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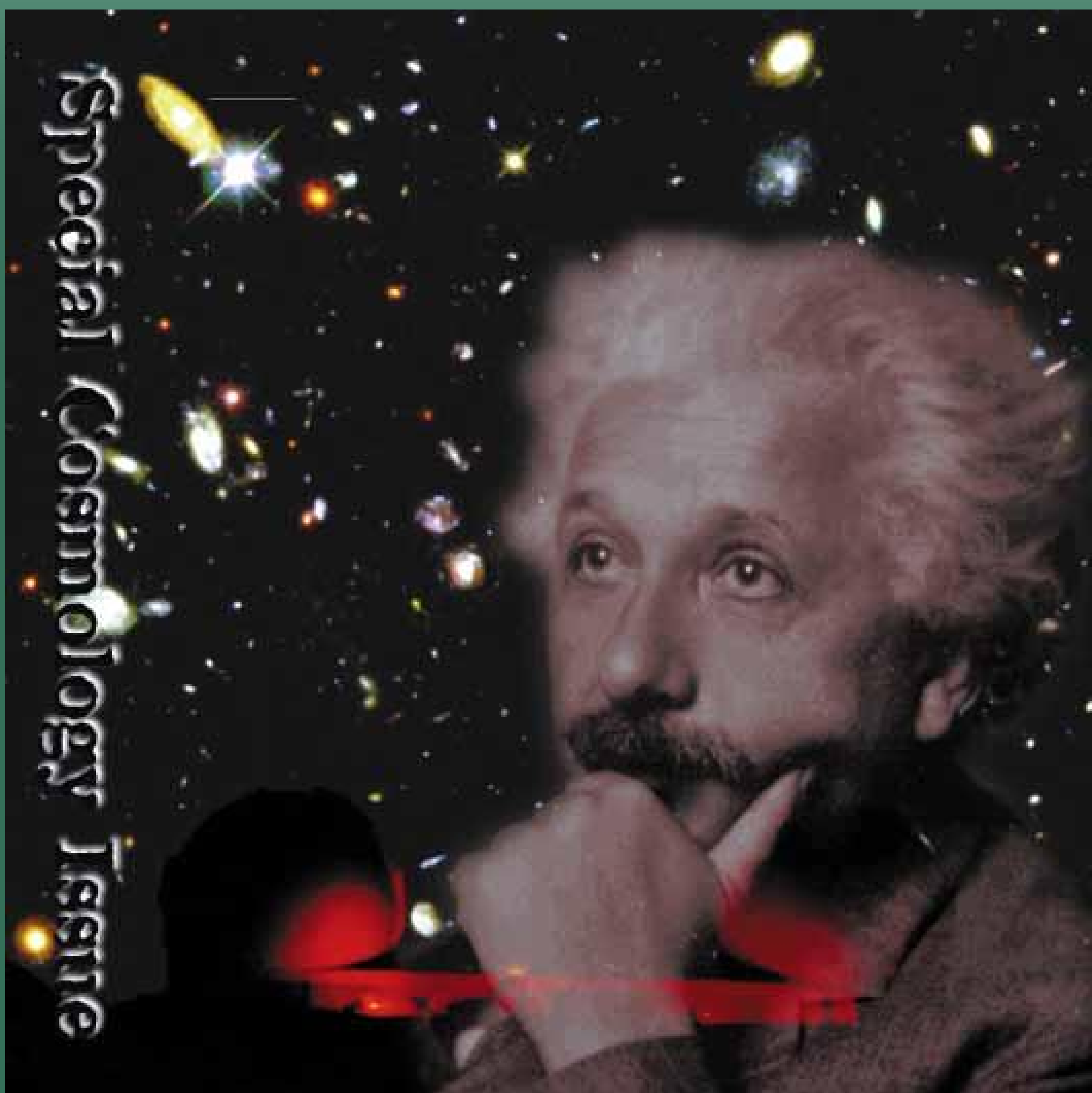

Beam Line

A PERIODICAL OF PARTICLE PHYSICS

FALL 1997 VOL. 27, NUMBER 3

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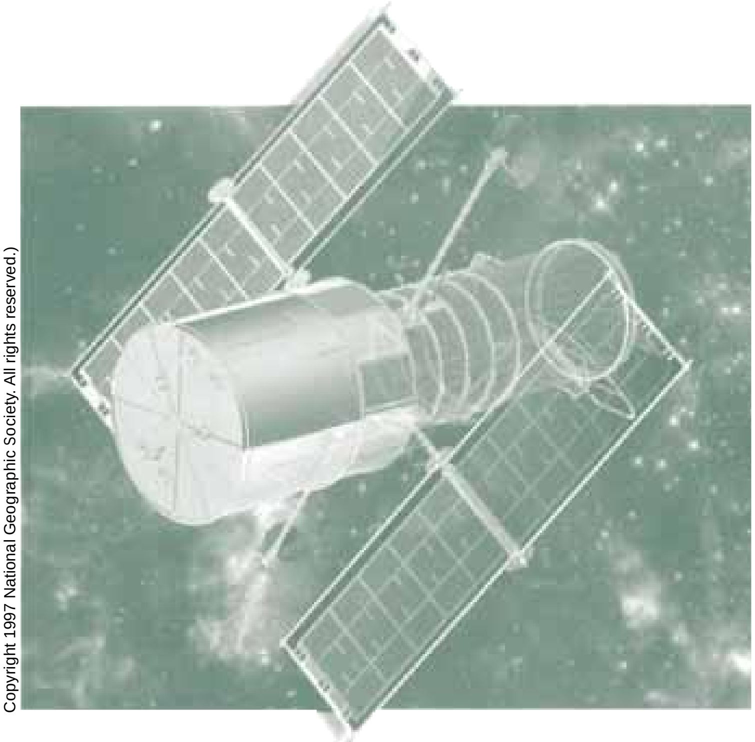

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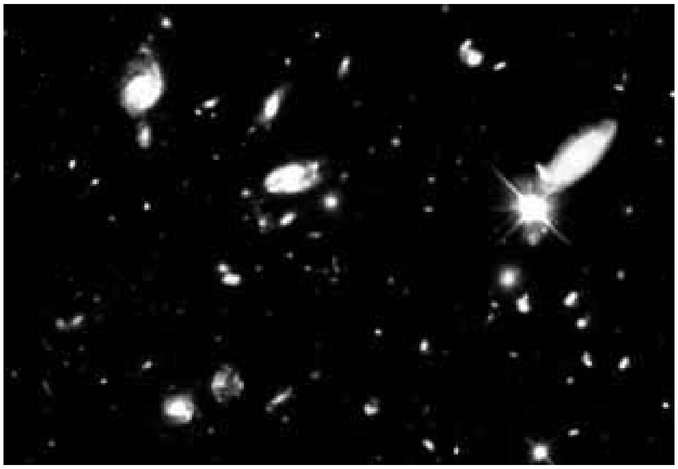


AURA/STScI

DEPARTMENTS

Dan Long

by MICHAEL S. TURNER

INNER SPACE & OUTER SPACE

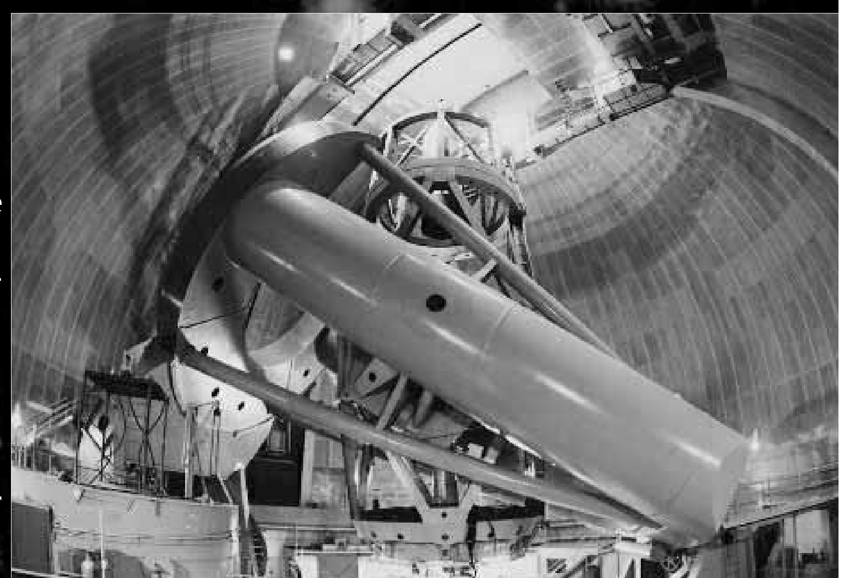
Cosmology is in the midst of a Golden Age triggered in part by ideas about the earliest moments of the Universe based upon the unification of the forces and particles of Nature.

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.



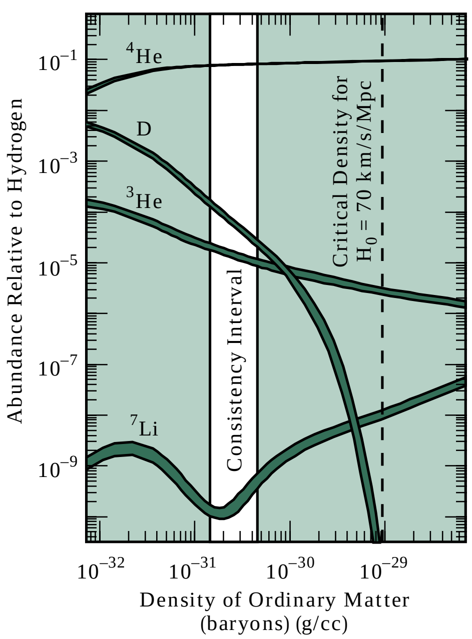
This issue of the *Beam Line* illustrates well the close relationship between particle physics and cosmology that has developed over the past two decades. All the articles relate to testing inflation and cold dark matter. Many of the protagonists (and authors) started their

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

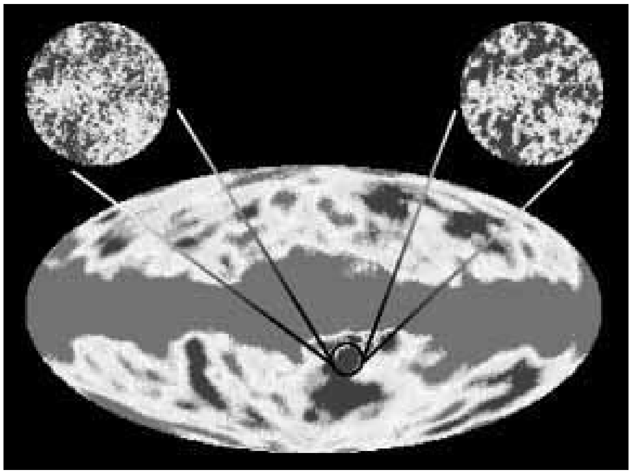
THE HOT BIG-BANG (standard) cosmology will likely be viewed as one of the intellectual triumphs of the twentieth century. It provides a tested account of the Universe from a fraction of a second after the beginning until the present 10 to 15 billion years later, as well as a firm base for speculations 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.



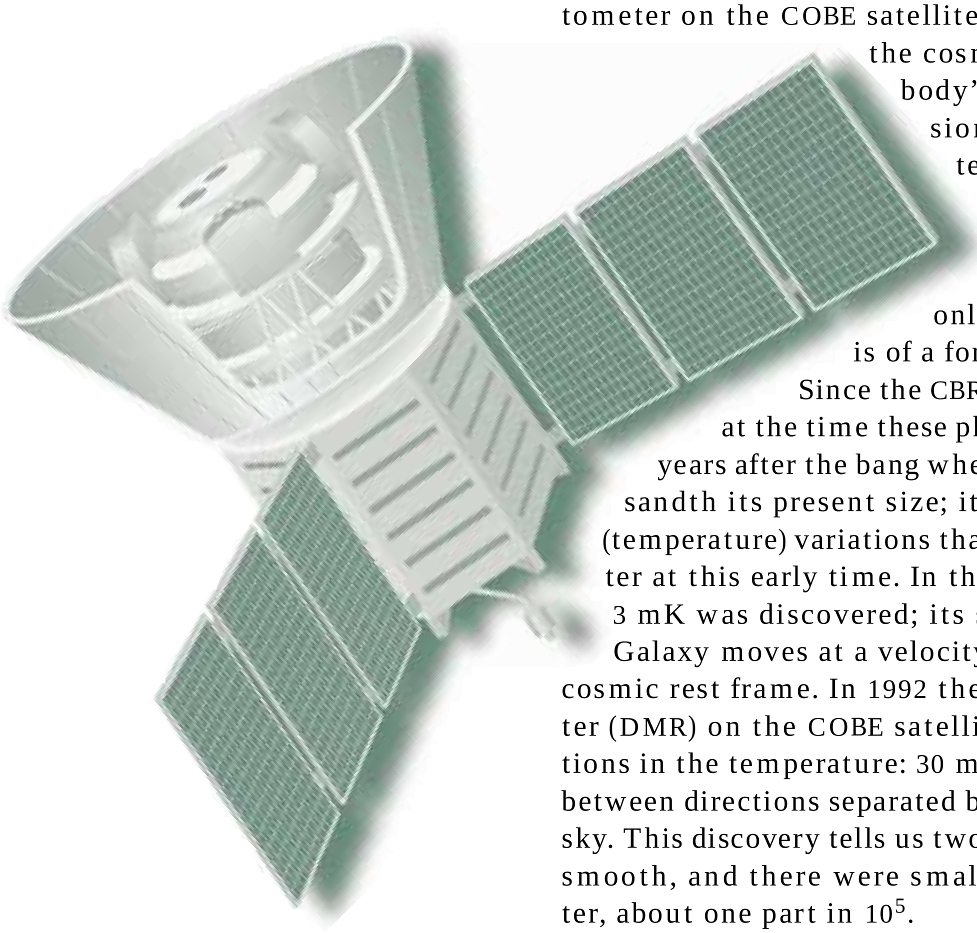
Big-bang production of the light elements depends upon the density of ordinary matter and agrees with the measured abundances for densities indicated by the white band, which falls far short of the critical density. (Courtesy Kenneth Nollett)

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 ($\Omega = 0.1$) on the left and a flat universe model ($\Omega = 1$) 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)

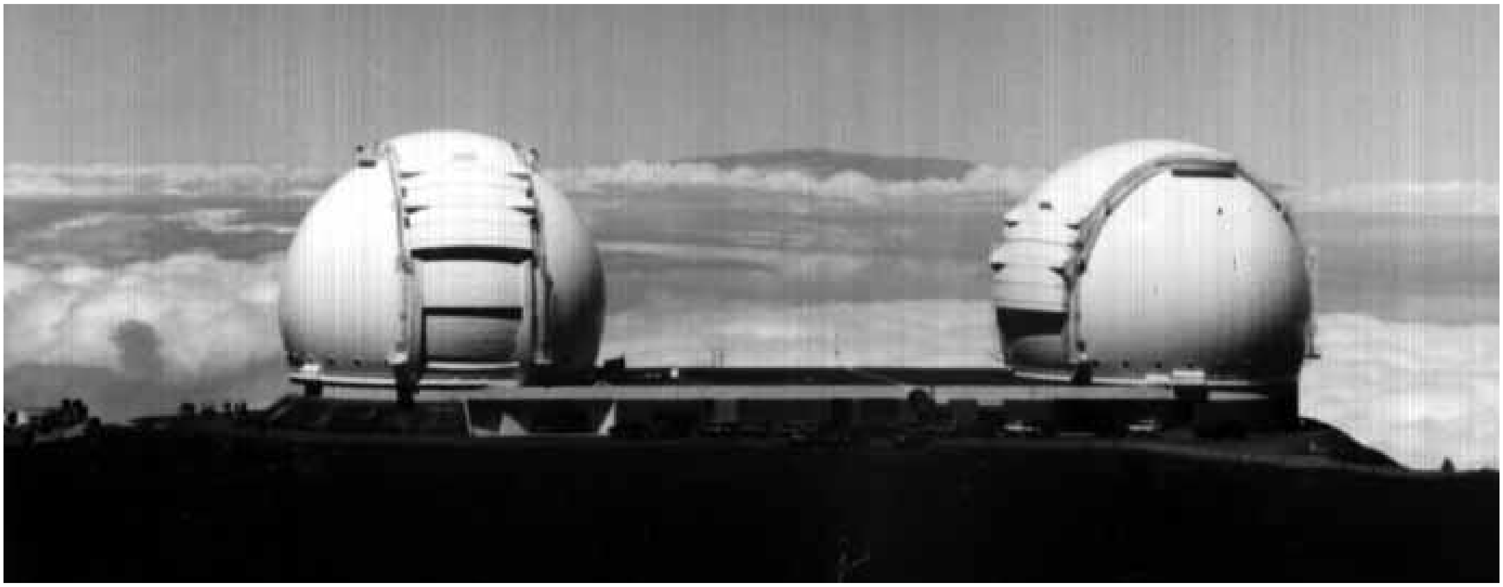
THE INNER SPACE/OUTER SPACE CONNECTION

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.

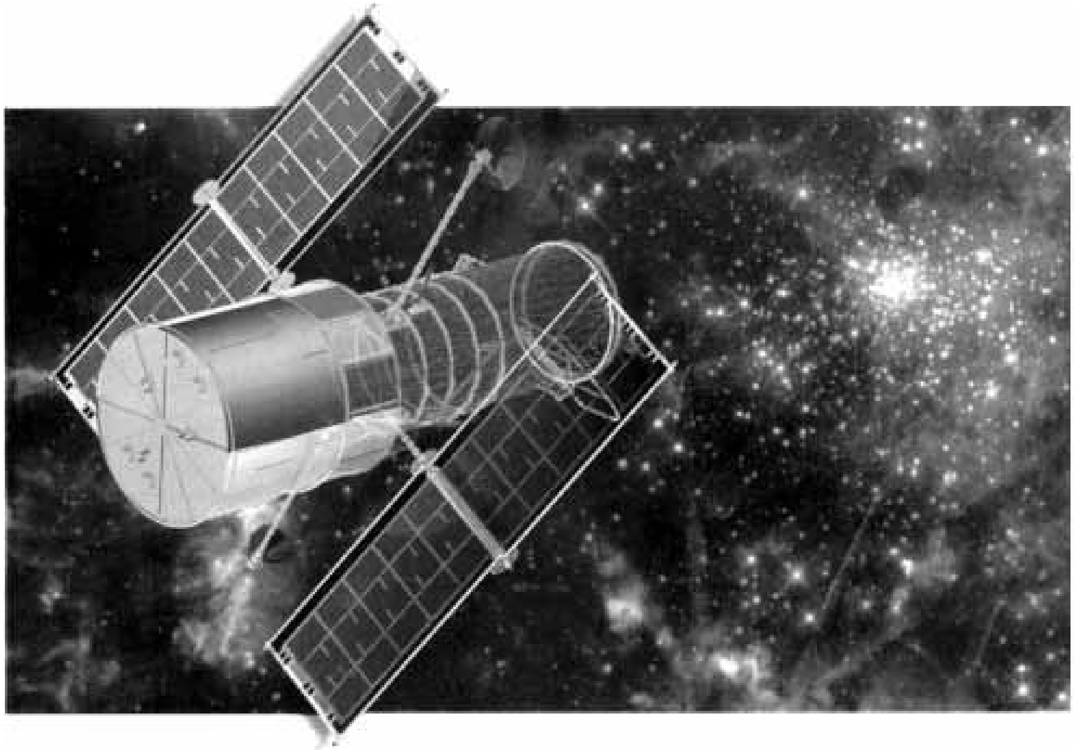
The twin 10-meter Keck telescopes on Mauna Kea in Hawaii. (Courtesy Paul Stomski)

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



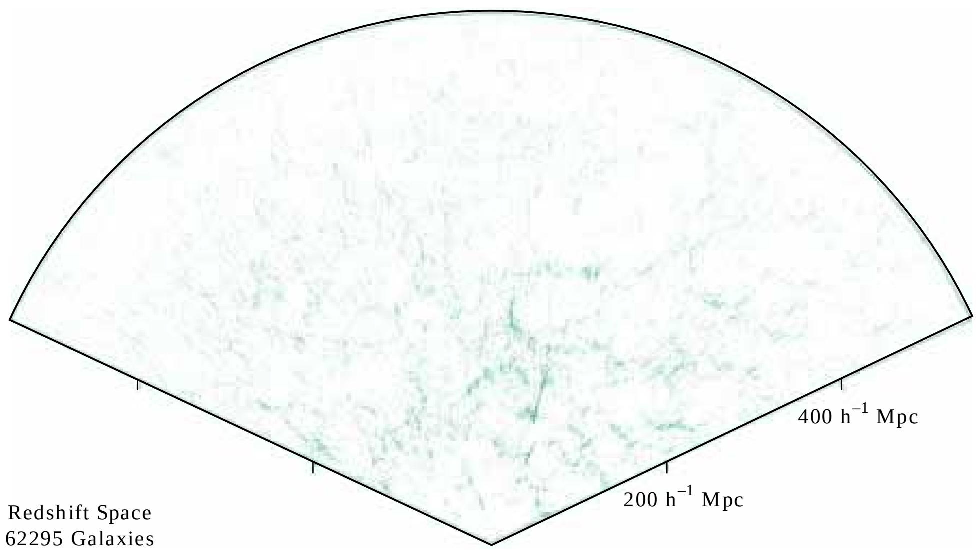
The Hubble Space Telescope, which has produced the highest resolution and deepest images of the Universe. (Copyright 1997 National Geographic Society. All rights reserved.)

