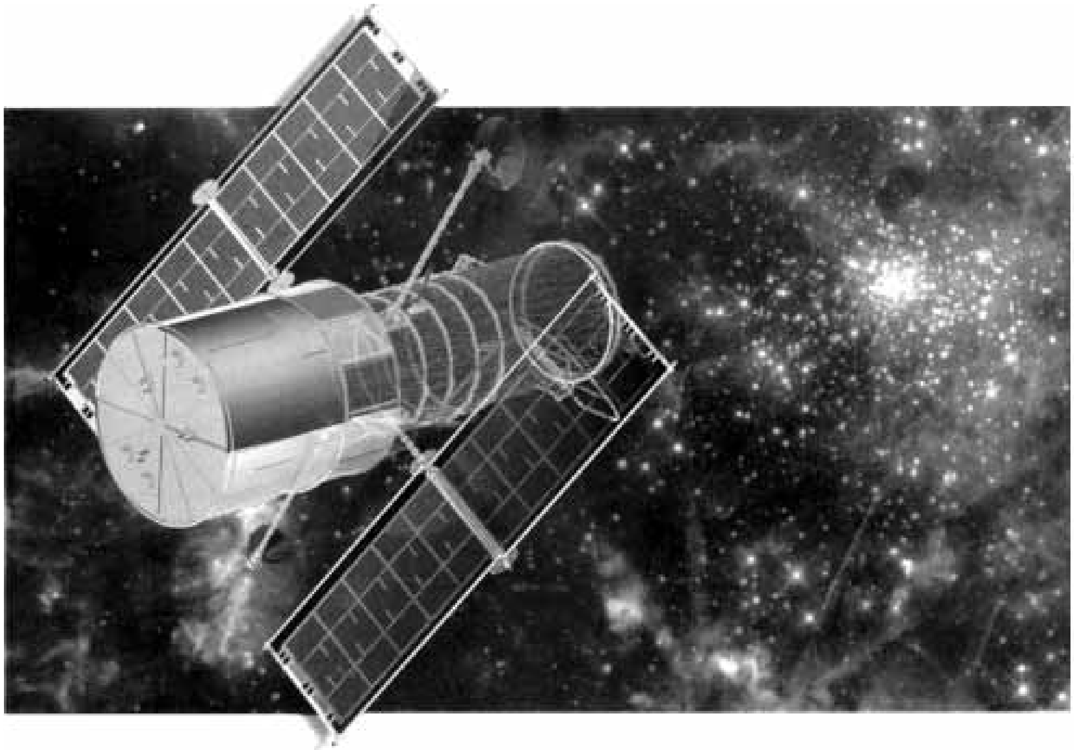
The twin 10-meter Keck telescopes on Mauna Kea in Hawaii. (Courtesy Paul Stomski)

violation and possibly of baryogenesis (see the article by Natalie Roe and Michael Riordan, "Why Are We Building B Factories?" in the Spring/Summer 1996 issue, Vol. 26, No. 1.)

As the Universe evolved it should have gone through a series of phase transitions as the different forces of Nature developed their own character and the forces became less unified. These phase transitions, not unlike the more familiar phase transition from steam to water, could well have left their imprint on the future evolution of the Universe. If a phase transition did not proceed smoothly and uniformly, "topological defects" may have been formed that could still be with us today. They include superheavy magnetic monopoles and cosmic strings, which are very thin concentrations of false vacuum energy. These defects could act as the seeds for the formation of structure or have other interesting consequences such as producing extremely high-energy cosmic rays. Some theorists have speculated that even the most well understood phase transition, from quark-gluon plasma to ordinary hadrons, may have left macroscopic nuggets of quark matter.

BEYOND THE STANDARD COSMOLOGY: INFLATION AND COLD DARK MATTER

THE MOST COMPELLING and expansive idea to come from the inner space/outer space connection is inflation and cold dark matter. It addresses essentially all of the fundamental questions being asked by cosmologists and has moved a generation of observers and experimenters to go out and disprove it! As Guth describes, the smoothness and flatness of the observed Universe arises because of an enormous burst of expansion caused by false-vacuum energy. The eventual decay of this energy produced all the heat of the Big Bang



The Hubble Space Telescope, which has produced the highest resolution and deepest images of the Universe. (Copyright 1997 National Geographic Society. All rights reserved.)

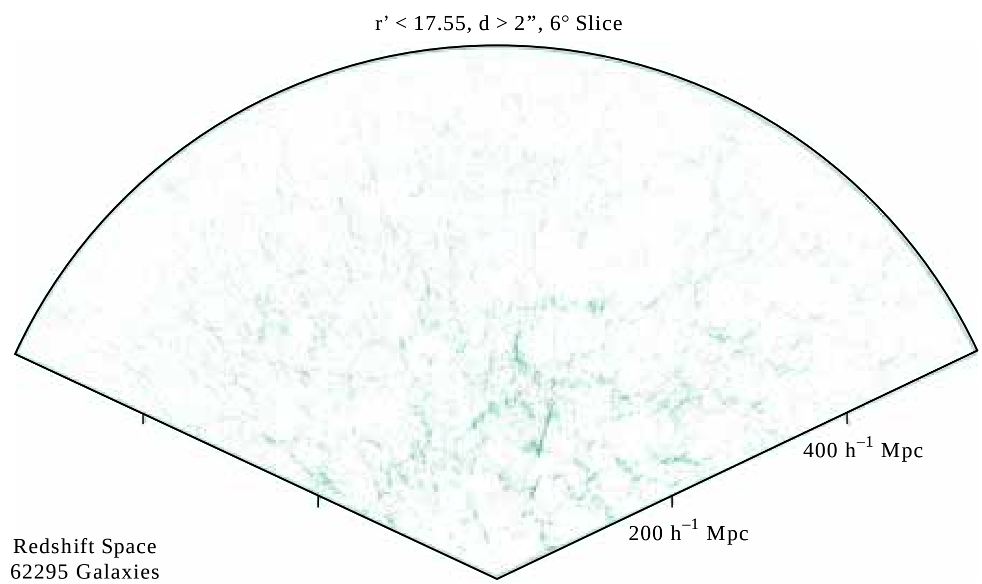
and eventually all the matter we see today. The most striking prediction is that the primeval lumpiness arises due to quantum mechanical fluctuations on subatomic scales, which were stretched to cosmic size by the enormous burst of expansion.

A flat universe has the critical density and expands forever. Big-Bang nucleosynthesis tells us that ordinary matter accounts for slightly less than 10 percent of the critical density; this means that something more exotic must take up the slack. Particle physics provides several promising particle candidates: the axion, a hypothetical particle that is supposed to weigh a million, million times less than the electron (discussed in the article by van Bibber and Rosenberg on page 43 of this issue); the neutralino, a hypothetical particle predicted to exist if Nature is supersymmetric and is supposed to be between ten and five hundred times heavier than the proton; and ordinary neutrinos if they have mass, as most unified theories predict. All three candidates should have been present during the earliest fiery moments in great abundance and according to calculations should be present today in about the right numbers to account for the critical density. Axions and neutralinos move slowly and for this reason are called cold dark matter; neutrinos move fast and are known as hot dark matter.

Having the bulk of the matter in the form of relic elementary particles fits nicely with the fact that most of the matter in the Universe is known to be dark. Cosmologists are more interested in cold dark matter than neutrinos because they are confident that the development of structure in a hot dark matter universe leads to a universe radically different from ours.

The idea that the bulk of the dark matter is cold dark matter particles and that the primeval lumpiness arose from quantum mechanical fluctuations provide the basis for a comprehensive theory for how cosmic structure formed and thereby a powerful way of testing inflation itself. The cold dark matter (or CDM) theory holds that CDM particles provide the cosmic infrastructure as it is their gravity that holds all cosmic structures from galaxies to superclusters together; and that structure forms from the bottom up. Galaxies form first when the Universe was one-third to one-half its present size; clusters of galaxies form next; and finally superclusters are just forming today. The bringing together of matter leaves voids. This picture is generally consistent with a broad base of observations, from measurements of tiny variations in the CBR temperature to the deepest images of the Universe from the Hubble Space Telescope.