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.

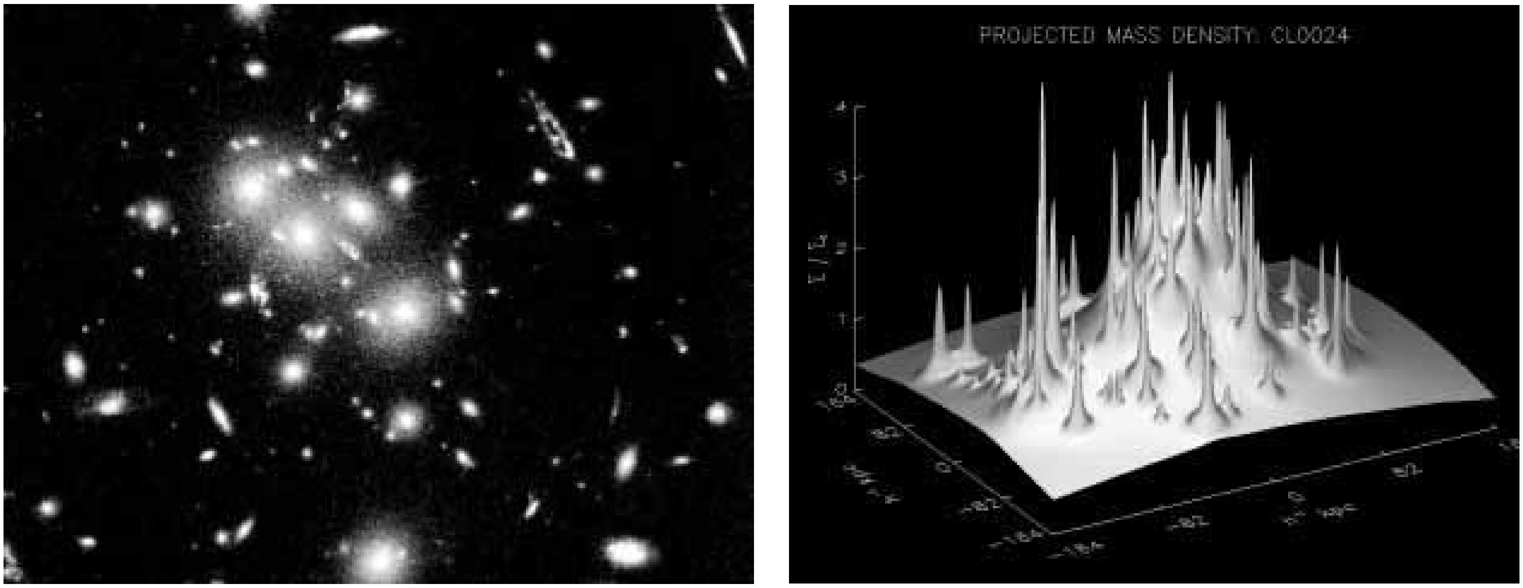


A simulation of the galaxy distribution that the Sloan Survey might find. We sit at the apex of the wedge. (Courtesy David Weinberg)

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.

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)

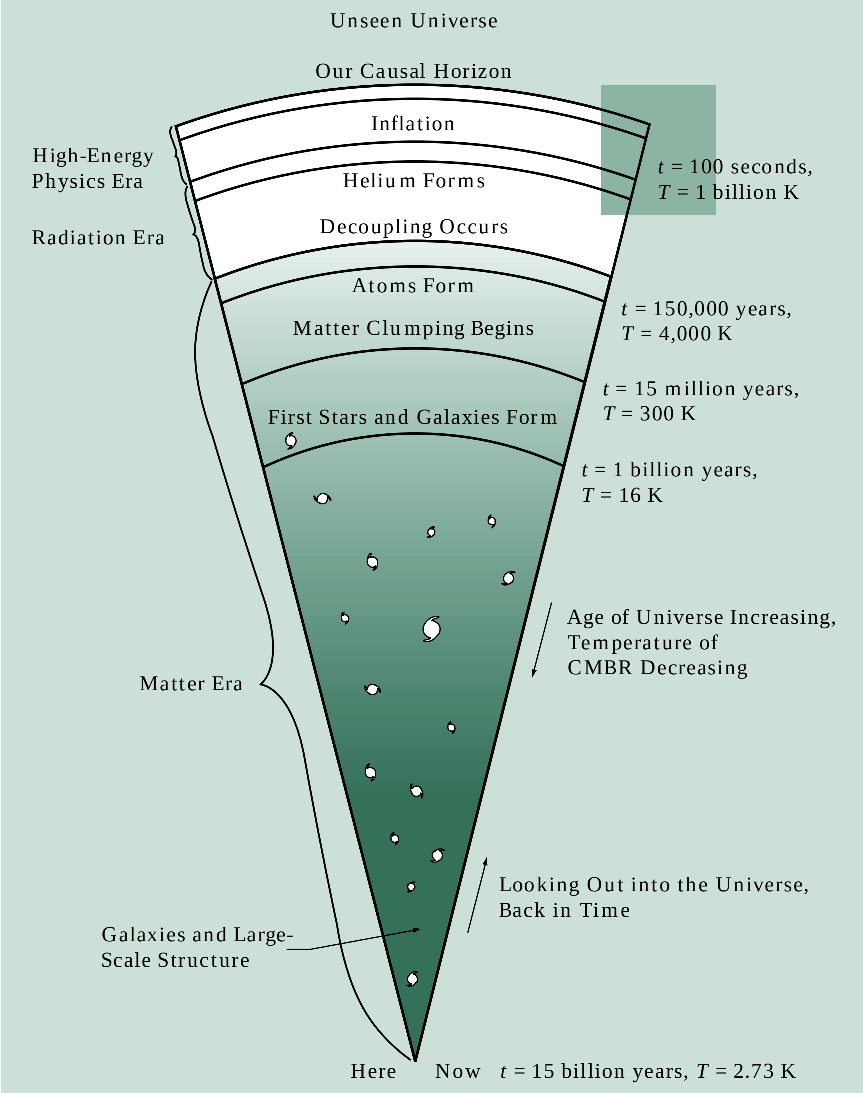
cosmological constant, the value of the vacuum energy that drove inflation, the spectrum and amplitude of the primeval lumpiness that arose from quantum mechanical fluctuations, and other important cosmological parameters.

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 sub-universe. 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)

Was Cosmic Inflation the

Two thousand years after Lucretius proclaimed that nothing can be created from nothing, inflationary cosmology asserts that he was wrong.

WHEN AN OBSCURE RUSSIAN METEOROLOGIST named Alexander Friedmann proposed, in 1922, that the Universe might be expanding, Albert Einstein was sure that he was wrong. Five years earlier Einstein had published a static model of the Universe, and he was still convinced that it was correct. In a rare but dramatic blunder, Einstein bolstered his unfounded beliefs with an erroneous calculation, and fired off a note to the *Zeitschrift für Physik* claiming that Friedmann's theory violated the conservation of energy. Eight months later, however, after a visit from a colleague of Friedmann's, Einstein admitted his mistake and published a retraction. The equations of general relativity do, he conceded, allow for the possibility of an expanding universe.

Today the Big Bang theory, which began with Friedmann's calculations in 1922, has become the accepted view of cosmology. The expansion of the Universe was first observed in the early 1920s by Vesto Melvin Slipher, and in 1929 was codified by Edwin Hubble into what we now know as "Hubble's Law": on average, each distant galaxy is receding from us with a velocity that is proportional to its distance. In 1965 Arno Penzias and Robert Wilson detected a background of microwave radiation arriving at Earth from all directions—the afterglow of the primordial hot, dense fireball. Today we know, based on

'Bang' of the Big Bang?

data from the *Cosmic Background Explorer* (COBE) satellite (see *Beam Line*, Vol. 23, No. 3, Fall/Winter 1993), that the spectrum of this background radiation agrees with exquisite precision—to 1/30 of 1 percent—with the thermal spectrum expected for the glow of hot matter in the early Universe. In addition, calculations of nucleosynthesis in the early universe show that the Big Bang theory can correctly account for the cosmic abundance of the light nuclear isotopes: hydrogen, deuterium, helium-3, helium-4, and lithium-7. (Heavier elements, we believe, were synthesized much later, in the interior of stars, and were then explosively ejected into interstellar space.)

Despite the striking successes of the Big Bang theory, there is good reason to believe that the theory in its traditional form is incomplete. Although it is called the "Big Bang theory," it is not really the theory of a bang at all. It is only the theory of the *aftermath* of a bang. It elegantly describes how the early Universe expanded and cooled, and how matter clumped to form galaxies and stars. But the theory says nothing about the underlying physics of the primordial explosion. It gives not even a clue about what banged, what caused it to bang, or what happened before it banged. The inflationary universe theory, on the other hand, is a description of the bang itself, and provides plausible answers to these questions and more.

A VERY SPECIAL BANG

Could the Big Bang have been caused by a colossal stick of TNT, or perhaps a thermonuclear explosion? Or maybe a gigantic ball of matter collided with a gigantic ball of antimatter, releasing an untold amount of energy in a powerful cosmic blast.

In fact, none of these scenarios can plausibly account for the Big Bang that started our Universe, which had two very special features distinguishing it from any typical explosion.

First, the Big Bang was far more homogeneous, on large scales, than can be explained by an ordinary explosion. In discussing homogeneity, however, I must first clarify that the Universe is in many ways conspicuously inhomogeneous. Palo Alto is very different from San Francisco, and the stars, galaxies, and clusters of galaxies are scattered through space in a lumpy, complex pattern. Cosmologically speaking, however, all this structure is small-scale. We can focus on the large scales, for example, by dividing space into cubes of 300 million light-years or more on a side. We would find that each such cube closely resembles the others in all its average properties, such as mass density, galaxy density, and light output. This large-scale uniformity can be seen in galaxy surveys, but the most dramatic evidence comes from the cosmic background radiation. Data from the COBE satellite, confirmed by subsequent ground-based observations, show that this radiation has the same temperature in all directions (after correcting for the motion of the Earth) to an accuracy of one part in 100,000.

Inflation

is a wildfire

that will inevitably

take over the forest,

as long as

there is some

chance that

it will start.

To see how difficult it is to explain this uniformity as the result of an ordinary explosion, we need to know a little about the history of the cosmic background radiation. The early Universe was so hot that electrons would have been ripped away from atoms, resulting in a plasma that filled space. Such a plasma is very opaque, so the photons that now make up the cosmic background radiation were constantly absorbed and re-emitted. After about 300,000 years, however, the Universe cooled enough for the plasma to form a gas of neutral atoms, which is very transparent. The photons of the cosmic background radiation have traveled on straight lines ever since, so they provide today an image of the Universe at an age of 300,000 years, just as the photons reaching your eye at this moment provide an image of the page in front of you. Thus, the observations of the cosmic background radiation show that the Universe was uniform in temperature, to one part in 100,000, at an age of several hundred thousand years.

Under many circumstances such uniformity would be easy to understand, since anything will come to a uniform temperature if left undisturbed for a long enough time. In the standard Big Bang theory, however, the Universe evolves so quickly that there is no time for the uniformity to be established. One can pretend, for the sake of discussion, that the Universe is populated by little purple creatures, each equipped with a furnace and a refrigerator, and each dedicated to the cause of creating a uniform temperature. Those little creatures, however, would have to communicate at roughly 100 times the speed of light if they are to achieve their goal of creating a uniform temperature across the visible Universe by 300,000 years after the Big Bang. Since neither sticks of dynamite nor balls of matter and antimatter can transmit their energy faster than light, they cannot account for the uniformity. The classical form of the Big Bang theory requires us to postulate, without explanation, that the primordial fireball filled space from the beginning. The temperature was the same everywhere *by assumption*, not as a consequence of any physical process. This shortcoming is known as the "horizon problem," since cosmologists use the word "horizon" to indicate the largest distance that information or energy could have traversed since the instant of the Big Bang, given the restriction of the speed of light.

The second special feature of the Big Bang, which is very difficult to imagine arising from a standard explosion, is a remarkable coincidence called the "flatness problem." This problem concerns the pinpoint precision with which the mass density of the early Universe must be specified for the Big Bang theory to agree with reality.

First, we need to review a little vocabulary. If the mass density of the Universe exceeds a value called the *critical density*, then gravity will be strong enough to reverse the expansion eventually, causing the Universe to recollapse into what is sometimes called the *big crunch*. If the mass density is less than the critical value, the Universe will go on expanding forever. The ratio of the actual mass density to the critical value is known to cosmologists by the Greek letter omega (Ω). General relativity implies that the geometry of the Universe is Euclidean only if omega is one, so an $\Omega = 1$ universe is called "flat" (see box on the right).

Omega is very difficult to determine, but it is safe to say that its present value lies somewhere in the range of 0.1 to 2. That seems like a broad range, but consideration of the time development of the Universe leads to a spectacularly different point of view. $\Omega = 1$ is an unstable equilibrium point of cosmological evolution, which means that it resembles the situation of a pencil balancing on its sharpened tip. The phrase equilibrium point implies that if omega is ever exactly equal to one, it will remain exactly equal to one forever—just as a pencil balanced precisely on end will, according to the laws of classical physics, remain forever vertical. The word unstable means that any deviation from the equilibrium point, in either direction, will rapidly grow. If the value of omega in the early Universe was just a little above one, it would have rapidly risen toward infinity; if it was just a smidgen below one, it would have rapidly fallen toward zero. For omega to be anywhere near one today, it must have been extraordinarily close to one at early times. For example, consider one second after the Big Bang, the time at which the processes related to Big Bang nucleosynthesis were just beginning. For omega to be anywhere in the allowed range today, at that time omega must have equaled one to an accuracy of 15 decimal places!

A simple explosion gives no explanation for this razor-sharp fine-tuning, and indeed no explanation can be found in the traditional version of the Big Bang theory. The initial values of the mass density and expansion rate are not predicted by the theory, but must be postulated. Unless we postulate that the mass density at one second just happened to have a value between 0.999999999999999 and 1.000000000000001 times the critical density, however, the theory will not describe a universe that resembles the one in which we live.

THE INFLATIONARY UNIVERSE

Although the properties of the Big Bang are very special, we now know that the laws of physics provide a mechanism that produces exactly this sort of a bang. The mechanism is known as cosmic inflation.

The crucial property of physical law that makes inflation possible is the existence of states of matter that have a high energy density that cannot be rapidly lowered. Such a state is called a "false vacuum," where the word "vacuum" indicates a state of lowest possible energy density, and the word "false" is used to mean

Critical Mass Density and Flatness

THE CRITICAL MASS density ρ_c is related to the Hubble constant H by

$$\rho_c = \frac{3H^2}{8\pi G}$$

where G is Newton's gravitational constant. The quantity Ω is defined by $\Omega \equiv \rho/\rho_c$, where ρ is the actual mass density. It is often assumed that the cosmological constant Λ introduced by Einstein is zero, in which case the Universe will recollapse if and only if $\Omega > 1$. If Λ is nonzero, the condition for recollapse is more complicated, but the equation above is still taken as the definition of ρ_c.

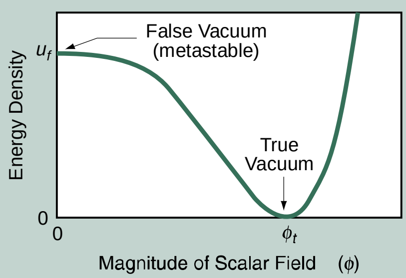
The spatial geometry of the Universe is determined by the quantity

$$\Omega + \frac{\Lambda}{3H^2}.$$

If this quantity exceeds one, the Universe curves back on itself to form a closed space of finite volume, but without boundary. In such a space the sum of the angles in a triangle would exceed 180 degrees, and a starship traveling on a straight line would eventually return to its point of origin. If the quantity above is less than one, the Universe is an open space in which triangles contain less than 180 degrees. If the quantity is exactly one, the space is Euclidean, which is also called flat.

Physics of the False Vacuum

THE FALSE VACUUM arises naturally in any theory that contains scalar fields, that is, fields that resemble electric or magnetic fields except that they have no direction. The Higgs fields of the Standard Model of particle physics or the more speculative grand unified theories are examples of scalar fields. It is typical of Higgs fields that the energy density is minimal not when the field vanishes, but instead at some nonzero value of the field. For example, the energy density diagram might look like



The energy density is zero if $\varphi = \varphi_t$, so this condition corresponds to the ordinary vacuum of empty space. In this context it is usually called the "true" vacuum. The state in which the scalar field is near $\varphi = 0$, at the top of the plateau, is called the "false" vacuum. If the plateau of the energy density diagram is flat enough, it can take a very long time, by early Universe standards, for the scalar field to "roll" down the hill of the energy density diagram so that the energy can be lowered. For short times the false vacuum acts like a vacuum in the sense that the energy density cannot be lowered.

temporary. For a period that can be long by the standards of the early Universe, the false vacuum acts as if the energy density cannot be lowered, since the lowering of the energy is a slow process. The underlying physics of the false vacuum state is described in the box on the left.

The peculiar properties of the false vacuum stem from its pressure, which is large and negative (see box on the right). Mechanically such a negative pressure corresponds to a suction, which does not sound like something that would drive the Universe into a period of rapid expansion. The mechanical effects of pressure, however, depend on pressure differences, so they are unimportant if the pressure is reasonably uniform. According to general relativity, however, there is a gravitational effect that is very important under these circumstances. Pressures, like energy densities, create gravitational fields, and in particular a positive pressure creates an attractive gravitational field. The negative pressure of the false vacuum, therefore, creates a repulsive gravitational field, which is the driving force behind inflation.

There are many versions of inflationary theories, but generically they assume that some small patch of the early Universe somehow came to be in a false vacuum state. Various possibilities have been discussed, including supercooling during a phase transition in the early Universe, or a purely random fluctuation of the fields. A chance fluctuation seems reasonable even if the probability is low, since the inflating region will enlarge by many orders of magnitude, while the non-inflating regions will remain microscopic. Inflation is a wildfire that will inevitably take over the forest, as long as there is some chance that it will start.

Once a patch of the early Universe is in the false vacuum state, the repulsive gravitational effect drives the patch into an inflationary period of exponential expansion. To produce a universe with the special features of the Big Bang discussed above, the expansion factor must be at least about 10^{25}. There is no upper limit to the amount of expansion. Eventually the false vacuum decays, and the energy that had been locked in it is released. This energy produces a hot, uniform, soup of particles, which is exactly the assumed starting point of the traditional Big Bang theory. At this point the inflationary theory joins onto the older theory, maintaining all the successes for which the Big Bang theory is believed.

In the inflationary theory the Universe begins incredibly small, perhaps as small as 10^{-24} cm, a hundred billion times smaller than a proton. The expansion takes place while the false vacuum maintains a nearly constant energy density, which means that the total energy increases by the cube of the linear expansion factor, or at least a factor of 10^{75}. Although this sounds like a blatant violation of energy conservation, it is in fact consistent with physics as we know it.

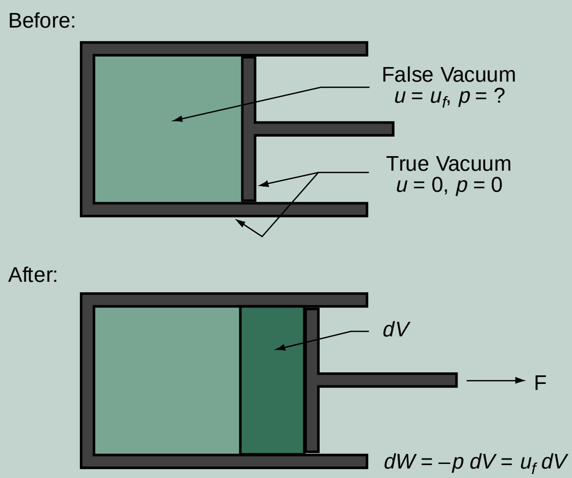
The resolution to the energy paradox lies in the subtle behavior of gravity. Although it has not been widely appreciated, Newtonian physics unambiguously implies that the energy of a gravitational field is always negative, a fact which holds also in general relativity. The Newtonian argument closely parallels the derivation of the energy density of an electrostatic field, except that the answer has the opposite sign because the force law has the opposite sign: two positive masses attract, while two positive charges repel. The possibility that the negative energy of gravity could balance the positive energy for the matter of the Universe was suggested as early as 1932 by Richard Tolman, although a viable mechanism for the energy transfer was not known.

During inflation, while the energy of matter increases by a factor of 10^{75} or more, the energy of the gravitational field becomes more and more negative to compensate. The total energy—matter plus gravitational—remains constant and very small, and could even be exactly zero. Conservation of energy places no limit on how much the Universe can inflate, as there is no limit to the amount of negative energy that can be stored in the gravitational field.

This borrowing of energy from the gravitational field gives the inflationary paradigm an entirely different perspective from the classical Big Bang theory, in which all the particles in the Universe (or at least their precursors) were assumed to be in place from the start. Inflation provides a mechanism by which the entire Universe can develop from just a few ounces of primordial matter. Inflation is radically at odds with the old dictum of Democritus and Lucretius, "Nothing can be created from nothing." If inflation is right, everything can be created from nothing, or at least from very little. If inflation is right, the Universe can properly be called the ultimate free lunch.

Pressure of the False Vacuum

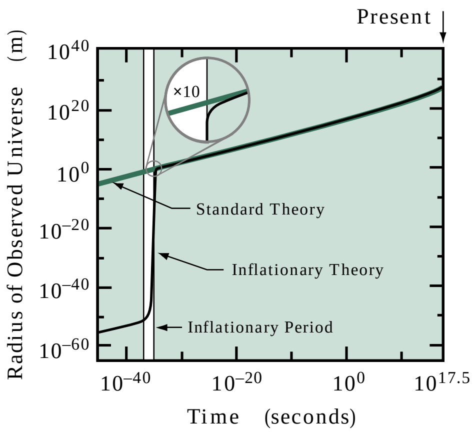
THE PRESSURE OF THE FALSE VACUUM can be determined by a simple energy-conservation argument. Imagine a chamber filled with false vacuum, as shown in the diagram below.



For simplicity, assume that the chamber is small enough so that gravitational effects can be ignored. Since the energy density of the false vacuum is fixed at some value u_f, the energy inside the chamber is $U = u_f V$, where V is the volume. Now suppose the piston is quickly pulled outward, increasing the volume by dV. If any familiar substance were inside the chamber, the energy density would decrease. The false vacuum, however, cannot rapidly lower its energy density, so the energy density remains constant and the total energy increases. Since energy is conserved, the extra energy must be supplied by the agent that pulled on the piston. A force is required, therefore, to pull the piston outward, implying that the false vacuum creates a suction, or negative pressure p. Since the change in energy is $dU = u_f dV$, which must equal the work done, $dW = -p dV$, the pressure of the false vacuum is glven by

$$p = -u_f .$$

The pressure is negative, and extremely large. General relativity predicts that the gravitational field which slows the expansion of the universe is proportional to $u_f + 3p$, so the negative pressure of the false vacuum overcomes the positive energy density to produce a net repulsive gravitational field.



The solution to the horizon problem. The green line shows the radius of the region that evolves to become the presently observable Universe, as described by the traditional Big Bang theory. The black line shows the corresponding curve for the inflationary theory. Due to the spectacular growth spurt during inflation, the inflationary curve shows a much smaller Universe than in the standard theory for the period before inflation. The uniformity is established at this early time, and the region is then stretched by inflation to become large enough to encompass the observed Universe. Note that the numbers describing inflation are illustrative, as the range of possibilities is very large.

INFLATION AND THE VERY SPECIAL BANG

Once inflation has been described, it is not hard to see how it produces just the special kind of bang that was discussed earlier.

Consider first the horizon problem, the difficulty of understanding the large-scale homogeneity of the Universe in the context of the traditional Big Bang theory. Suppose we trace back through time the observed region of the Universe, which has a radius today of about 10 billion light-years. As we trace its history back to the end of the inflationary period, our description is identical to what it would be in the traditional Big Bang theory, since the two theories agree exactly for all times after the end of inflation. In the inflationary theory, however, the region undergoes a tremendous spurt of expansion during the inflationary era. It follows that the region was incredibly small before the spurt of expansion began—10^{25} or more times smaller in radius than in the traditional theory. (Note that I am not saying that Universe as a whole was very small. The inflationary model makes no statement about the size of the Universe as a whole, which might in fact be infinite.)

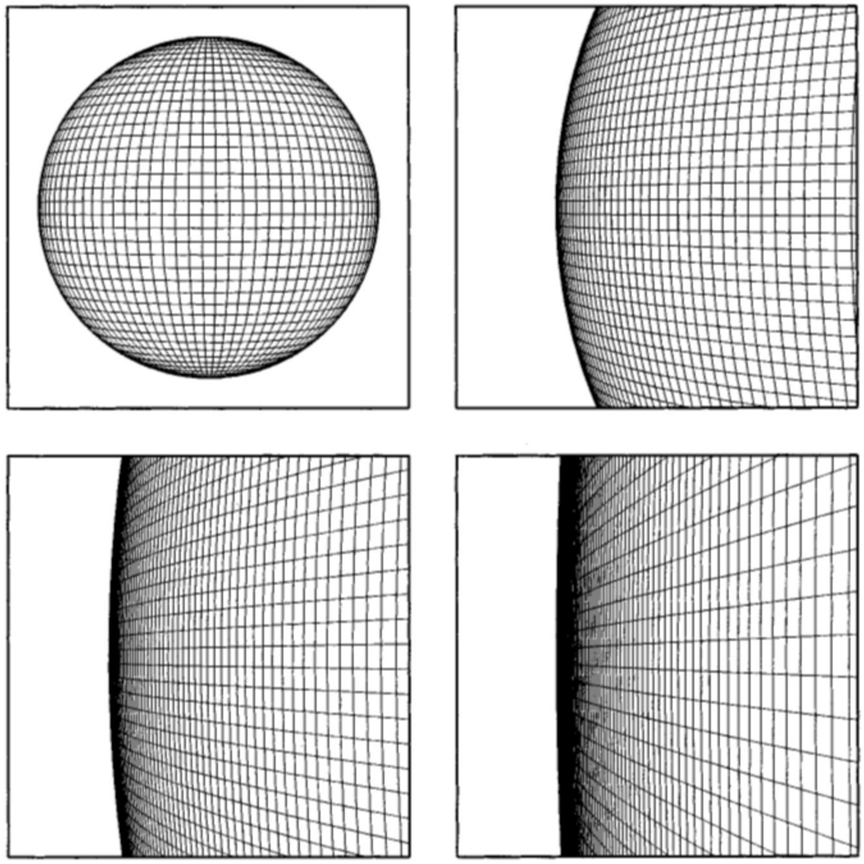
Because the region was so small, there was plenty of time for it to come to a uniform temperature, by the same mundane processes by which a cup of hot coffee cools to room temperature as it sits on a table. So in the inflationary model, the uniform temperature was established before inflation took place, in an extremely small region. The process of inflation then stretched this region to become large enough to encompass the entire observed Universe. The uniformity is preserved by this expansion, because the laws of physics are (we assume) the same everywhere.

The inflationary model also provides a simple resolution for the flatness problem, the fine-tuning required of the mass density of the early Universe. Recall that the ratio of the actual mass density to the critical density is called omega, and that the problem arose because the condition $\Omega = 1$ is unstable: omega is always driven away from one as the Universe evolves, making it difficult to understand how its value today can be in the vicinity of one.

During the inflationary era, however, the peculiar nature of the false vacuum state results in some important sign changes in the equations that describe the evolution of the Universe. During this period, as we have discussed, the force of gravity acts to accelerate the expansion of the Universe rather than to retard it. It turns out that the equation governing the evolution of omega also has a crucial change of sign: during the inflationary period the Universe is driven very quickly and very powerfully *towards* a critical mass density. This effect can be understood if one accepts from general relativity the relationship between a critical mass density and the geometric flatness of space. The huge expansion factor of inflation drives the Universe toward flatness for the same reason that the Earth appears flat, even though it is really round. A small piece of any curved space, if magnified sufficiently, will appear flat.

Thus, a short period of inflation can drive the value of omega very accurately to one, no matter where it starts out. There is no longer any need to assume that the initial value of omega was incredibly close to one.

Furthermore, there is a prediction that arises from this behavior. The mechanism that drives omega to one almost always overshoots, which means that even today the mass density should be equal to the critical value to a high degree of accuracy. (If Einstein's cosmological constant Λ is nonzero, this prediction is modified to become $\Omega + \Lambda/3H^2 = 1$, where H is Hubble's constant.) Thus, the determination of the mass density of the Universe could be a very important test of the inflationary model. Unfortunately, it is very difficult to reliably estimate the mass density of the Universe, since most of the matter in the Universe is "dark," detected only through its gravitational pull on visible matter. Current estimates of omega range from 0.2 to 1.1. Nonetheless, it is likely that this issue can be settled in the near future. The high precision measurements of the microwave background radiation that will be made by the Microwave Anisotropy Probe, scheduled for launch in about 2001, are expected to pin down the value of omega to about 5 percent accuracy.



The expanding sphere illustrates the solution to the flatness problem in inflationary cosmology. As the sphere becomes larger, its surface becomes flatter and flatter. Similarly the inflation of space causes it to become geometrically flat, and general relativity implies that the mass density of a flat universe must equal the critical value.

THE CURRENT PICTURE

While it may be too early to say that inflation is proved, I claim that the case for inflation is compelling. It is hard to even conceive of an alternative theory that could explain the basic features of the observed Universe. Not only does inflation produce just the kind of special bang that matches the observed Universe, but quantum fluctuations during inflation could have produced nonuniformities which served as the seeds of cosmic structure. These nonuniformities can be observed directly in the cosmic background radiation, with an amplitude of about one part in 100,000. So far the measurements of the spectrum have been beautifully consistent with the predictions of inflation, although it must be admitted that nonuniformities created by cosmic strings are also consistent with the observations. Cosmic strings, however, cannot explain the large-scale homogeneity or the flatness of the Universe.

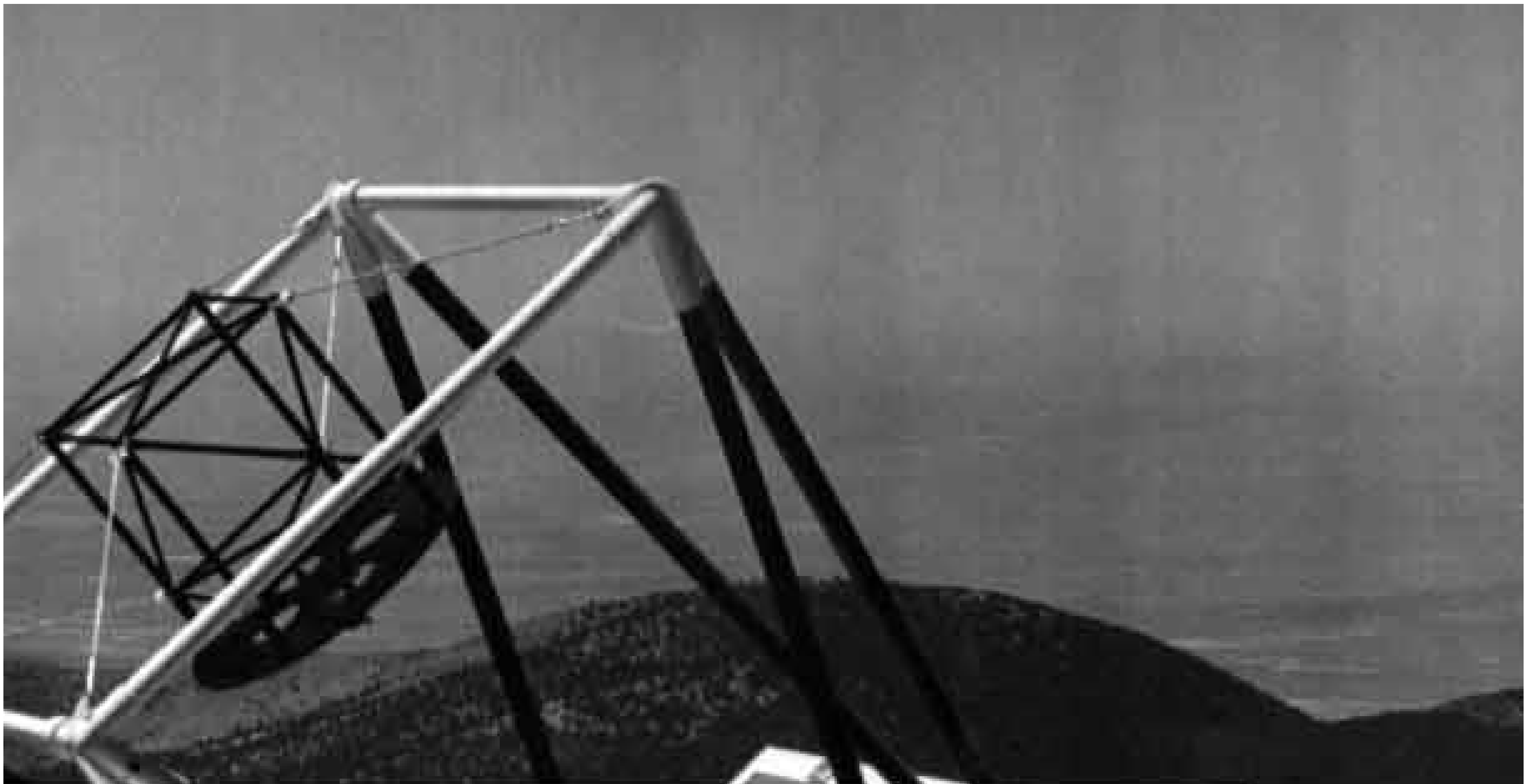
While the case for inflation is strong, it should be stressed that inflation is really a paradigm and not a theory. The statement that the Universe arose from inflation, if it is true, is not the end of the study of cosmic origins—it is in fact closer to the beginning. The details of inflation depend upon the details of the underlying particle physics, so cosmology and particle physics become intimately linked together. While I cannot see any viable alternative to the general idea of inflation, there is still much work to be done before a detailed picture is established. And I suspect that there is room for many new important ideas.

Pi on the Sky

The Sloan Digital Sky Survey

by HEIDI JO NEWBERG

WHEN THE originators of the Sloan Digital Sky Survey (SDSS) met at O'Hare International airport in the fall of 1988, their intent was to form a collaboration that would measure the size of the largest structures of galaxies in the Universe. Previous galaxy surveys had shown that the largest structures were at least 400 million light years in extent—as large as the largest structures that could have been found by these surveys. In particular, the results of the CfA Redshift Survey were astounding. From the spectra of one thousand galaxies, the researchers were able to depict a slice of our Universe with large "voids" (where the galaxy density was very low) surrounded by dense "walls" of galaxies.



Cosmology had already seen the demise of the perfect cosmological principle in 1929 with Edwin Hubble's discovery that the Universe is expanding, and therefore changes over time. We continue to believe, however, in the cosmological principle—that the Universe is homogeneous and isotropic. To demonstrate the validity of this basic assumption about our Universe, we must be able to find some volume of the Universe that is representative of the whole. It is clear that a much larger galaxy redshift survey is required to find a representative sample of the Universe.

With projects to measure ten to one hundred thousand galaxies already planned or underway, the early organizers of the Sloan Digital Sky Survey (SDSS) proposed a redshift survey of one million galaxies. Rather than looking at a slice of the Universe, this new survey would measure the position of every galaxy in a patch of sky π steradians (one quarter of the sky) in size. The survey would measure the distances to galaxies three magnitudes fainter (about four times farther away) than those observed in the CfA Redshift Survey. In addition, these million galaxies would not be chosen from the photographic sky surveys already in existence. Rather, they would be selected from a new, carefully controlled survey of the sky using a large charge-coupled device (CCD) camera. By imaging the sky in several optical passbands, including an ultra-violet passband, the data from this sky survey would also be used to select quasi-stellar objects (QSOs). As the most distant collapsed objects ever observed in our Universe, these would give us information about the structure of the Universe on the largest possible scales. The survey was projected to take five years to build, with an additional five years of operation to complete the scientific objectives.

Kurt Anderson

Above: The Apache Point Observatory in Sunspot, New Mexico. The SDSS 2.5 meter telescope (left) is shown with its protective building rolled away, as for nightly operation. Also shown is the monitor telescope dome (top right). (Courtesy Apache Point Observatory)

Middle: Prototype fiber plug-plate for the SDSS spectrograph. During operation, all 640 fibers will be inserted into the plug-plates by hand. Several plates will be plugged during the day in preparation for a night's observations. Each fiber will guide the light from a galaxy, QSO, or star into the spectrograph camera. (Courtesy Fermilab Visual Media Services)

Although it may not have been recognized at the time, the addition of the imaging survey transformed the SDSS project from an ambitious attempt to trace the large scale structures in the Universe into a plan to statistically sample everything in a large corner of the visible Universe. What these planners had dreamed up was an imaging survey covering ten thousand square degrees of the sky in four filters; a catalog of the 70 million stars, 50 million galaxies, and one million QSOs visible in the imaging survey; and a spectroscopic survey of more than a million of these objects—all rolled into one enormous project. This statistical sample will have a tremendous impact not only on our understanding of the largest structures, but on every aspect of astronomy.

Any one of these three projects (the imaging survey, the catalog, or the spectroscopic survey) would have been considered large by the standards of ground-based astronomy. Any one of the three could be scientifically justified on its own merit. All together, the project is as colossal as its impact will be on astronomy. Okay—the goals, the timeline, and the budget were optimistic. But if we were not attempting the impossible, we would not be on the forefront of research.

THE SLOAN DIGITAL SKY Survey has attracted the active participation of over one hundred scientists, engineers, and software professionals from eight astronomy groups and departments, including: Princeton University, The University of Chicago, The Johns Hopkins University, the Japan Participation Group (scientists at the Universities of Tokyo and Kyoto), the United States Naval Observatory, the University of Washington, the Institute for Advanced Study, and Fermi National Accelerator Laboratory. The survey is being carried out under the auspices of the Astrophysical Research Consortium (ARC) and has received significant funding, totaling about 54 million dollars, from the Alfred P. Sloan Foundation (NY), from the National Science Foundation, and from each of the member institutions.

The goals and scope of the project have changed only slightly from those put forth by the "O'Hare group." Since the main survey area is not observable during part of the year, three extra strips of sky have

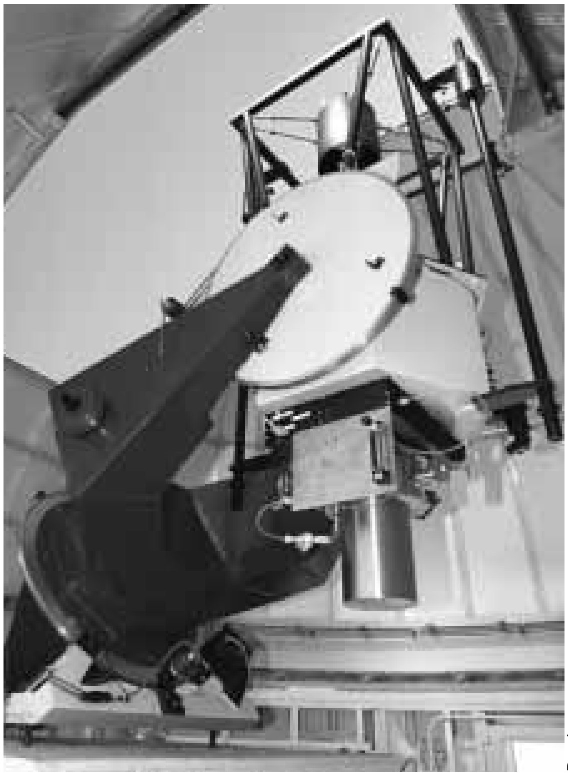
been added to fill in the gap. Also, we have added one passband to the imaging survey, for a total of five filters. Mostly, we have made tremendous progress designing and building the hardware and software necessary to assure our success.

The astronomical data for the SDSS will be obtained from two dedicated telescopes located at Apache Point Observatory in Sunspot, New Mexico. The data will be partially processed at the observatory before being sent to Fermi National Accelerator Laboratory, where the majority of the data processing, storage, and distribution will take place. The main SDSS telescope has a primary mirror 2.5 meters in diameter and a field of view three degrees in diameter. It will support two instruments: a photometric camera containing 54 CCDs and a spectrograph with 640 fibers. A fully automated 24-inch diameter telescope will operate simultaneously. The survey software is designed to operate these telescopes, plan imaging and spectroscopic observations so as to minimize the survey time-to-completion, acquire the data from all survey instruments, process imaging data into catalogs of astronomical objects and their associated parameters, calibrate the positions and luminosities of the measured objects, merge the data from different CCDs and different nights into one large catalog, select from this catalog the sources for which we will obtain spectra, organize the targeted objects into separate spectroscopic exposures, reduce spectroscopic exposures into lists of objects with classifications and redshifts, and store the results of all of these steps in a large database.

Dan Long

Telescope engineer Charlie Hull poses with the skeleton of the Sloan Digital Sky Survey's 2.5 meter telescope shortly after it was installed.

THE SDSS is aggressively charting new territory both in the design of the telescope and instruments, and in the processing and acquisition of the scientific data. The spectrograph will be capable of observing more objects at one time than any other in the world. The photometric camera will have more pixels in the focal plane than any other CCD camera in



Dan Long

This 24-inch telescope will be used to define the SDSS filter system and will also monitor the atmosphere during operations.

existence. Our catalog of objects will be the largest, and will have better positional and photometric accuracy than any other catalog of its kind. In order to assure the astrometric and photometric uniformity we require for describing our statistical samples of the sky, we have included in the design several novel instruments which will allow us to evaluate and calibrate the data better than any previous survey. I will discuss here only a few of the innovations which make the survey possible.

The 2.5 meter telescope is specially designed to reduce "dome seeing," the distortion of images caused by turbulence in the air very close to the telescope. To reduce distortion caused by disruption of the laminar flow of air over the observatory, the SDSS telescope is cantilevered over the edge of a cliff in the direction of the prevailing wind. In addition, we use a roll-off building which eliminates the telescope building as a potential cause of heat, which also contributes to image distortion. During operation, the telescope is protected from wind and stray light by a baffle that is mechanically separated from the telescope, but that moves and tracks with it.