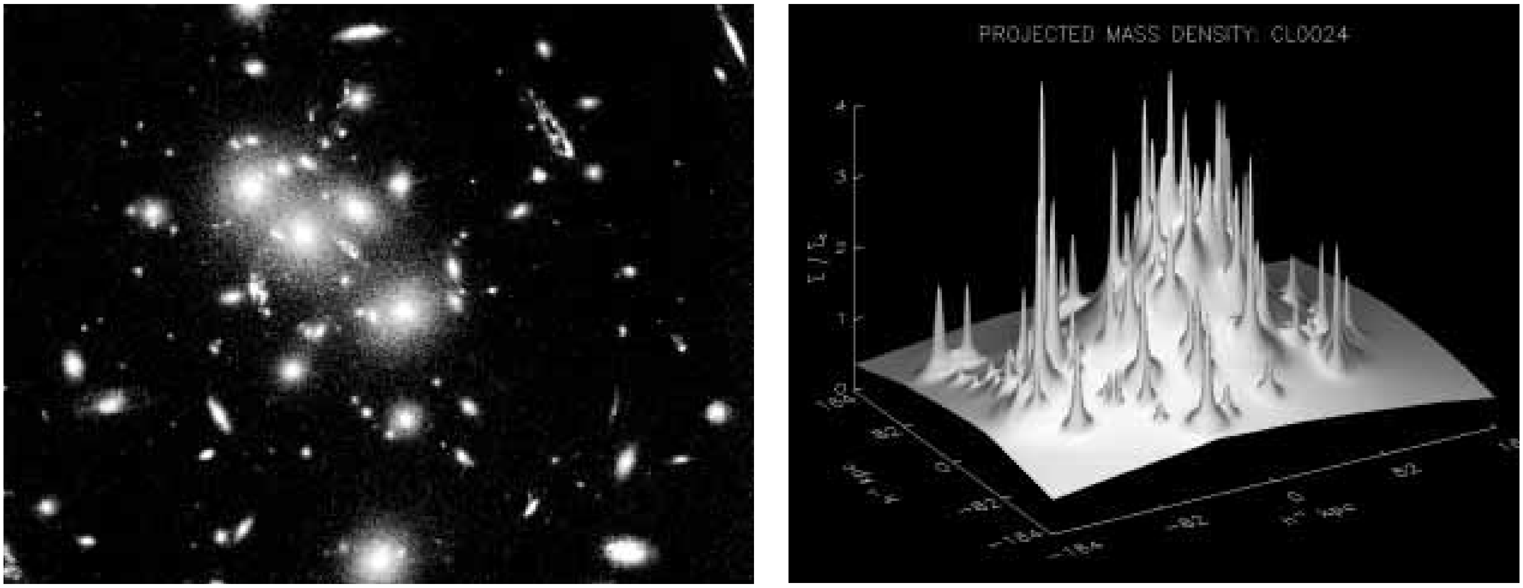
The CDM theory is being further tested by a flood of observations and experiments; four key tests are described in this issue of the *Beam Line*. Newberg describes how the SDSS will map cosmic structure by determining the positions of a million galaxies. Phillips and Vogt discuss the DEEP Project whose scientific goal is the study of the origin and evolution of galaxies. Van Bibber and Rosenberg tell about their search for the axions, which may be the CDM that holds our Galaxy together. Finally, the Goldhabers discuss the quest for omega and the testing of the inflationary prediction of a flat universe.



A simulation of the galaxy distribution that the Sloan Survey might find. We sit at the apex of the wedge. (Courtesy David Weinberg)

Many other important tests are underway; some at particle accelerators. While too much hot dark matter is a bad thing, a little bit may be just what the CDM theory needs to agree with existing observations. Neutrino experiments at Fermilab and CERN are testing this possibility. The neutralino, the other promising CDM candidate, is being hunted around the world, both with particle accelerators and with cryogenic detectors designed to detect the neutralinos that may be the dark matter in our own galaxy.

Finally, let me mention what I believe is the most powerful test of inflation + CDM as well as a precision probe of the standard cosmology itself. Encoded in the tiny variations of the temperature of the CBR across the sky are both the values of the cosmological parameters and the details of inflation. A precision, high-resolution map of the CBR has the potential to determine accurately the Hubble constant, baryon density, total density (omega), the value of the



The arcs seen in the left panel are produced by gravitational lensing of distant galaxies by a closer cluster of galaxies. Analysis of the gravitational lensing led to the map of the cluster mass distribution shown on the right. Such maps have helped to establish the existence of large amounts of dark matter in the Universe. (Courtesy Tony Tyson)