In all areas of optical astronomy except surveys, data from CCD cameras has supplanted data from photographic plates. CCD cameras, unlike the plates, have linear response functions and much higher efficiency for detecting light, which makes possible more accurate photometric (luminosity) measurements. Until now, these cameras were not used for surveys because it was not possible to cover enough sky with one camera for a large area survey to be tractable. By building a camera with 30 large CCDs and using a drift-scanning technique, we will not only be able to survey large areas of sky, but also to obtain the images simultaneously in five filters.

In addition to the array of 30 photometric CCDs, the focal plane contains 22 smaller astrometric CCDs, which are used to calibrate the positions of the survey objects. These CCDs image both the astrometric standard stars (which are saturated on the photometric CCDs) and also some of the brighter stars that will be unsaturated on the photometric CCDs. This allows us to tie our data to a coordinate system that is fixed on the sky. Also, it allows us to measure more accurately the relative positions of the objects found in separate CCDs in the photometric array. By comparing the same stars as imaged at the beginning and end of the CCD array, we can assess how well the telescope is tracking its trajectory in the sky.

The photometric accuracy of our catalogs will be limited by our ability to characterize the atmospheric conditions during the night. Even though photometry will be attempted only on the clearest, most stable nights, we will measure the transparency of the atmosphere as a function of time, filter, and position in the sky. The suitability of a given night for photometry will be determined with data from a weather station which logs the temperature, wind speed and direction, humidity, and dust level. In addition, the weather station includes a camera which images the whole sky at 10 microns every 20 minutes. At this wavelength, clouds stand out very

Mike Carr

Project Scientist Jim Gunn mounts the quartz corrector for the SDSS photometric camera.

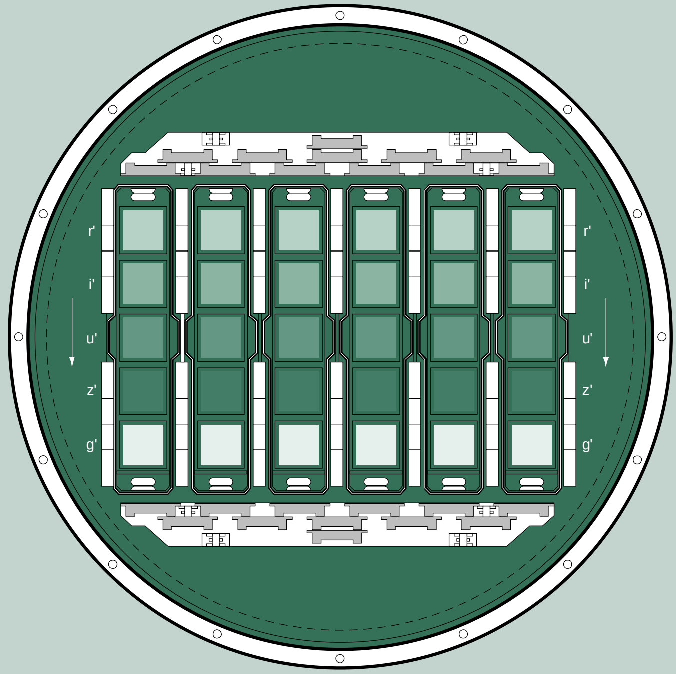
Drift-Scanning the Sky

THE SDSS CAMERA will drift-scan the sky, rather than using the more common point-and-shoot method, in order to increase the fraction of the time that the imaging camera is integrating light from the sky and to reduce the number of images that must be pieced together. Point-and-shoot observations are obtained by tracking the apparent motion of the target object in the sky, and opening and closing a shutter to expose the detector. Drift-scanning is usually done by fixing the position of the telescope and moving the photo-sensitive material to track the target object. The Sloan Digital Sky Survey will have to move both the telescope and the detector to image the survey area.

Before explaining how the SDSS camera works, let me first describe a much simpler drift-scanning camera. Imagine a telescope in a fixed position on the Earth's equator, and pointing directly overhead. The telescope focuses light from the sky onto a single charged coupled device (CCD) in the focal plane. As the Earth turns, stars will enter the field-of-view of the CCD, travel across it at constant speed, and then disappear from view. To drift-scan, the two dimensional array of pixel detectors on the CCD must be aligned so that the crossing star travels exactly along one column. As light from the star moves from one row of the CCD to the next, all of the accumulated photoelectrons are also moved to the next row. This leaves one empty row of pixels at the beginning of the CCD, ready to start exposing a new part of the sky. The photoelectrons in the last row are read out and digitally stored in a computer. The camera accumulates data continuously along one equatorial strip of sky, without stopping to read the data out of the CCD while the shutter is closed. The effective exposure time of the data is the crossing time of a star across the camera.

To scan across the sky in a direction that is not along constant latitude or that is far from the equator requires the telescope to track and (in most cases) the CCD to rotate. Tracking is also required to drift at arbitrary rate (which sets the exposure time) across the sky. The first telescope and CCD combination capable of driven drift scans in arbitrary directions was the Fermilab Drift-Scan Camera mounted on the ARC 3.5 meter telescope at Apache Point Observatory, adjacent to the SDSS telescope site. The camera, which was commissioned in 1994, was built as a prototype for testing SDSS data-acquisition software.

The SDSS camera puts 30 large, 2048×2048 pixel CCDs in the focal plane of the telescope—six columns of five CCDs. The six columns each scan a separate strip of sky while the camera is imaging. Each of the five CCDs in a given column images the same strip of sky, but using a different filter. The effective exposure time in each filter is about 55 seconds. A given object will first traverse the CCD with the *r′* filter, then the *i′*, *u′*, *z′*, and *g′* filters, in succession. It takes about 5.8 minutes to traverse all five filters. Each column images a strip of sky 13.7 arc minutes wide which increases in length by 15 degrees per hour. A similar camera operated in point-and-shoot mode would spend about as much time exposing a 55-second image as it did reading out the CCD. Also, we would need to piece together 250,000 individual images rather than about 1000 long, continuous strips.



The focal plane of the SDSS camera. The camera contains 30 photometric CCDs (shaded squares), 22 astrometric CCDs (shaded rectangles), and 2 focus CCDs (topmost and bottommost shaded rectangles). (Courtesy Mike Carr)

In addition to the photometric CCDs, there are 22 astrometric chips and two focus chips in the focal plane. Since these CCDs are the same width and pixel scale as the photometric chips, each row is read out with the same frequency—producing the same 9.5 megabytes per minute per CCD. Fewer rows in the astrometric and focus CCDs produce shorter exposure times rather than lower data rates. The data from the focus chips will be used to automatically adjust the focus in real time. Twelve of the astrometric chips, those at the leading and trailing edge of each column of photometric CCDs, will be used to assure that the rotation of the camera is aligned with the transit of the sky across the camera and to measure the uniformity of the tracking rate. The ten interleaving astrometric CCDs tie together the positions of the objects found in adjacent columns of CCDs.

The SDSS photometric camera will image 164 square degrees of sky on an average night. Including overhead and overlaps between strips of sky, we will be able to cover the SDSS survey area in ninety dark, photometric nights.

clearly against the dark sky. This unique camera alerts us to nightly weather changes and detects lone clouds on what is otherwise a completely clear night.

The 24-inch "monitor" telescope has three functions in the survey. First, it will be used to calibrate bright stars of known luminosity with the specially designed SDSS filters. Second, the telescope will allow us to use these bright primary photometric standards to calibrate a fainter and more numerous set of secondary photometric standard stars. These secondary standards will be unsaturated in the photometric array, and allow us to directly calibrate our scans of the sky. Last, this telescope will repeatedly image the primary standard stars throughout the night to track the transparency of the atmosphere. The use of a separate telescope to track the atmosphere is unprecedented in sky surveys.

WITH ALL of these innovations in hardware, the software requires innovative solutions to process the incoming data. Some of the challenges are unique to our survey, such as separating blended objects and matching up the detections in all five filters, merging catalogs of objects measured in separate strips of sky, optimizing the placement of the spectroscopic exposures, and planning observations to reduce time-to-completion. Even tasks that have been done many times before, such as removing instrumental effects from the raw data, object detection and measurement, and extraction and calibration of spectral data, must be optimized for our experiment. In addition, the data must be analyzed within a week or two after it is obtained so that spectrocopic targets can be selected for observation during the next lunation.

By far the most critical challenge for the software is the ability to produce highly accurate and uniform results without human intervention. In one night, the imaging camera for this survey will write to tape 140 gigabytes of data at a rate of 4.8 megabytes per second. By the time the survey has finished, it will have generated on the order of 20 terabytes of imaging data, organized into 3.3 million 6-megabyte images. It would take four and a half years of solid 40 hour weeks for one person to devote ten seconds to each of these images. It would take an additional 1.5 person-years to spend ten seconds on each spectrum. In practice, we will be able to look critically at only a tiny fraction of the data. This means the software will have to identify and correctly handle the brightest stars, the faintest galaxies, satellite trails, globular clusters, nebulae, cosmic-ray hits, telescope glints and reflections, diffraction spikes, and big spiral galaxies on its own. If the image processing software de-blends a big galaxy into many smaller objects, or finds many objects along a satellite trail, the final catalog of objects will be contaminated. Then, the processes that automatically calibrate the data and choose spectroscopic targets will have to be clever about discarding questionable data to prevent large sections of the catalog from being miscalibrated and from wasting many spectroscopic observations on junk. The uniform results rely not only on the software that identifies the objects, but also on the software that records the time, conditions, and telescope position when the data were acquired; the software that controls the automated monitor telescope and reduces the images; the software that selects several dozen different types of spectroscopic targets with their individual selection criteria; and on our ability to effectively monitor the process.

Building the data processing and storage systems necessary to run the SDSS requires a higher level of infrastructure than is available at any of the universities involved with this project. In implementing the data acquisition system, the infrastructure for the data processing software, and the mechanisms for data storage, we have benefited from Fermilab's many years of experience with high energy physics experiments. Like high energy physics experiments, the scientific objectives, instruments, and software are provided by scientists at Fermilab and at each of the institutions in the collaboration. The staff at Fermilab supplies the expertise in managing large scientific projects, and the accompanying infrastructure that bring the project together. Fermilab staff have been instrumental in instituting coding standards; maintaining code management and versioning systems; specifying and procuring hardware; supporting the database; and making vast amounts of storage on tape robots available to the collaboration. Because of our presence at Fermilab, we were one of the first projects in the world to put our documentation on the World Wide Web (we were there before X-Mosaic, let alone Netscape, ever existed!). In the future, we will be using Fermilab's resources and experience to operate our production system. In return, experience gained from implementing the new technologies used by our project will benefit high energy physics projects of the future.

by ANDREW PHILLIPS & NICOLE VOGT

PROBING THE EVOLVING UNIVERSE

The evolution of the Universe can be compared to a display of fireworks that has just ended. Some few wisps, ashes and smoke. Standing on a well-chilled cinder, we see the slow fading of the suns and try to recall the vanished brilliance of the origin of the worlds.

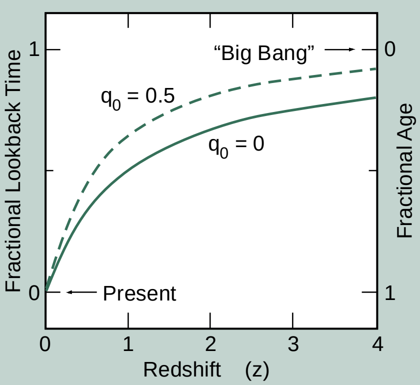
—George Lemaitre (1930)

FAR ABOVE TROPICAL blue seas, in the rarefied air atop Hawaii's Mauna Kea volcano, astronomers are seeking clues to understanding the evolution of galaxies in the Universe. When did galaxies form? What physical processes dominated? Why do galaxies have different morphologies? What is the distribution of matter in the Universe, and how did it change with time?

Astronomers working on the evolution of the Universe have a unique opportunity: because of finite light-travel time, the more distant a galaxy is, the further back in time we are seeing it. The "look back" time to a galaxy is directly proportional to its distance, but galaxy distance is not directly measurable. However, in an expanding universe, the distance to a galaxy can be derived from its redshift—how much its light has been shifted to longer, or redder, wavelengths (see sidebar on the next page).

The Expanding Universe

IN 1929, Edwin Hubble discovered the expansion of the Universe, noting that most galaxies have Doppler shifts in their spectra indicating motion away from us, with the most distant receding the fastest. This so-called redshift is now generally interpreted as due to the stretching of the fabric of space-time in the expanding Universe. It is parametrized as $z = (\lambda_{obs} - \lambda_0)/\lambda_0$, the fractional ratio of observed to emitted wavelengths of light. Redshift is related to the distance of the object—astronomers often use redshift and distance interchangeably—and is key to converting observed quantities like a galaxy's apparent size and brightness into actual size and luminosity. Due to the finite speed of light, as we look to greater distance we are looking back in time, meaning we observe distant galaxies not as they are today but as they were some time in the past. The most distant galaxies known have redshifts of $z \sim 3$–4, corresponding to look back times of 80–90 percent of the age of the Universe.



Two major problems impede the comparison of past and present galaxies. At different redshifts, we observe different regions of the spectrum. For example, what we observe as the optical spectrum of a $z \sim 3$ galaxy was emitted in the ultraviolet near Lyman α (1216 Å), a spectral region which is little studied for local galaxies because it is accessible only to space-based instruments. At the same redshift, the familiar optical region of the spectrum has been shifted into the infrared to wavelengths of ~2–3 μm, a region of poor sensitivity from the ground and for which space-based instruments have not yet been built.

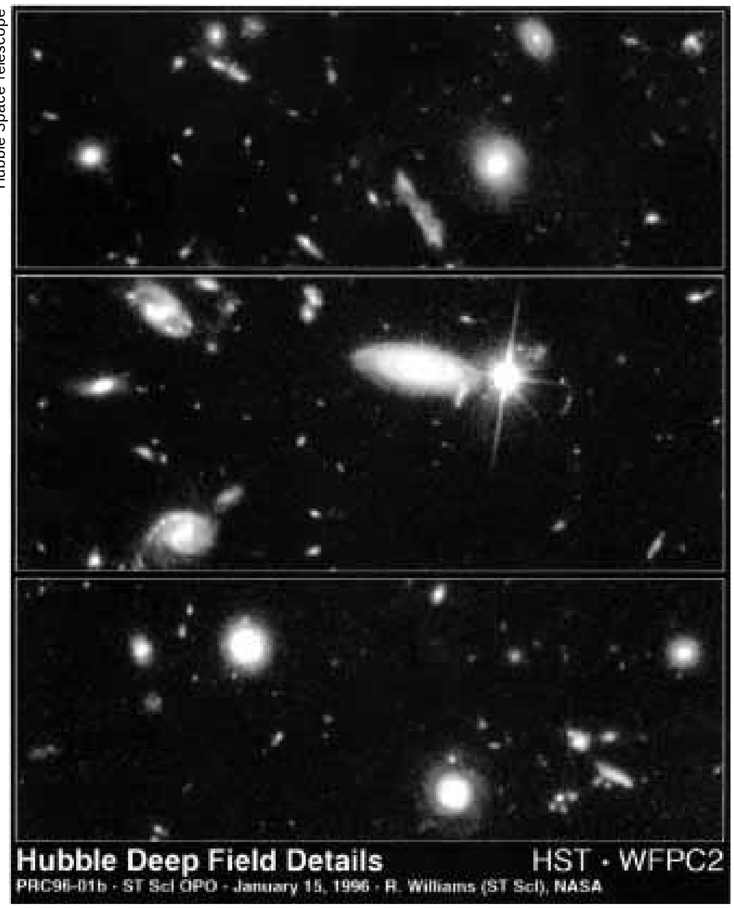
The second problem involves the conversion of observed parameters such as size and brightness into intrinsic properties, for which we also need to know the geometry of the Universe—that is, the rate of expansion and the curvature of space-time, which depends on its overall density. These two quantities are described by the "Hubble constant," H_0, and the deceleration parameter, q_0. Astronomers now agree on the value of H_0, which describes the rate of expansion, to within ±30 percent. The effects of q_0 only become strongly apparent at redshifts $z \sim 1$ and greater, however, and its value is controversial. Galaxy counts and apparent size distributions favor a low value ($q_0 < 0.1$), indicating a Universe of such low density that gravity does little to slow the expansion. Cosmologists, however, favor a value of $q_0 = 0.5$, a critical value required by popular models and for which the Universe contains just enough matter to stop the expansion after an infinite amount of time. These two models for the Universe are sometimes referred to as "open" and "critically closed" universes.

The most widely accepted model of the Big Bang theory has structure forming very early in the expanding, cooling Universe, as small fluctuations in matter density grow under the influence of gravity. Smaller clumps of matter form first; these later merge to form larger and larger structures. Initially, mass concentrations are in the form of gas and mysterious dark matter, but at some point the gas collapses to form stars. The exact point at which galaxies form is not yet known, nor is the sequence clear—do they form as units of gas with masses similar to galaxies today, or as small units of stars and gas that then merge into more massive galaxies? Some clues are found in the morphologies of present-day galaxies. Certain galaxies, called ellipticals, have light profiles and kinematics consistent with the merging of already-formed stellar systems. Disk galaxies, including the well-known spirals, have flattened, rotating components of stars formed from a pre-existing gas disk. Most spirals also contain a "bulge" component similar in many respects to a small elliptical. The ages of stars in these galaxies are consistent with ellipticals and bulges forming early in the history of the Universe, within the first few billion years, and disks forming much later.

While the details of galaxy formation are still vague, certain expectations for the early Universe are clear. The basic mass units should be smaller than in the present-day Universe, because at very early times the massive galaxies of today should have been in pieces. Star formation should have been much more vigorous than it is today, in order to explain the currently-seen stellar populations of galaxies.

Until quite recently, studies of distant galaxies were limited to counting the number of faint galaxies per square degree in each brightness interval, in different colors. Such number counts were then compared to models of how the local population of galaxies would appear if projected back in time, making various assumptions about the star formation rate, how stellar populations in galaxies age, the rate at which galaxies merge, and the geometry of the Universe. More detailed studies were hampered by two main problems. First, distant galaxies have very small angular sizes, and the blurring caused by the Earth's atmosphere prevented astronomers from determining the structure, or even the size, of such galaxies. Second, distant galaxies are exceedingly faint, and existing telescopes were unable to gather enough photons for even low-resolution spectroscopy—crucial to determining the redshift, and hence distance, age, and the means to convert observed properties into intrinsic sizes and luminosities.

With the launch of the Hubble Space Telescope (HST), and particularly following the refurbishment mission in 1992 to correct its flawed optics, astronomers were finally able to analyze the shapes and angular sizes of truly distant galaxies, those seen back in time at a significant fraction of the age of the Universe. While the Hubble Space Telescope is not large by ground-based standards, from its vantage point above the atmosphere it is able to detect galaxies much fainter than is possible from the ground. However, the superb HST images are impossible to interpret without knowing the redshifts of the galaxies, which are essential to converting apparent size and brightness to intrinsic values. Thus, the second key advance was the building of a next generation of large ground-based telescopes, beginning with the 10-meter Keck telescope in 1994, providing photon-gathering advantages of four to six times over existing instruments. These new telescopes would have the spectroscopic capabilities needed to provide redshifts for the galaxies imaged by HST.



Hubble Space Telscope images of galaxies have superb resolution unattainable from ground-based observatories, but without distance information there is little we can tell about each galaxy. (Courtesy AURA/STScI)

IN 1991, in view of these pending developments, Garth Illingworth, David Koo, and Sandra Faber, three galaxy experts at the University of California at Santa Cruz (UCSC), decided to team up with other experts across the country to orchestrate a systematic study of distant galaxies that had to date been impossible. This project, called the Deep Extragalactic Evolutionary Probe, or DEEP, makes use of the unique facilities of HST and the Keck telescope to push faint galaxy observations to look back times within one or two billion years of the Big Bang.

The study of evolution in galaxies is easy in principle: one simply takes an inventory of galaxies in a nearby volume of space and a similar inventory at greater distances (and

DEIMOS

DEIMOS, the Deep Imaging Multi-Object Spectrograph, is central to the large survey aspect of the DEEP project. In spectroscopic mode, DEIMOS will acquire spectra of roughly 150 faint galaxies simultaneously. For normal survey operations, spectra from 0.4–0.9 μm, at a spectral resolution of ~2000, will be acquired in a single exposure.

DEIMOS consists of two separate optical paths or "beams," each imaging a region roughly 5×16 arcminutes on the sky. For spectroscopy, a thin metal sheet with precisely positioned "slitlets" milled into it is placed in the lightpath; each slitlet covers not only a targeted object but also the adjacent blank sky, as night sky emission lines can be two orders of magnitude stronger than the galaxy signal and must be carefully removed during analysis. The spectrograph camera design, by Harland Epps of the University of California, Santa Cruz is the most ambitious ever attempted in astronomy. The camera consists of seven elements (three of CaF_2), and includes three highly aspheric surfaces. The detector is a mosaic of eight low-noise, high quantum efficiency CCDs arranged in an overall format of 8192×8192 pixels. This configuration is mirrored in the second beam.

As designed, DEIMOS should be roughly 14 times more efficient for faint galaxy spectroscopy than existing instruments. This advantage comes from the large area covered on the sky and the very large detector format which permits observing a wide spectral range at fairly high resolution. In addition, there will be an active optical control to remove any effects of mechanical flexure as the instrument changes position to track the sky, allowing highly precise instrumental calibration.

Currently, DEIMOS is under construction with one of the two proposed beams and is scheduled to be placed on the Keck-II telescope in mid-1998. The second beam is awaiting funding from a private source.

hence look back times) and compares them. In practice, the situation is much more complicated. The local Universe is surprisingly difficult to inventory—since galaxies come in a wide range of morphologies, sizes, and brightness, the inclusion or exclusion of galaxies is affected severely by selection criteria. In addition, covering a sufficiently large volume to get a representative sample means covering large areas on the sky, which has not been feasible to date. Fortunately, the Sloan Digital Sky Survey (see article on page 22), will clarify immensely our understanding of the local galaxy population.

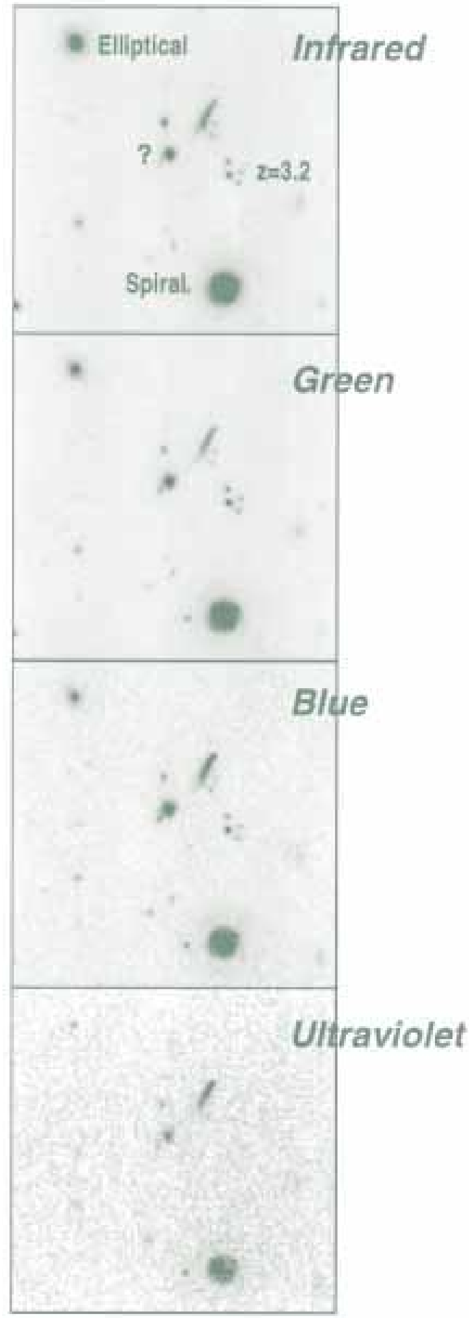
Now consider more distant galaxies. The redshift of each galaxy must be known in order to place it in the correct volume, and to determine its intrinsic luminosity and size. Clearly, the inventories will only be complete down to a particular observed brightness—only the most luminous galaxies will be observed in each volume, and this selection bias worsens with distance. Since we expect the luminosities of galaxies to evolve, this makes a comparison with local samples much more complicated to interpret. Furthermore, any interpretation must include the effects of galaxy merging. Finally, with increasing redshift, the optical observing window corresponds to increasingly shorter wavelengths in the galaxy's spectrum. By a look back time of half the age of the Universe, the visible spectrum of a galaxy corresponds to light emitted in the ultraviolet, a spectral regime dominated by hot, luminous young stars, rather than the older stellar population that accounts for most of the luminous matter in a galaxy.

In order to disentangle evolutionary changes from selection biases, especially given the wide range in galaxy properties, large samples of galaxies with well-defined selection criteria are needed. Furthermore, these samples need to be acquired in several different directions on the sky, both to study the clumpiness in the matter distribution, and to smooth over its effects for evolution studies. Obtaining and interpreting these samples is the primary goal of the DEEP project.

DEEP IS ENVISIONED as a two-phase program. The initial phase seeks to characterize the basic properties of distant galaxies: masses, luminosities, sizes, the abundance of elements other than hydrogen and helium, and dust content. For these purposes, spectra of approximately 1000 distant galaxies must be acquired. The initial phase also permits exploration of various observing strategies for the second phase, a large-scale survey of about 15,000 targets. This second phase depends on the completion of a new spectrograph, DEIMOS (see sidebar on the left).

The initial phase of DEEP has been underway for about two years, and has already generated important discoveries. Most of these—but not all—support the standard view of galaxy evolution.

A few years ago, astronomers realized that young, star-forming galaxies at very high redshift ($z > 3$) would exhibit a unique spectral signature that permits their identification merely from images taken in different colors. Shortward of λ = 912 Å, photons emitted by



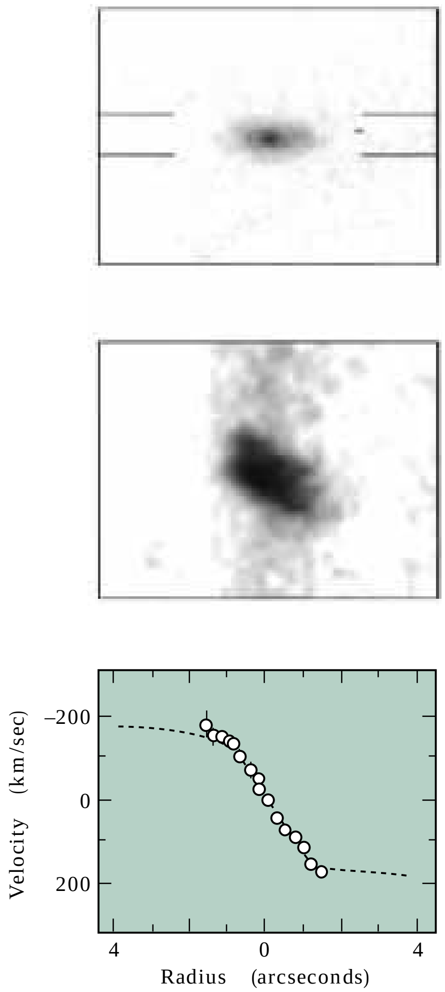
HST images in different colors give limited spectral information. Going from near-infrared through ultraviolet, the intrinsically red elliptical becomes fainter. The spiral remains bright, although its morphology changes as star-forming regions progressively dominate toward the UV. The cluster of four objects at redshift z = 3.2 is intrinsically blue, and stays bright until the UV, when it disappears or "drops out." The object labeled "?" shows similar behavior, although it does not completely disappear in the UV, suggesting a high redshift but with z < 3.

galaxies have sufficient energy to ionize hydrogen in intervening clouds; in effect, the transparency of space falls dramatically and suppresses the light escaping from the galaxy. These changes in the spectrum are so strong that they are easily detected in broad passband images—the high-redshift objects appear relatively blue, but virtually disappear in ultraviolet images (see figure on the right). The technique of selecting such high-z objects was pioneered by Charles Steidel at Caltech (see Virginia Trimble's article in the last issue of the *Beam Line*, Vol. 27, No. 2, p. 31) and has opened up an opportunity to study galaxies at a mere 10 to 20 percent of the age of the Universe.

Last year, DEEP researchers led by James Lowenthal obtained spectra for a dozen such "UV dropout" galaxies, confirming redshifts of $z \sim 3$. These distant objects are luminous yet surprisingly small and display a wide range in morphologies and spectral characteristics. While some astronomers believe these are the progenitors of the bulge components of present-day massive galaxies, caught near the moment of formation, Lowenthal and his coworkers find their numbers to be too great for this—the number of these distant objects matches or exceeds that of luminous galaxies of all types seen today. This, along with the small sizes, suggests that we are seeing "pieces" of galaxies that will later merge into the larger systems seen today.

DEEP researchers Andrew Phillips and Rafael Guzmán headed a study that determined the nature of small, bright galaxies seen in deep images from the HST—galaxies of such small apparent size that even their HST images tell us little. The spectra of these galaxies reveal a redshift distribution roughly similar to that of other galaxies of comparable apparent brightness, showing them to be intrinsically small and luminous. The majority have strong emission lines, revealing vigorous on-going star formation. Also, the width of the emission lines implies low internal velocities, meaning these objects have small masses. These tiny galaxies are very similar to local "H II galaxies," low-mass dwarf galaxies which are forming stars at an extremely high rate. It appears that a significant fraction of the total star formation in the Universe at redshift $z = 0.4$–1.0 took place in such dwarf galaxies, whereas in the present-day Universe a much smaller fraction does so. The fate of these galaxies has yet to be determined—do they fade into faint systems of aging stars, difficult to detect in local surveys, or are they accreted by larger galaxies?

DEEP researchers led by Nicole Vogt have, for the first time, measured the rotational velocity of spiral galaxy disks out to redshifts of $z \sim 1$, or roughly half the age of the Universe. Since the rotational velocity is directly proportional to a galaxy's mass, this enables us to probe galaxy masses at these earlier epochs. In the local Universe, there is a well known linear relation (the "Tully-Fisher Relation") between rotational velocity and luminosity. Surprisingly, the more distant galaxies follow nearly this same relationship, meaning that galaxies very similar to local galaxies existed at significantly earlier ages—even near the expected epoch of disk formation, when we might expect disks to be



Rotation in a distant disk galaxy seen by HST (top) is reflected in the tilted emission lines due to ionized oxygen (middle). The receding and approaching sides of the galaxy disk produce Doppler shifts to the red and blue of the average redshift, z = 0.50. The lower panel shows the measured velocity shifts.

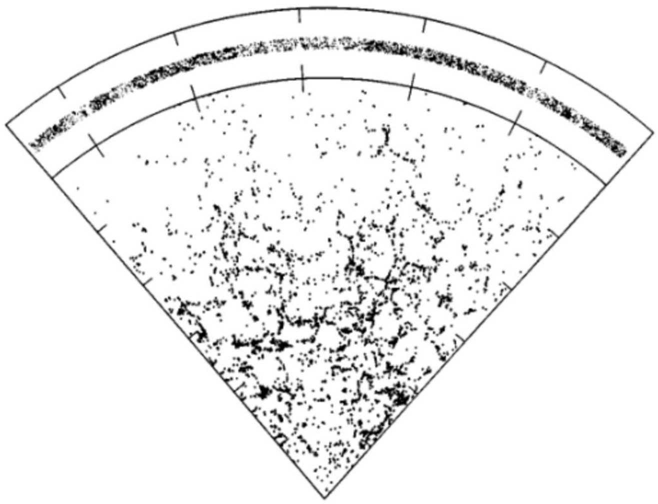
unusually bright due to the vigorous production of new, luminous stars. The exact interpretation of this result is uncertain, but it clearly constrains the amount of evolution in the luminosity of large disk galaxies. The mere existence of well-formed, massive disks so early is problematic for some theories of galaxy formation.

Finally, DEEP and other groups have found sharp "spikes'' in the overall distribution of galaxy redshifts at least out to $z \sim 1$. We know that in the local Universe, galaxies are concentrated in "walls" that outline great bubbles or "voids" (see figure on the next page). These giant structures show up as clumps in the redshifts along any given line of sight. Distant redshift spikes confirm that galaxies at earlier epochs were already organized in similar large structures, as expected from cosmological models. In depth study of the sizes, shapes and velocity dispersion of these distant structures should provide estimates of values of cosmological parameters and insight into the nature of the mysterious dark matter in the Universe. At present the number of galaxies observed is too small to draw significant

Forefront Instruments in Optical Astronomy

STUDIES of distant galaxies such as DEEP have been made possible through the advent of two unique instruments. The Hubble Space Telescope, despite its relatively modest size, provides superb images of faint galaxies that would be impossible to achieve from below the Earth's atmosphere. The W. M. Keck telescope, on the other hand, provides the light-gathering capability needed for spectroscopy of such faint objects. The 10-m Keck telescope, the largest in the world, is based on a novel segmented mirror design by Jerry Nelson of UC's Lawrence Berkeley Laboratories (now at UCSC). Its construction was made possible by a donation from the W. M. Keck Foundation to the California Institute of Technology. The observatory is operated jointly by University of California and Caltech. It is located at the world's best site for optical astronomy, the 4000-m summit of Mauna Kea in Hawaii. The telescope saw first light in 1994, and was joined by an identical twin in 1996. The next telescope of comparable size, the Hobby-Eberly Telescope, at the McDonald Observatory in Texas, is expected to be completed later this year.

Observing time at the Keck telescopes is granted via a proposal/review process at each institution. Generally, no more than two or three nights per semester are granted for any proposal, and specific observing dates are assigned to winning proposals based on the required instrumentation, time of year, and maximum acceptable level of moonlight. A small group of observers travels to the summit to conduct the observations, although an increasing number of observers are opting for remote operation from the headquarter facilities near sea-level, or even via satellite link from their home institutions. Vagaries of weather and equipment add a strong element of chance to the success of any observing run, and time lost to these factors usually means starting over at the initial proposal stage the following year.



The distribution of galaxies in the nearby Universe is not smooth, as shown in this redshift survey across a 1.5˚ × 80˚ "slice" of the sky. We are located at the apex, looking out. The furthest galaxies seen here are about 3 billion light-years away. (Courtesy A. Oemler)

conclusions, but the large-scale DEEP survey will provide the necessary statistics.

As LARGER samples of galaxy spectra are collected, the focus of DEEP will shift toward investigating the large-scale structure of matter in the Universe and how this structure evolves. In addition to the large numbers of redshifts that are determined directly from spectra, the sample will be increased several-fold by measurements of "photometric redshifts." This approach, spearheaded by DEEP scientist Alex Szalay and collaborators at Johns Hopkins University, makes use of multi-color images to construct very coarse "spectra" of hundreds of galaxies in each observed field. While spectral features such as emission and absorption lines are clearly not accessible, the overall energy distribution in the galaxy's spectrum can provide a good estimate of its redshift. The "UV dropouts" discussed above are examples of galaxies identified by this method. The technique requires spectroscopically-measured redshifts for calibration, but once calibrated it can provide both major increases in sample size for determining large-scale structure, and a means of pre-selecting candidates in narrow redshift ranges for high-resolution spectroscopic observations. Such observations will, in turn, provide estimates of the sizes, depths and mass densities of walls and clusters at different look back times.

The questions in extragalactic research and cosmology are well-posed, but until recently the answers have been beyond our reach. With the advances provided by HST, new large telescopes like the Keck, and dedicated surveys like SDSS and DEEP, many of these answers should soon appear. It is an exciting time for astronomy.

The Fate of the Universe

ONE OF THE FUNDAMENTAL PROBLEMS in astrophysics and cosmology concerns the ultimate fate of the Universe. Will it go on expanding, as it has been doing ever since the Big Bang? Or will the gravitational pull of the objects in it eventually halt the expansion so that it either comes to rest or begins a contraction that ends in a Big Crunch?

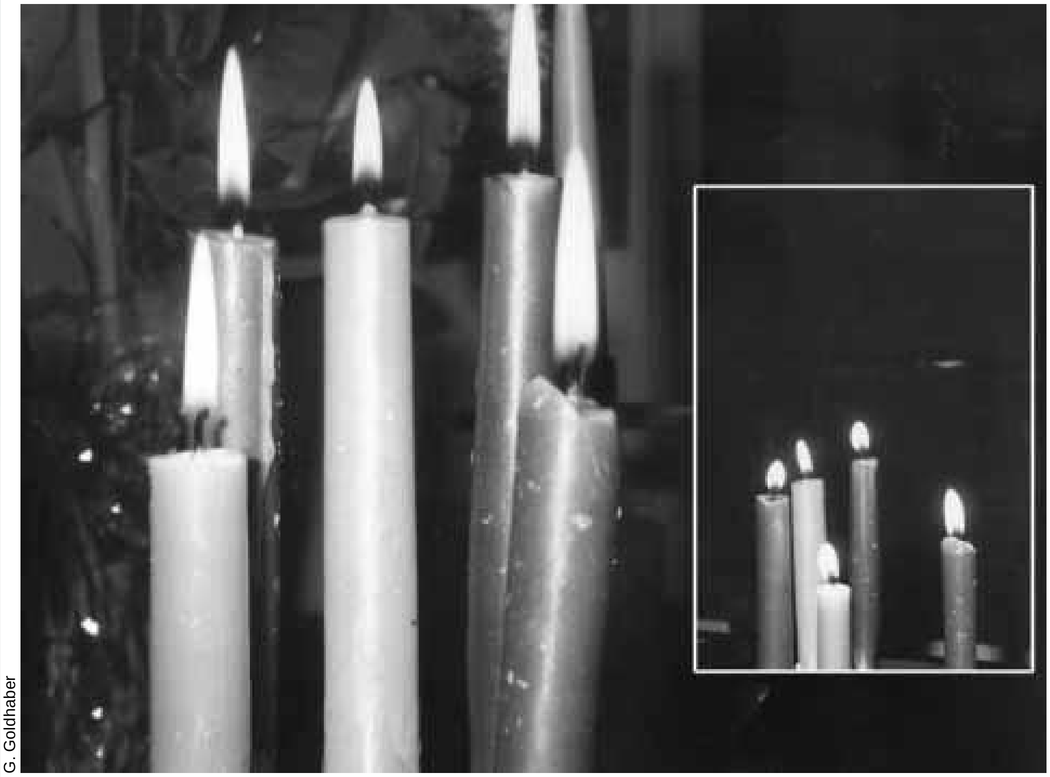
One promising approach to finding an answer is to measure the rate at which galaxies and other cosmological objects are slowing down over time. Around eight years ago, a group of astrophysicists at the Lawrence Berkeley National Laboratory (LBNL), in collaboration with groups in Australia and England, decided to measure this "deceleration rate" through the study of very distant supernovae. This group, known as the Supernova Cosmology Project and headed by Saul Perlmutter, is affiliated with LBNL's Institute for Nuclear and Particle Astrophysics and UC Berkeley's Center for Particle Astrophysics. We now have data from more than 45 distant supernovae (or exploding stars) and have completed a pilot study on the first seven. Soon we can begin to resolve the question of the fate of the Universe.

When we talk about the Universe's expansion, we must be careful not to think of it as analogous to a bomb exploding outwards from a single central point. It is better to imagine space itself expanding between every two points in the Universe, like the space between two dots on the surface of a balloon being blown up. In opposition to this expansion, however, there is another factor at work—the gravitational pull of all the matter in the Universe,

by GERSON GOLDHABER AND JUDITH GOLDHABER

"Standard candles" illustrating the brightness versus inverse square of the distance law. The inset shows the candles at three times the distance to the nearby candle image.

With their discovery of the most distant supernovae ever observed, an international scientific team led by researchers from Lawrence Berkeley National Laboratory hope to learn the ultimate fate of our Universe.


G. Goldhaber

which acts like a brake on the expansion and leads to a deceleration. We know that this deceleration must exist, but we do not know how large it is, or how effective it may be in counterbalancing the expansion.

In the face of this uncertainty, several alternative scenarios for the history and fate of the Universe have been proposed. The first, known as the "negative curvature" or open universe, is one in which the density of matter (and thus the gravitational force) is too small to overcome the initial velocity of the expansion. Such a universe is infinite, one that would continue to expand forever. The second scenario, known as the "positive curvature" or closed universe, is a finite universe—one in which the density of matter is great enough to cause the expansion to come to a halt, reverse direction, and contract towards a final Big Crunch. Finally, in the flat universe, the density is high enough to stop the expansion, but not to bring about a contraction. Such a universe (also considered an infinite universe) would slow down its expansion at such a rate that it would come to rest only after an infinite amount of time.

TYPE IA SUPERNOVAE AS STANDARD CANDLES

What can supernovae tell us about the fate of the Universe? Their usefulness comes about through a rather interesting feature that certain types of supernovae (known as Type Ia) share. They are all of virtually identical intrinsic brightness, and, because of this, we can tell how far away they are.

Readers may be surprised to learn that astronomers still have difficulty measuring distances in the Universe, but they do. A bright object may appear closer to us than a dim one; on the other hand, it may simply be intrinsically brighter. A calculation based on the "redshift"—

the degree to which the spectral lines of light from an object are shifted towards the red end of the spectrum—can provide an estimate within about 20 percent accuracy, but that's not good enough for many cosmological puzzles. What has been needed is an object of known and intense brightness to use as a unit of measure—a "standard candle." Fortunately, there is good reason to believe that Type Ia supernovae (the brightest of all the different types of supernovae) can, with some additional detailed measurements, function as calibrated standard candles.

WHY DO TYPE IA SUPERNOVAE BEHAVE AS STANDARD CANDLES?

There is a Type Ia supernova going off somewhere in the Universe every few seconds. These supernovae begin with a kind of star known as a white dwarf—stars of about the mass of our sun that have gone through a nuclear aging process. First, through fusion, they have converted most of their hydrogen and helium to carbon and oxygen. Then, through a collapse caused by gravitational force, electrons have been stripped from the carbon and oxygen atoms, resulting in the formation of what is called a "degenerate electron gas," in which their nuclei are embedded. A typical white dwarf has a mass close to the mass of our sun, but a radius comparable to that of the Earth.

In order for a white dwarf to end its life as a supernova, it must be part of a binary system with another star—a common occurrence in the heavens. Under these conditions the white dwarf, with its powerful gravitational pull, accretes matter from its large, gaseous companion, and continues to grow ever more massive. When it reaches a critical mass of 1.4 solar masses, the gravitational force overcomes the electron-gas pressure, which occurs due to the quantum mechanical rule that more than two electrons cannot be squeezed into the same space. The star collapses within seconds, and explodes in a Type Ia supernova. These supernovae therefore behave as standard candles; because they all have about the same mass at the time they collapse, they all have about the same intrinsic brightness.