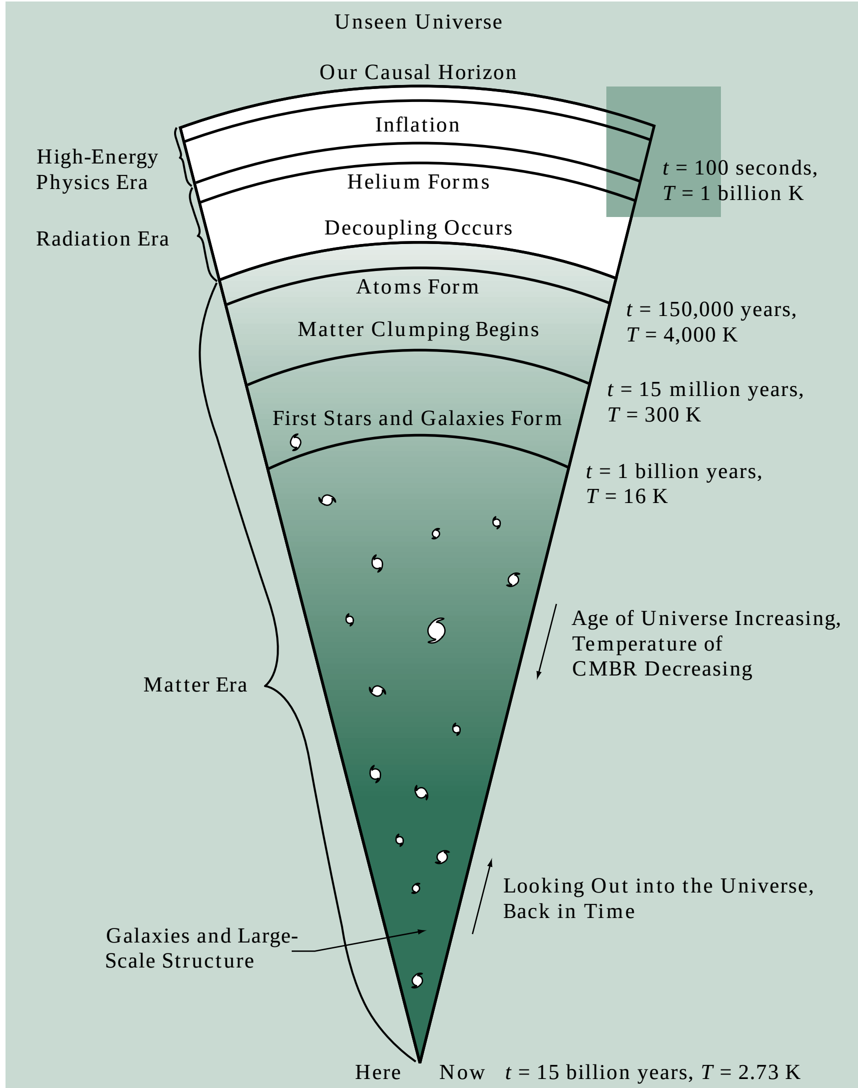
cosmological constant, the value of the vacuum energy that drove inflation, the spectrum and amplitude of the primeval lumpiness that arose from quantum mechanical fluctuations, and other important cosmological parameters.

The COBE satellite mapped the full CBR sky with angular resolution of seven degrees. Ground-based and balloon-borne instruments are mapping small patches with resolution of better than one degree. NASA plans to launch the Microwave Anisotropy Probe in August 2000 which will map the CBR sky with a beam of 0.2 degree. In 2005 the European Space Agency plans to launch the Planck satellite, which will map with a beam of less than 0.1 degree. Over the next decade, ground-based, balloon-borne, and satellite-borne instruments should reap the full scientific potential of this snapshot of the adolescent Universe. In process, inflation + CDM will be put to the test and the details of inflation may be revealed. In addition, precision checks of the standard cosmology will be made.

BEYOND INFLATION AND COLD DARK MATTER

IF INFLATION AND COLD DARK MATTER prove correct, it will be a great triumph for the inner space/outer space connection. The known history of the Universe will be extended to times as early as 10^{-32} sec and a window to the unification of the fundamental forces and particles of Nature will have been opened. Our conception of the Universe and our place in it will have been changed profoundly. As Guth describes, inflation answers what banged: What we refer to as the Big Bang and beginning of the Universe was simply the inflationary event that was our beginning. Andrei Linde of Stanford University has emphasized, if inflation has occurred at all, it has occurred countless times in the past and will continue to occur forever. Each inflationary event spawns a region large enough so that it never communicates with others and can be rightfully called a subuniverse. Sub-universes may be very different as the realization of the laws of physics, including the number of spatial dimensions, may depend upon historical accidents associated with the loss of symmetry between the forces.

These are exciting times in cosmology. We should find out soon whether or not our most promising and expansive ideas about the origin of the Universe are correct. Even if current thinking proves wrong, or only partially correct, there are interesting times ahead as we search for new ideas. They will almost certainly involve the inner space/outer space connection.



The cosmic picture. Here and now is at the bottom; as we look out into space we look back in time. (Courtesy Scott Dodelson)