The heat generated in the collapse of the white dwarf leads to fusion of the carbon and oxygen nuclei, and within seconds, the energy released by these fusion reactions causes a rebound. The newly created material is ejected with velocities of about 10,000 to 30,000 kilometers per second. The fusion process continues through a number of steps, ending in a large mass of the radioactive isotope nickel-56, which begins to decay (with a half life of about six days) into its daughter isotope cobalt-56. The cobalt-56, in its turn, decays with a half life of about 77 days to iron-56, which is stable. The ionization produced by these radioactive isotopes yields light that reaches our instruments; their slow decay permits us to observe and study the supernova for about two months. The light intensity reaches a maximum value after about 15 days and then begins to fade.

The Supernova Cosmology Project data were taken at the Isaac Newton and William Herschel Telescopes at the Spanish Observatorio del Roque de las Muchachos; the Kitt Peak National Observatory telescopes; the Keck 10-meter telescopes; the Chilean Cerro Tololo Inter-American Observatory 4-meter telescope, and the Hubble Space Telescope.

FINDING SUPERNOVAE

All the supernovae we see in distant galaxies occurred billions of years ago (typically 4 to 8 billion). By the time their light reaches us, they have long since disappeared—all their mass having dispersed through space in an ever-expanding sphere. Several times a year, in the week just after the new moon, members of our group visit one of several cooperating observatories (in Arizona, Canary Islands, Chile, and elsewhere) and take a series of 10-minute exposures of the night sky with a very sensitive CCD (charge-coupled device) camera mounted on a telescope. We use a powerful telescope (about 4 meters in aperture) and aim it at a region of the sky not too thickly sprinkled with nearby stars from our own galaxy—we are trying to peer out beyond our own cosmological neighborhood into the vastness of the Universe beyond, almost two thirds of the way to its edge. Typically, in two nights we may make about 50 such exposures, observing a total of about 4 square degrees. Each "snapshot" is repeated again some 30 minutes later to give ample exposure time for the most distant galaxies and also to permit us to identify transient phenomena like asteroids or cosmic rays.

Three weeks later, just before the new moon, we go back to the same telescope and take another series of images of the exact same region. We then compare the first set of images (the reference images) with the second set (optimistically called the "discovery images"). When a supernova explodes, it can be as bright or even much brighter than all the rest of the stars in its galaxy combined. Thus a supernova that appeared in the three weeks between the two sets of images reveals itself as a bright spot that shows up clearly when the discovery image is compared with the reference image (see figure on the right). Nearly all the supernovae we find are Type Ia (even though only about 20 percent of the supernovae in the nearby region of the Universe are), since we are looking out into the very distant regions, where dimmer supernovae cannot be detected.

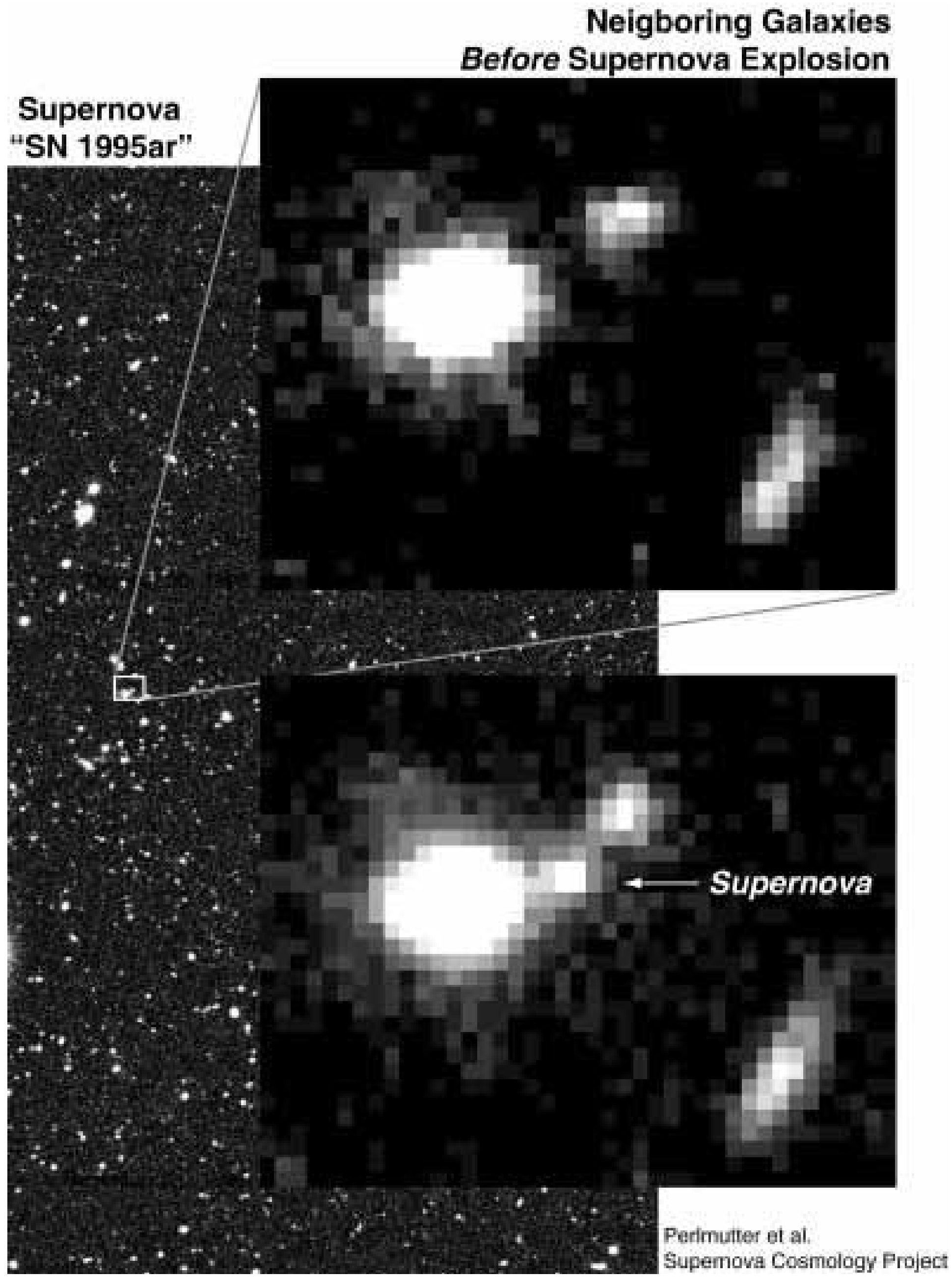
We have described this process as if it were done with visual scanning (as indeed it could be and was some years ago for nearby supernovae), but we actually use computers for almost every step. The CCD images are sent back to Berkeley from the telescope over the Internet, and our computer programs subtract one image from another and flag likely candidates the very same night.

These candidates must then be scrutinized and analyzed further, because several phenomena—a cosmic ray passing through the telescope, a nearby asteroid, a "hot pixel" in the CCD camera—can mimic the bright light of a supernova. We have developed reliable methods of identifying and discarding these three types of impostors; however, a fourth type—an Active Galactic Nucleus (AGN) is harder to identify, and must be eliminated at a later stage through spectroscopy.

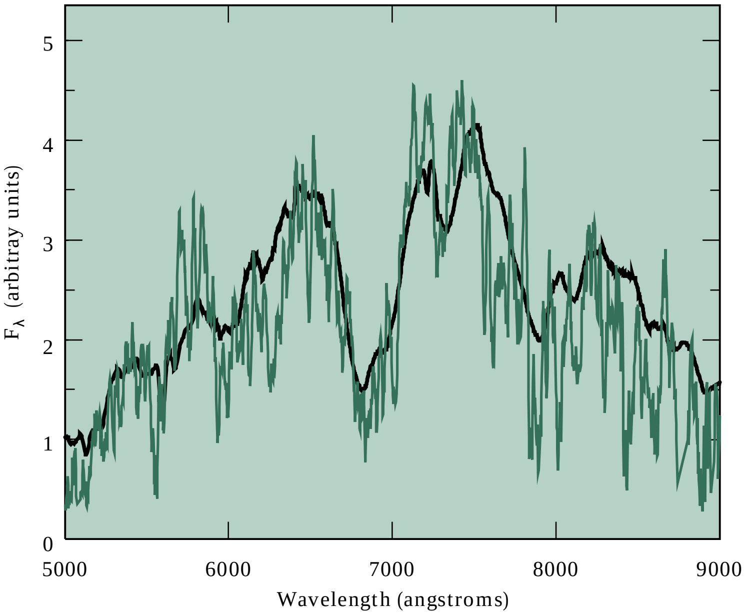
ANALYZING THE DATA

Once we think we have found a supernova, a much more detailed analysis begins. For this analysis, we use two approaches, spectroscopy and photometry.

Spectroscopy has two important functions in our experiment. First, it permits us to recognize candidates



An image of a supernova, SN1995ar, discovered by the Supernova Cosmology Project at a redshift of z = 0.46. Both images were taken using a red filter on the Cerro Tololo, Chile, Inter-American Observatory 4-meter telescope. The Supernova Cosmology Project now has members at Berkeley, California; Cambridge, England; Stockholm, Sweden; Paris, France; Garching, Germany; Batavia, Illinois; Baltimore, Maryland; Sydney and Mt. Stromlo, Australia; and La Silla, Chile.



The spectrum of the most distant clearly identified Type Ia supernova, at a redshift of z = 0.83, SN1997bp. The green curve is the spectrum measured at the 10-meter Keck telescope of the California Association for Research in Astronomy in Hawaii. The black curve is the spectrum of a nearby supernova (SN 1989B), for comparison, with its spectrum shifted to the red by multiplying its wavelength scale by a factor of 1+z = 1.83.

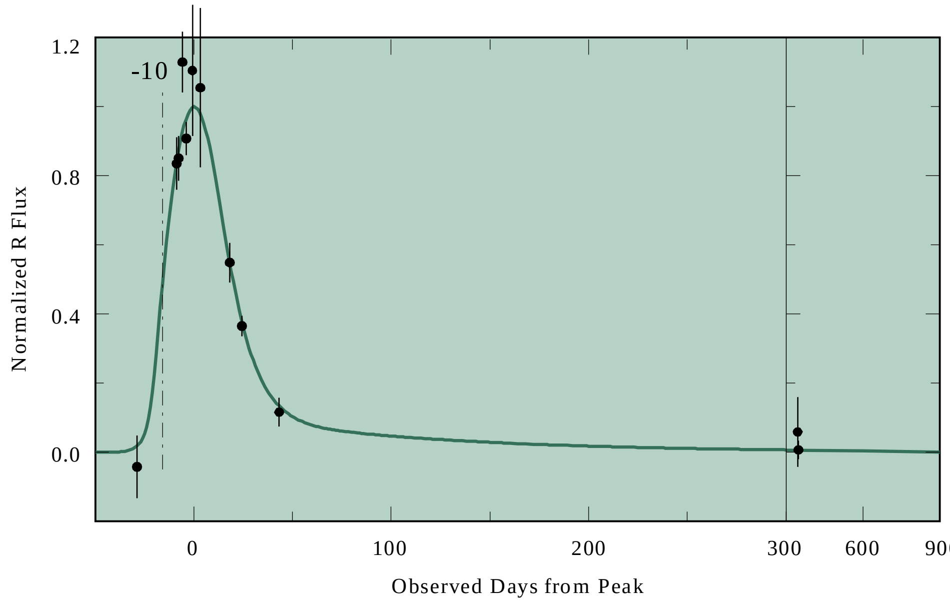
that are clearly identified as Type Ia supernovae and those that are really not (AGNs and supernovae of other types). We do this by identifying the characteristic line spectrum associated with elements between hydrogen and iron in the material ejected from the supernova. Because of the explosive expansion of this material, the spectral lines are characteristically very broad. This so-called "Doppler broadening" comes about because different parts of the ejecta have widely different projected velocities.

Spectroscopy also allows us to calculate the recession velocity—how fast the galaxy containing the supernova was receding from us at the time of the event. In order to find the recession velocity, we observe the degree to which the supernova's spectral lines are shifted towards the red end of the spectrum. As Hubble discovered in 1929, the more pronounced this redshift (which means greater velocity relative to the observer), the more distant the galaxy.

However, terms like "recession velocity"—though adequate for discussing the motion of nearby stars and galaxies—do not describe with sufficient precision what happens to light over immense distances. For this, we must turn to the terminology of General Relativity, in which redshift is expressed not as due to a Doppler shift from a receding object but rather as an increase in the wavelength of light as it traverses space, which is expanding. Cosmologists use the following rule: take the distance between two points at some early time, and multiply it by a scale factor that increases with time. In relativistic terms, then, the redshift equals the difference between the present-day scale factor (a_o) and the smaller scale factor at the earlier time when the supernova occurred (a_s), divided by the scale factor a_s. For simplicity in this article, however, we will continue to use the term "recession velocity"—the language of the Doppler shift for a receding galaxy.

In parallel with the spectroscopic analysis, we also follow up each supernova discovery by obtaining additional images at other telescopes around the world. This allows us to measure the supernova's light curve, the plotted graph of its brightness over time. Typically, the light rises to a peak a few days after it is first observed, and then dims in a slow curve over a period of about two months. It has been established from studies of nearby Type Ia supernovae that this curve is very nearly the same for all. A final image is taken a year later, when the supernova's light has essentially disappeared. This gives us a good measurement of the brightness of the galaxy without the supernova, and—through subtraction—allows us to calculate the peak brightness of our now-vanished supernova.

With the measurement of spectrum and light curve, the observational part of our experiment for a particular supernova is complete, and we are now in a position to calculate the deceleration rate. Clearly, if this rate is large (that is, the expansion is rapidly slowing down) the galaxy containing the supernova will be



Light curve for the supernova SN1995ar discovered by the Supernova Cosmology Project. The points are the measured values. Most of the follow-up points were taken at the Wisconsin-Indiana-Yale National Optical Astronomy Observatory in Arizona. The curve is a standard template in the supernova rest system, fitted to the data. The template curve has been expanded along the time axis by a factor 1+z = 1.46 to take into account the relativistic time dilation due to the expansion of the Universe.

closer to us than it would have been in a universe in which the deceleration rate is small. We are speaking here in general, qualitative terms; however, an equation based on General Relativity directly relates deceleration rate to the three quantities that we have determined—the intrinsic brightness of Type Ia supernovae (based on measurements from known nearby supernovae), their apparent brightness (based on our own measurements of the light curves), and the recession velocity (as indicated by our measurements of the redshift).

OMEGA & LAMBDA

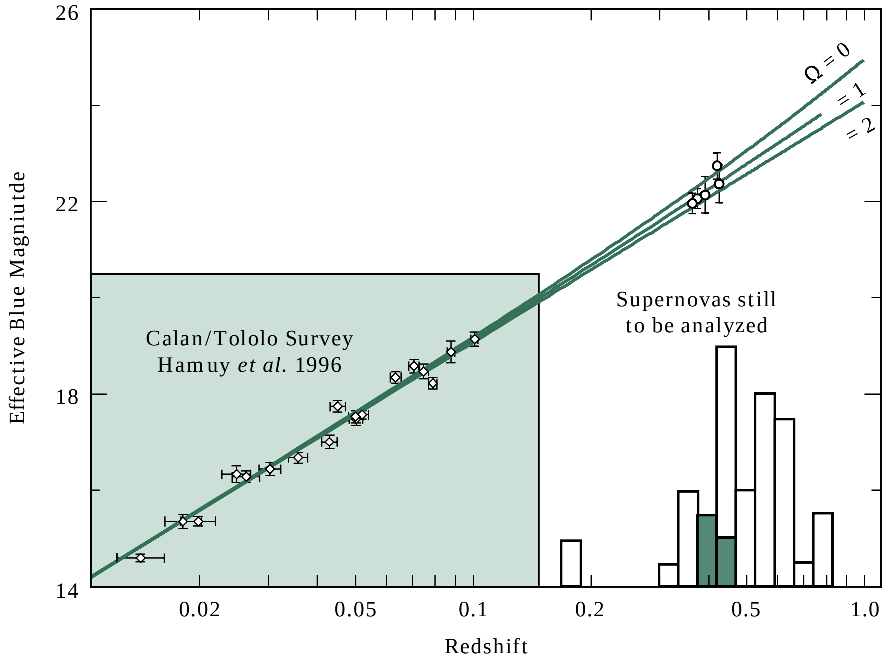
Cosmological theories about the fate of the Universe frequently refer to a quantity known as omega (Ω), which is related to the deceleration rate and to two other quantities, matter density and vacuum energy density.

By matter density we mean the mass of all the matter—visible and dark—in a given region of the Universe, divided by the volume of that region (assuming that for a sufficiently large region, the Universe can be considered uniform). Obviously, matter density, because it is the source of gravity, is directly related to the deceleration rate. The higher the density, the greater the deceleration. Omega is the ratio of matter density to a "critical" density, at which the pull of gravity becomes strong enough to yield just enough deceleration to stop the expansion of the Universe. Thus, if the value of omega is less than 1, the negative curvature case is most likely, and the Universe will continue expanding forever. If it is exactly 1, the flat universe case looks like the winner (refer to Alan Guth's article on page 14 in this issue); if it's greater than 1, we're headed for the Big Crunch.

When Einstein introduced his General Theory of Relativity in 1916, the Universe was assumed to be static. To understand such a static universe, Einstein had to introduce a repulsive force to compensate for gravitational attraction. He called the origin of this force "the cosmological constant" lambda (Λ).

Later, when Hubble discovered that the Universe is actually expanding, Einstein called the cosmological constant his greatest mistake. However, we dare not agree with this assessment without further examination. Since Λ is consistent with General Relativity, the existence and value of Λ must be regarded as experimental questions. Recently, certain cosmologists have appropriated the cosmological constant and proposed that it may be related to the energy density of the vacuum—a concept also dear to the heart of particle physicists. If the cosmological constant exists, it will affect the rate of deceleration; indeed, if its value is large enough, it could even result in a universe whose expansion is accelerating rather than decelerating.

To include Λ in our picture, (we now define omega total (Ω_T) which



High redshift supernovae from the Supernova Cosmology Project compared with low redshift supernovae from the Calan-Tololo Survey on a graph of magnitude versus redshift distribution. Magnitude is a logarithmic measure of brightness, and brightness decreases toward larger numbers.The points near z = 0.5 are the supernovae used in the first determination of the mass density of the Universe, with three comparison values of this mass density, Ω_M, shown as three solid curves for the case $\Lambda = 0$. The redshift distribution of the supernovae still to be analyzed is shown as white bars.

is omega for matter density (Ω_M) plus omega for vacuum energy density, or omega due to the cosmological constant (Ω_Λ). For the remainder of this article, we shall use the unmodified term Ω to mean Ω_T.

Before the work described in this article, estimates of Ω, based on a variety of experiments, ranged from 0.1 to 1.5. At the beginning of our experiment, we limited ourselves to measuring Ω_M. As the experiment evolved, however, we realized that we could expand it in such a way as to obtain both Ω_M and Ω_Λ. As it turns out, the redshift is related in different ways to matter density and vacuum energy density, so if we divide our Type Ia supernovae into two groups—those with a very large redshift and those with a significantly smaller one—we hope to be able to measure each component separately.

RESULTS & CONCLUSIONS

So where do we stand? And where is the Universe heading? In mid-1997, data from more than 45 supernovae were in various stages of analysis in our group. Moreover, it should be pointed out that ours is no longer the only group collecting such data. Beginning about 1995, Brian Schmidt and co-workers from Australia, Chile, the University of Washington, Harvard, and Berkeley began a similar search, known as the High-*z* Supernova team.

As of this writing, the Supernova Cosmology Project has completed its first analysis of 7 supernovae, and we are working on the analysis of 15 discovered more recently, which should be completed soon. For an additional 25 Type Ia supernovae observed in 1997, another year must pass before we can take the final images of the galaxy after the supernova has died out. Finally, we hope to measure 100 more supernovae over the next few years, with emphasis on very distant ones (with redshifts approaching 1, as compared to our current typical redshift of 0.5).

Although the number of supernovae is still too small to support reliable conclusions about the fate of the Universe, we have analyzed the data by making certain assumptions. For example, if we assume that $\Omega_\Lambda = 0$ (that is, that there is no repulsive force at work in the Universe) we can calculate a value for Ω_M equal to 0.9±0.6. On the other hand, if we make the assumption of a flat universe in which $\Omega = 1$, we obtain a value for Ω_Λ of 0.06±0.3, and Ω_M is given by $1 - \Omega_\Lambda$. Of course, the statistical and systematic error of 0.3 is large enough to move the value of Ω_M clear over to the other side of 1, so our present results still overlap all three possible scenarios for the Universe!

However, some interesting conclusions can already be drawn from the data. The visible part of the Universe is believed to correspond to a very small value of $\Omega_M \simeq 0.01$, and baryonic matter (that is, matter that is made up of protons and neutrons) perhaps to only 0.1. Thus for the value of Ω_M we obtained, there must be an enormous quantity of dark matter of as yet unknown composition.

And the envelope, please? We will all just have to wait and see.

Searching for Dark Matter Axions

by LESLIE J ROSENBERG & KARL A. VAN BIBBER

The search is on for one of the dark matter candidates so eagerly sought by astrophysicists—a conjectured relic particle from the time of the Big Bang called the axion.

HUBBLE'S DISCOVERY IN THE 1920S of the uniform outward expansion of the Universe raises the profound question of its ultimate fate. Averaged over the whole Universe,* a matter density equivalent to a mere thousand or so hydrogen atoms in the volume of your room would provide just enough gravitational attraction to eventually arrest its outward expansion, which we call the "critical density." When we tally up the mass of the Universe by what we can see—stars, galaxies, gas clouds—we find this visible matter accounts for less than one percent of critical density. Nevertheless, in the past few decades astronomers and astrophysicists have found compelling evidence for the existence of "dark matter" which seems to total to about critical density. More intriguing still is that the bulk of it is not likely to be ordinary stuff such as hydrogen or heavier atoms, but rather relic particles from the time of the Big Bang. The most etherial of the usual suspects is an extremely light particle called the "axion," whose interactions with anything are so vanishly small that—in spite of accounting for 90 percent of the mass of the Universe—it has evaded

**A comment concerning nomenclature. An under-dense universe would expand forever with a finite expansion rate; it is termed an "open universe." If the density of the universe were to be too high, it would eventually stop expanding and then begin contracting towards the "Big Crunch." This is called an "over closed universe." The twilight case of exactly the right density would lead to an "exactly closed universe" or just a "closed universe"; here the universe asymptotically approaches zero outward expansion, but never turns around. Refer to previous articles in this issue by Alan Guth and the Goldhabers for more detailed explanations.*

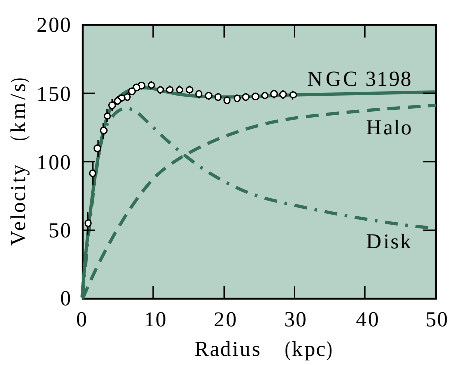
Roberto Peccei

being discovered or discarded since it was predicted to exist by particle physicists twenty years ago. But an experiment now underway at Lawrence Livermore National Laboratory (LLNL) may finally be able to tickle the axion into decaying inside our apparatus. Or then again, as so often before, it may have the last laugh.

FIRST, WHY DO WE BELIEVE in the dark matter? Much of the now overwhelming evidence in gravitationally bound astronomical systems is dynamical—for example the rotation curves of spiral galaxies, including our own Milky Way galaxy. Basically, just as the speed of rotation of the earth about the sun measures the mass of the sun, the tangential velocity of a star in the disk of a spiral galaxy determines the total mass interior to its orbit. In the case of the planets of our solar system, the further one goes out, the weaker is the force exerted by our sun, and therefore the orbital velocities of the planets go down roughly like the inverse square root of the mean orbit radius. (Pluto's year is roughly 250 of ours, not only because its radius and therefore circumference is 40 times larger than ours, but because it is traveling $40^{1/2}$ or approximately six times slower than we are.) Naively one would expect that for the stars or gas clouds further and further out from the center of a spiral galaxy to see the same behavior. But there's the rub—in every spiral galaxy we have seen, the rotation curve (velocity versus radius) is flat as far out as there is light or radio signals to look at (see the illustration on the right). The flatness of the rotation curve bespeaks a total galactic mass many times greater than the visible mass, and there are no indications that the dark matter "halo" may not extend much further beyond the visible spiral.

From this dynamical weighing of spiral galaxies, one would infer a density of the Universe now several percent of closure density. Estimates from rich clusters of galaxies move the number up 10 to 30 percent, and systematic residuals from the smooth outward Hubble flow on huge distance scales are consistent with numbers like 40 to 200 percent of closure density. Other ways of determining the total mass of the Universe are more or less consistent with this picture.

Rotation curve of the galaxy NGC 3198. Beyond 10 kiloparsec or so (approximately 30,000 light years), where the rotation curve should have begun to exhibit a 1/√r falloff, the rotation velocity hangs up at 150 km/sec.



Couldn't the missing mass simply be dark baryons—that is, ordinary nucleons and nuclei? Some, yes, but hardly all. A powerful limit on the total baryonic contribution to the mass of the Universe is provided by primordial nucleosynthesis—the formation of the light elements up through lithium, in the first few minutes after the Big Bang. The predicted abundances of deuterium, helium-4, and lithium-7 are each sensitive to the baryon-to-photon ratio in the early Universe. Consistency with our best observational abundances is only obtained within a narrow range of baryon-to-photon ratio corresponding to 2–8 percent of closure density. This constraint on the fraction of ordinary matter to less than 10 percent of closure density, in a universe that is at least 20 percent closed, is *prima facie* evidence for non-baryonic dark matter—relic particles from the Big Bang.*

Helen Quinn

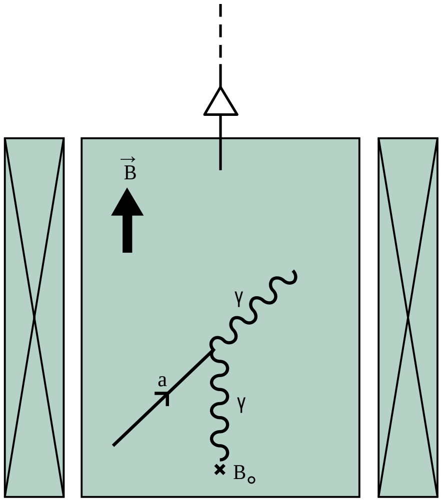
WHAT CONSTITUTES the dark matter of the Universe, and by implication the dark matter of our own halo is one of the premier questions in all of science today. As just mentioned, the baryonic contribution to the mass density is expected to be only a few percent, more than what is presently observed, mind you, but significantly less than the lower bound on the total mass density. Particle dark matter candidates fall into one or two camps. Namely they are categorized either as cold dark matter (CDM), that is, any particle relic which is slow-moving when it decouples from thermodynamic equilibrium in the early Universe, or massive neutrinos, which are relativistic at decoupling.

**The lower bound from primordial nucleosynthesis, 0.02, is well above the visible mass of the Universe, 0.005. Thus dark baryons must exist. The recently discovered MACHOs, observed through gravitational microlensing, are excellent candidates for such a baryonic component.*

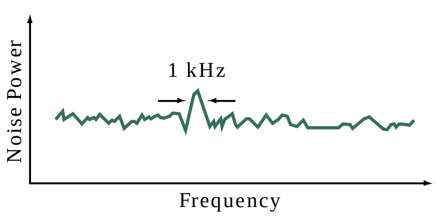
The distinction is more than just formal. Neutrinos must be considered a good candidate for at least some of the dark matter—after all we know they exist—and that they would have some small non-zero mass is certainly plausible. On the other hand, they are not likely to be dominant; too many swift neutrinos would have erased the structure formation we know grew into galaxies in the first few billion years. Also, the fermion spin statistics of the neutrino limits how many can be packed into confined volumes such as galactic gravitational potentials, and therefore neutrinos cannot constitute any significant fraction of our halo. The dominant term, rarely disputed any longer, must be cold dark matter (see the first article in this issue, "Inner Space & Outer Space" by Michael Turner). There are two leading candidates for CDM, one being a stable, weakly-interacting massive particle or WIMP, perhaps 10 or 100 billion electron volts in mass (10–100 GeV), arising from supersymmetric theories. The other is the axion.

A last remaining blemish in the theory of the strong interactions is the unexpected conservation of a particular symmetry of Nature. This symmetry, called CP, designates how the world looks after the product operation of charge conjugation (changing particles into their antiparticles) and parity (spatial reflection). The evidence of the conservation of strong-CP is the absence of any measurable electric dipole moment of the neutron, whose best upper limit is now eleven orders of magnitude (one hundred billion times) smaller than the value one would expect from the Standard Model.

ALMOST TWENTY YEARS ago, Roberto Peccei and Helen Quinn at Stanford Linear Accelerator Center proposed a minimal and elegant extension of the Standard Model that did just the trick of suppressing strong CP violation in a natural way. Hot on the heels of their paper, Steven Weinberg and Frank Wilczek independently pointed out that if the Peccei-Quinn picture was in fact correct, there would be a smoking gun—a neutral spin-zero particle they termed the axion, that one could think of as a very light cousin of the neutral pion π^0. (A clear if somewhat fanciful discussion of exactly how the axion arises in particle physics is found in Pierre Sikivie's article "The Pool-Table Analogy to Axion Physics," *Physics Today*, December 1996.) The original model suggested a relatively heavy axion, a few hundred keV in mass, with couplings to matter strong enough to permit a host of searches in conventional nuclear and particle physics experiments. These searches found no such axion. Characteristically, the theorists quickly realized how to construct axion models with arbitrarily small mass and couplings, thus beating a hasty retreat from the encroaching experimentalists.



The Feynman diagram above shows the conversion of a dark matter axion into a single real monochromatic photon in the presence of an external electromagnetic potential.



Hypothetical power spectrum showing what the axion signal would look like sitting on top of the black body plus electronic noise background.

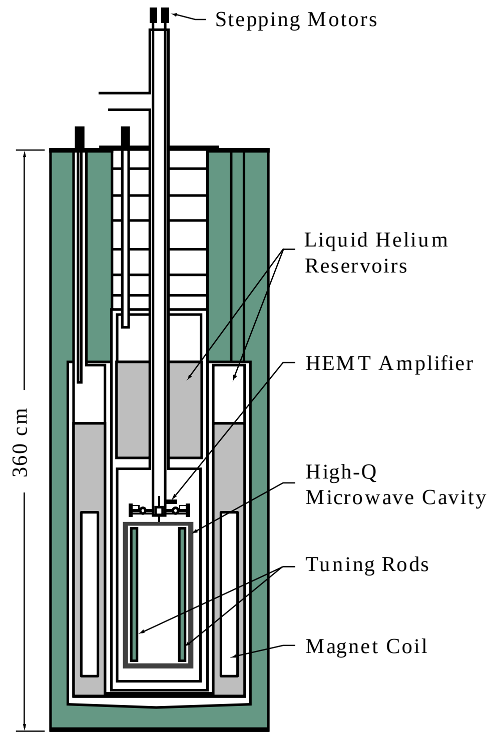
But the most ironic feature implied by the theory of the axion was that the smaller the mass of the axion itself, the greater the fraction of the mass of the whole Universe the axion sea would comprise. As the couplings of the axion to anything (leptons, quarks, photons) are proportional to the axion mass, a daunting paradox arose. An axion of mass in the range of approximately 1 microelectron volt (1 μeV) would be an ideal dark matter candidate to close the Universe exactly, but possess couplings so vanishingly small as to be virtually undetectable.

In fact, had the Universe been overclosed by even a miniscule fraction in the earliest moments after the Big Bang, we would have already recollapsed and not been here to tell the story. That's why we believe that a value of approximately 1 μeV represents a fairly secure lower bound to the axion mass. An upper limit of 1 meV results from the fact that too much axion radiation from the core-collapse of supernova 1987a would have dramatically altered the neutrino burst that was observed by the Kamiokande and IMB experiments ten years ago. There are some dodges on both the high and low mass end of the presently allowed mass window for the axion, but the unaltered conclusion is that lighter values of the axion mass are likely to be more cosmologically significant, and that's where you want to begin looking.

If the axion is like the π^0, it can decay into two photons, $a \rightarrow 2\gamma$. So if it's the dark matter, why not just point a radio telescope towards the halo around a galaxy, and look for a monochromatic emission line not corresponding to a known source? In principle yes, but there's the gotcha. Both the extreme lightness and weakness of its coupling to radiation conspire to make the axion so irrelevantly long-lived as to be essentially a stable particle. (Overall the lifetime goes like the inverse-fifth power of the mass, so over the allowed range the lifetime goes from $10^{(38-53)}$ seconds.) The conundrum was beautifully solved by Pierre Sikivie in 1983, who realized that the axion could be stimulated to decay into a single real photon in the presence of a magnetic field, which represents a sea of virtual photons. To detect dark matter axions, he proposed an experiment consisting of three basic components (see top figure on the left): a high-Q tunable microwave cavity, permeated by a strong magnetic field, whose radio frequency power spectrum is measured by state-of-the-art ultra-low noise microwave amplifiers. The experiment is nothing more than a very sensitive radio receiver! The microwave cavity is slowly tuned, and the axion will show up as a narrow line in the spectrum when the frequency (times Planck's constant) equals the axion mass (times the speed of light squared). The line will be very slightly broadened by the average velocity of the axions in the halo; the fractional width of the sought-for-peak should not be more than about 10^{-6} (bottom figure). One should think of the local population of axions as a cold Bose gas of prodigious density (trillions in each sugar-cube volume) and with a very large quantum wavelength (10–100 meters).*

Simple enough, but there is some fine print. The first problem is that the expected axion signal is exceedingly small. Even in the present large-

Design of the present experiment. The superconducting magnet has a clear-bore diameter of 60 centimeters, a length of 1 meter, and a maximum field of 8 tesla. The coil itself weighs 6 tons, and the entire experiment 12 tons.



scale experiment, the axion signal is optimistically 10^{-22} watts. Compare this with the signals received on earth from the 4-watt transmitter aboard the Voyager spacecraft at the periphery of our solar system—a whopping 10^{-17} watts. And secondly—unlike the axion—in the case of the Voyager, you obviously knew where to look in frequency!

Undaunted, two small pilot experiments ran in the late 1980s, one a Rochester-Brookhaven National Laboratory-Fermi National Accelerator Laboratory collaboration sited at Brookhaven, and one at the University of Florida. Both were proof-of-principle efforts to validate the technology and strategy of the microwave cavity experiment. Not surprisingly, no axion was found by either, as they lacked power sensitivity by two to three orders of magnitude than required even for the more optimistic axion-photon couplings. But plenty was learned, and in 1989 a collaboration drawing on the expertise and personnel from both experiments was formed to explore launching a full-scale experiment capable of realizing cosmological sensitivity. The collaboration presently consists of Lawrence Livermore National Laboratory, Massachusetts Institute of Technology, University of Florida, Lawrence Berkeley National Laboratory, Fermilab, and Institute of Nuclear Research, Moscow.

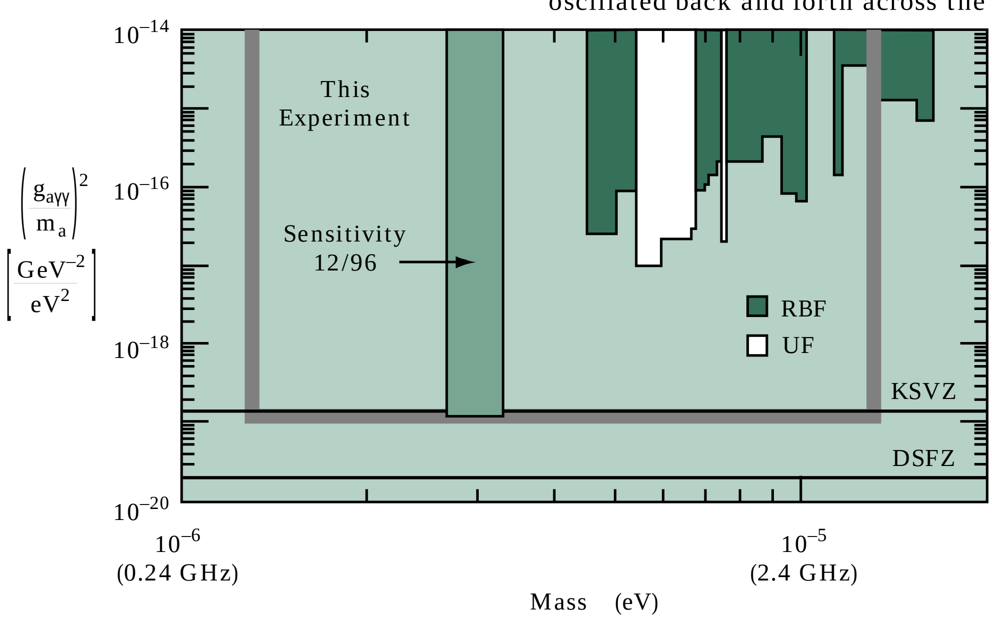
**This density may seem at variance with the much smaller value at the beginning of the article. It should be remembered that galaxies are very special places, representing deep gravitational potentials formed precisely by the accumulation of cold dark matter.*

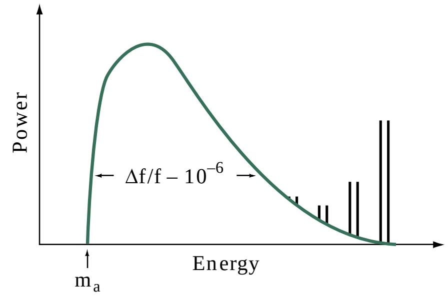
THE PHILOSOPHY of the present full-scale experiment was to close the gap on two fronts. The first was an increase in scale, as the power conversion goes like the total magnetic field energy, or B^2V. Whereas the first-generation experiments had the sensitive volume of a small coffee can, the present experiment has microwave cavities the size of an oil drum (see the drawing on the right). The second prong of the attack was to stay on top of the steady improvements in very low-noise HEMT microwave amplifiers. (HEMTs—High Electron Mobility Transistors—are exotic semiconductor structures originally developed heavily for military communications; they have become workhorses of radioastronomers.) The latest HEMT microwave amplifiers have noise temperatures below 2 kelvin.

The magnet cryostat being installed at Lawrence Livermore National Laboratory in spring 1995.

Top: The cryogenic tower and microwave cavity being assembled by Livermore physicist Chris Hagmann.

Bottom: The mass-coupling constant plane. Indicated are regions excluded by the first-generation experiments and the region already covered by the present experiment but still being analyzed. KSVZ and DFSZ indicate two very different axion models, but whose axion-photon coupling imply signal power differing by less than an order of magnitude.





Possible ultra-fine phase-space structure of the axion spectrum.

There is one additional feature of the new experiment worth commenting on, namely a parallel data stream which searches for extremely narrow structures, motivated by recent theoretical work on the phase space structure of cold dark matter. Sikivie and co-workers recently have proposed that as cold dark matter is dissipationless, that is, cannot transfer energy with its environment except by long-range gravitational interactions, axions falling into the gravitational potential of our galaxy will not quickly get "stirred up" into a thermal distribution. Their simulations of galactic evolution suggest rather that the spectrum of axions seen at the earth would consist of a series of sharp lines, the highest energy of which represents the last-infall component, and the lower-lying lines resulting from earlier-infall axions which have already oscillated back and forth across the galaxy one or more times, as the potential deepened (see figure on the left). Numerically, the last-infall lines could be several percent of the total axion signal. That much signal in such a narrow peak would represent a large gain in the signal-to-noise capability of the experiment, and needless to say, its discovery would contain a wealth of information about our galactic history!

The experiment was commissioned in November 1995, and data-production running began in early February 1996. The experiment has operated remarkably smoothly, the duty factor being nearly 100 percent. The experimental power sensitivity is demonstrably below the KSVZ limit (see illustration below). Note that KSVZ is not a radio station but one of two prototypical axion models named after its proponents. The other model, indicated as DFSZ (also named for its proponents), is somewhat more generic and is regarded as the goal for a definitive axion search. (Of course, the collaboration's point of view is that the definitive search is one that actually finds the axion!) The aim of the present effort is to cover the lowest decade in the next three years at or below the KSVZ limit. A future upgrade of the experiment may utilize Superconducting Quantum Interference Devices, or SQUIDs, with noise temperatures around 300 mK. This reduction in noise temperature would give us the required sensitivity to reach the DFSZ limit.

The particle astrophysics approach complements accelerator-based research on the most fundamental problems in physics and cosmology. It is not unrealistic to expect that between new initiatives in astronomy and particle dark matter searches such as this one, we will have within a decade an accurate understanding of the mass budget of the Universe. And if axions prove to be the right "dark horse" to have bet on, a half-century long puzzle in the Standard Model will have also have finally been put to rest.

Astronomy & The Internet

by FRED HAPGOOD

In November 1996, the author toured the Harvard-Smithsonian Center for Astrophysics for OMNI Online. *The complete text at http://www.omnimag.com/live_science/astro.html touches on quasars, meteor strikes, robot telescopes, SETI, spectrum tourism, and the X-ray Hubble. This piece on the Internet and astronomy led the series.*

YET THERE ARE A FEW CORNERS where the degree of change has been as radical as any futurist could could hope for; where a profession has been torn up and remade practically overnight. Astronomy is one such case. Over this decade the digitization of astronomical data, the continuously falling prices of bandwidth, processing, and data storage, and a community-wide effort to hammer out data standards and write sophisticated analysis and data handling software, have all combined to create huge increases in connectivity among astronomers, their instruments, and their libraries. This new power has changed almost everything about the field.

For one, it has ruined astronomy's logo. Historically when directors of TV programs or journalists writing a story have wanted a scene that says "astronomer" they have gone to observatories: large, echoing, cold, red-dark, silent spaces (because observing has to be done at night, with only dim red lights on, in structures open to the sky, often at the top of mountains). Here the intrepid scientist could be found, wedged uncomfortably into the observing cage of a great telescope, sitting hour after hour while the world slept, in heroic pursuit of images from the edge of the Universe.

In the last five or so years this canonical image has vanished from practice, though no doubt it will linger on in TV science series for another decade. Today astronomers keep the same hours, work in the same environment, and go through the same motions as everyone else: they come to their office in the morning, sit down at a workstation, and surf the net.

> *"The astronomer used to go to the data; now the data go to the astronomer."*
>
> —Stephen Murray

When observations need to be made the researchers define the coordinates of the region in question and then email them to an observing facility. The request goes into a stack; eventually, depending on details like the popularity of that particular instrument and the scale of the request, the observations will be made and the results returned, also by email. "The astronomer used to go to the data; now the data go to the astronomer" is how CFA scientist Stephen Murray sums up the change.

This new connectivity also allows astronomers to find and retrieve historical observations from research libraries all over the world in minutes, without traveling to those institutes or waiting for film to arrive by mail. With a bit of searching, a scientist can retrieve and inspect almost all the observations ever made of an object. This increase in access means that more and more useful research can be conducted from archives instead of new observations, which are expensive and take time to complete. (Murray says now half the publications in his field are based on archival research as opposed to new observations.)

Pulling observations out of the archives not only saves time and money; archives have the further advantage that they are indifferent to frequencies. Type in "Sirius" and you can get all the observations made of that object, across 15 magnitudes of wavelength, from the longest radio waves to the brightest gamma rays. By contrast, a given physical observing instrument never sees beyond a small slice of the spectrum. Over the last 50 years this specificity balkanized the profession by spectral region, into X-ray astronomers, radio astronomers, and so on. A database is blind to these distinctions: once the right observations have been made, a researcher can pull the entire profile of an object up on the display. He or she can can see it complete and entire. This new perspective has begun to bring the profession back together, to make it whole as well. "We're all just astronomers now," Murray says.

Professional facilities like the Center of Astrophysics have changed as well, from being exclusively concerned with the building and operation of telescopes to organizing and running the equivalent of a WAN for astronomers, clearing (in the case of the CFA) 25,000 email messages a day from researchers looking for data or requiring assistance of some sort. The Center runs a half dozen data services, each organized around separate missions or instruments (such as organizing the data sent from different satellites), encyclopedic data archives, online bibliographic databases, libraries of programs used to manipulate data, and banks of support personal for astronomers using those programs or needing access to the data. The website of one the larger of these data services, the Astrophysics Data System (adswww.harvard.edu) got 1.7 million hits in October 1996.

This new connectivity has obvious implications for amateur astronomy and astronomy education. As mentioned above, professional astronomers can order observations from any facility in the world (in theory). No one would think of requiring a professional astronomer to build his own facility before conducting his research. Amateurs have not had this freedom: an amateur astronomer has had to build or buy his own instrument or do without. Since good instruments are expensive and since most people live in areas where the viewing conditions are poor, most of us who were interested in the stars as children have had to let that interest die.

Steve Leiker of the CFA is working on an NSF-funded project that will bring the flexibility of a professional viewing to amateurs. He and his colleages at the CFA have built five small but serious unmanned optical telescopes (5.5-inch reflectors), all competent to be placed on a rooftop somewhere and then operated through the internet. They will work the same way contemporary professional telescopes do, automatically accepting observing requests, carrying them out, and then sending the results back over the net.

While the NSF project contemplates purely educational functions for these instruments, Leiker is well aware of another market: amateurs willing to pay a few dollars an hour for a few hours a week of observing time. Assuming the instrument is sited in a region permitting 1000 hours of viewing time a year (out of a total of 8746 hrs/yr), a $10/hour fee would return the purchase price of a $20,000 instrument in two years. One can imagine a range of instruments available at differing sensitivities and prices: time on weaker telescopes might be a dollar an hour; stronger machines, $25/hr, and so on. If these economics work out, the range of observing opportunities open to enthusiasts would increase spectacularly.

Of course the same revolution in connectivity makes it simpler for amateurs to build up their own star atlases, to extract and coordinate material drawn from multiple archives, and publish those atlases on the net. Over time perhaps the most important effect of the new connectivity—in astronomy and elsewhere—will be to blur the line between the professional and lay science communities.

Favorite Astronomy Internet Sites

Observing and Research Data Sites

http://www.ucolick.org/~deep/home.html	DEEP Homepage
http://www-sdss.fnal.gov:8000/	SDSS (Fermilab)
http://tarkus.pha.jhu.edu/database/sdss.html	SDSS (Johns Hopkins)
http://tarkus.pha.jhu.edu/deep/deimos.html	DEIMOS
http://panisse.lbl.gov:80/public/	Supernova Cosmology Project Homepage
http://www.ifa.hawaii.edu/~cowie/hdf.html	Hubble Deep Field data

Global Resources Sites

http://www.nasa.gov/	NASA homepage
http://guinan.gsfc.nasa.gov/	High Energy Astrophysics Science Archive Research Center
http://www.stsci.edu/	Space Telescope Science Institute
http://oposite.stsci.edu/pubinfo/Latest.html	New HST photographs
http://oposite.stsci.edu/pubinfo/Pictures.html	HST Public Pictures
http://www.jpl.nasa.gov/	Jet Propulsion Laboratory
http://www.ucolick.org/	Lick Observatory Homepage
http://www.apo.nmsu.edu/	Apache Point Observatory
http://www.mtwilson.edu/	Mt. Wilson Observatory Tour
http://astro.caltech.edu/observatories/palomar/	Palomar Observatory
http://physics7.berkeley.edu/home.html	Center for Particle Astrophysics
http://www.fisk.edu/vl/astro/astro.html	Astronomy/Astrophysics Directory
http://www.aas.org/AAS-homepage.html	American Astronomical Society
http://www.aspsky.org/	Astronomical Society of the Pacific
http://www.journals.uchicago.edu/ApJ/	Astrophysical Journal
http://heasarc.gsfc.nasa.gov/0/docs/acronyms.html	Commonly Used Astrophysics Acronyms
http://www1.tmisnet.com/~abdale/Astronomy/Astronomy.html	What's Up This Month in Astronomy
http://bolero.gsfc.nasa.gov/~odenwald/ask/askmag.html	Ask the Space Scientist
http://www.windows.umich.edu/	Windows to the Universe
http://www.seds.org/	Students for the Exploration and Development of Space
http://bang.lanl.gov/solarsys/homepage.htm	Views of the Solar System
http://www.astro.princeton.edu/~frei/galaxy_catalog.html	The Galaxy Catalog
http://ngst.gsfc.nasa.gov/	Next Generation Space Telescope
http://engr.arizona.edu/~stetson/	Astronomical Tools
http://www.wpo.net/	Windowpane Observatory
http://www.skypub.com/	Sky & Telescope Magazine
http://www.astronomy.com/	Astronomy Magazine
http://www.fisk.edu/vl/astro/astroweb/yp telescope.html	History of Astronomy
http://jean-luc.ncsa.uiuc.edu/Exhibits/	Numerical Relativity Exhibitions

Literature Databases

http://adswww.harvard.edu/	NASA Astrophysics Data System
http://www.noao.edu/apj/ypages/last10.html#\apj	Papers Submitted to Selected Astronomical Publications
http://xxx.lanl.gov/archive/astro-ph	Astrophysics Preprints

Meetings

http://cadcwww.dao.nrc.ca/meetings/meetings_without.html	International Astronomy Meetings
http://yorty.sonoma.edu/people/faculty/tenn/BayAreaLectures.html	Colloquia in the San Francisco Bay Area

Cosmology: Where in the $&#**(

by VIRGINIA TRIMBLE

Being a compilation of tabular and narrative material designed to provide a framework for the more detailed and technical articles that appear elsewhere in this issue. It can also be used as a ready reference resource for when people ask you things like: "Are there any other galaxies in our solar system?"

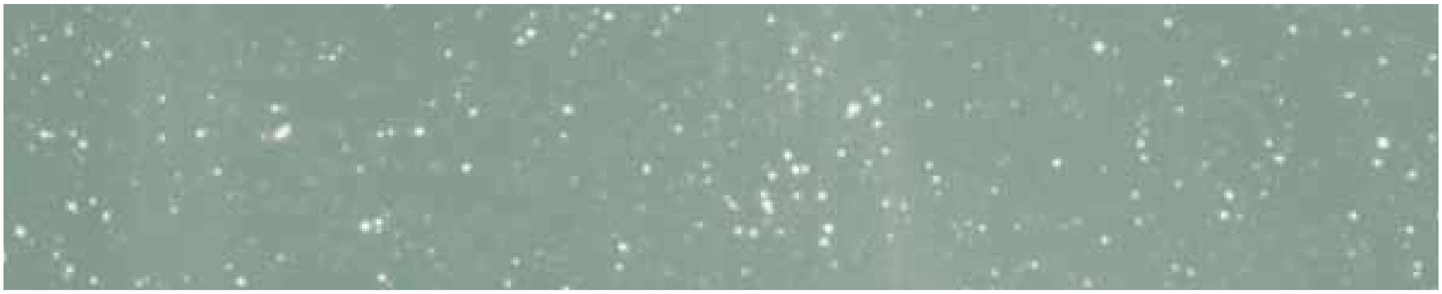
"Is it bigger than a bread box?" (Steve Allen, c. 1954, *What's My Line?)*

POWERS OF TEN

A remarkably delicate balance between the small scale phenomena of atomic and nuclear physics and the large scale phenomena of astronomy and cosmology is required for the Universe to be hospitable to chemically based life. Efforts to prove that this must be so are sometimes dignified by the name "anthropic principle." My goal here is the much more modest one of indicating where we fit into the range of objects and events. A subsidiary goal is to use common astronomical terms (solar system, galaxy, Local Group, and so forth) so many times in suitable contexts that you will never again have an excuse for forgetting which fits inside which others.

Time, length, and mass are advertised as the most fundamental physical quantities (though the $c = G = 1$ relativists and the $c = h = 1$ particle physicists manage to survive with only one, length or energy). Taking one example of each, we find:

- Geometric mean of diameter of atomic nucleus and distance to the nearest star = 14 feet, the height of a dean at a prestigious university
- Geometric mean of halflife of excited nucleus and age of the Universe = 2 minutes, upper limit to the time you will listen to telephone solicitor
- Geometric mean of mass of hydrogen atom and mass of sun = 60 kg, large dog or small dog owner.



% Universe Are You?

The first three tables provide additional examples of logarithmic steps in length, time and mass that take us from atomic to astronomical scales. The units are centimeters, years, and grams. Some powers of 10 are missing because I couldn't think of anything interesting that exists or happens on that scale. Suggestions from readers of items to fill the gaps would be much appreciated.

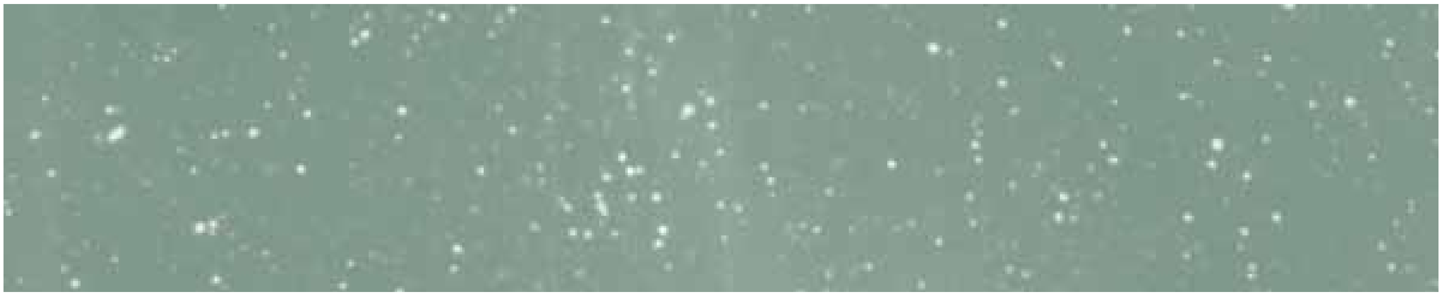
In these days of energy-consciousness, one ought perhaps to have one more table, of energies or a related quantity. The one shown on page 55 is called power if you are a householder and paying for it, or luminosity if you are an astronomer and not paying for it. Students in introductory astronomy courses are always a little surprised by the enormity of the answer they find to the question: What would it cost you to keep the sun shining for a year if you had to pay Southern California Edison Company 12¢ per kilowatt hour to do it?

A COOK'S TOUR OF THE UNIVERSE

The Earth is a planet, and there are times when one feels that the most important issue is whether the

Time Scales of Human and Astronomical Phenomena

Log *t* (years)	**Event**
-50	Planck time
-9	shortest human reaction time; rotation of Crab Nebula pulsar
-8	heart beat after running; QPOs in X-ray binaries
-7	breath after running; core collapse in type II supernova, rotation periods of old pulsars
-6	time you expect to wait when told "just a minute"; most rapid rotation of white dwarfs
-5	attention span of freshman physics class; solar oscillations
-4	the 50-minute hour; orbit periods of cataclysmic binaries
-3	work day; most rapid variability in active galaxies, quasars, etc.
-2	long weekend; pulsation and orbit periods of moderately compact stars and binaries
-1	number of days I need in a month; pulsation periods of Cepheid variables; orbit periods of "hot Jupiters"
0	length of small NSF contract; orbit period of earth, detectable changes in luminosity of most active galaxies and in pulsation and orbit periods of stars and binaries
+I	lifetime of breadbox; age of SN 1987A, evolution of stars undergoing last helium flash
+2	age of professor; life of nova shell
+3	significant changes in spoken languages; age of Crab Nebula as now seen
+4	neolithic culture (agriculture, cities, pottery, baskets, writing); lifetimes of planetary nebulae
+5	paleolithic culture, anatomically modern man; ages of youngest detectable protostars and star bursts
+6	assorted hominids, earliest tools; lifetime of very massive star
+7	giant mammals; lifetime of progenitor of SN 1987A, lifetimes of pulsars
+8	dinosaurs; lifetime of moderate-mass stars, crossing times in dense cores of clusters of stars and galaxies
+9	single-celled life; relaxation times in dense cluster cores
+9.66	age of solar system
+10	lifetime of solar mass star, dynamical time scale of less dense clusters
+10.2	age of Universe



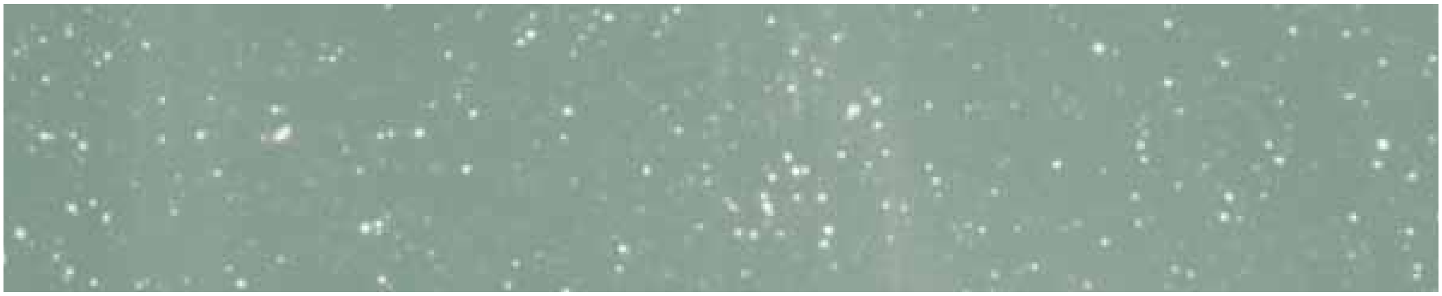
capital E and the “the” are forbidden, compulsory, both, or neither. Planets are undoubtedly the most familiar of astronomical objects, since most of us have lived on one most of our lives (if there is anyone out there for whom this is not true, I don’t want to know about it). The nine planets of our Solar System can be categorized as terrestrial or earthlike (meaning made of rocks and metals with at most thin layers of other stuff) and Jovian or Jupiterlike (meaning made mostly of gases, especially hydrogen and helium). The former are Mercury, Venus, Earth, and Mars; the latter Jupiter, Saturn, Uranus, and Neptune. Pluto is a misfit, possibly related to the moons of the outer Jovian planets or to the mostly-icy denizens of the Kuiper belt slightly further from the sun. Kuiper belt objects are the source of comets with relatively small orbits. The (still unseen) objects that feed into the supply of nearly-parabolic comets come from the Oort Cloud.

We now know of a dozen or more planets orbiting other stars (*Beam Line*, Vol. 27, No. 2, p. 31–35), the largest class of which have masses like the Jovian planets but orbits like the terrestrial ones, and so are called hot Jupiters by their friends. We expect, but do not know, that observations will eventually reveal large numbers of other planetary systems, both like and unlike ours, and that moons, comets, asteroids, meteors, and so forth will be common features. No comet with an orbit suggesting it originally belonged to another star has ever been seen. Planets and subplanetary detritus are not a major contributor to the mass or luminosity anywhere, but they are, of course, the only life-bearing entity we know of.

The Sun is a star, with a mass (2×10^{33} g), radius (7×10^{10} cm), luminosity (4×10^{33} erg/sec), age (4.55 Gyr), heavy element abundance (1.7 percent everything that is not hydrogen or helium), and all the other properties you can think of, very much in the middle of the range for stars in general. The extremes of the ranges (for example all stellar masses are between 0.085 and 120 $M_\odot$) are understood in terms of the physics of gravitation, electromagnetism, and nuclear reactions, though the distributions through the ranges are not. We also

Sizes of Terrestrial and Celestial Objects and Systems

Log l (cm)	**Object (etc.)**
-33	Planck length
-13	atomic nucleus (1 fm)
-8	Bohr orbit; divide between X-ray and gamma-ray wavelengths (1 Angstrom)
-4	near infrared wavelengths (1 μm), largest bound interstellar atoms
-3	magnetic domains
0	distance between atoms in interstellar space; rules of thumb
+l	small bread box
+2	distance between atoms in intergalactic space; people, radio waves
+3	biggest animals
+4 to 5	biggest buildings and trees
+6	tallest mountains, comets, small asteroids, and moons; neutron stars, Schwarzschild radii of stellar mass black holes (approximate division between dominance of solid body and gravitational forces)
+7 to +8	moderate to big moons and asteroids
+9	earth, white dwarfs
+10	Jupiter, brown dwarfs
+11	sun and other main sequence stars
+12	distance of “hot Jupiters” from parent stars
+13	sun-earth distance (1 astronomical unit)
+15	diameter of Pluto’s orbit, heliosphere
+17	Oort cloud of comet progenitors (limit of solar system)
+18	widest bound star pairs; core of dense star cluster
+19	diameter of globular star cluster (3 parsecs)
+20	giant molecular cloud
+21	width of spiral arm in Milky Way
+22	thickness of disk of old stars in Milky Way
+23	diameter of visible part of Milky Way and other biggish galaxies
+24	diameter of massive halo of Milky Way and other biggish galaxies, distance between galaxies in rich cluster
+25	core of rich cluster of galaxies
+26	diameter of rich cluster of galaxies; our distance from Virgo
+27	largest scales on which we see structure and streaming in the Universe
+28	distance light travels in 10^{10} years (radius of “observable” Universe)



Masses of Terrestrial and Celestial Objects and Systems

Log M (grams)	Object (etc.)
-27	electron
-24	proton
-19	big molecule
-16	small virus
-5	Planck mass
-3	large cell (not ostrich egg!)
0	grain of salt you should take all this with
+2	typical bread box
+5	large people
+16	mass of fresh water needed each year for optimum health of current world population
+18	comet, small asteroid or moon (dividing line between dominance of solid body forces and gravitation)
+27	terrestrial planets
+30	Jovian planets
+32 to 35	stars
+36	typical young star clusters (unbound)
+39	large old star clusters giant molecular clouds
+39 to 43	small galaxies
+45	big galaxies
+48	rich cluster of galaxies
+56	Universe to $r = c \times$ age

A Few Powers and Luminosities

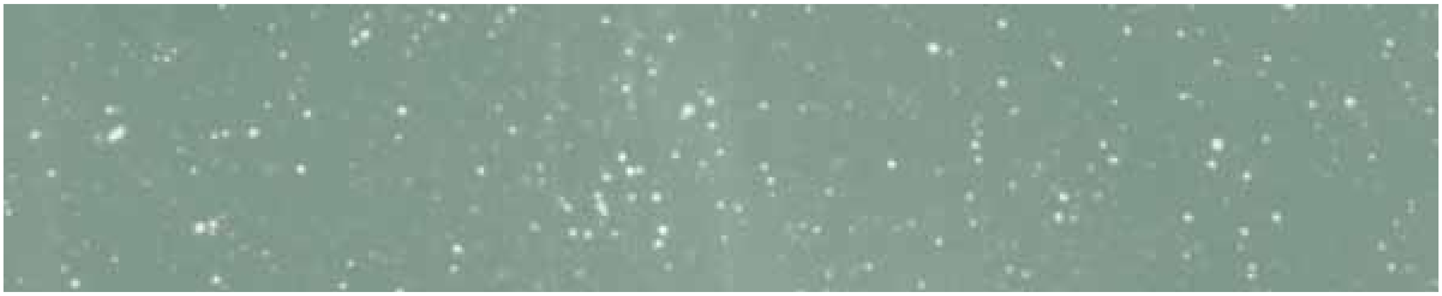
Log L (erg/sec)	Object (etc.)
-3	hardworking hydrogen atom
+7	hardworking bread box (thermal radiation at room temperature)
+9	human metabolism
+10	hardworking horse
+22	world energy consumption (*very* crude)
+24	solar flux hitting earth
+30 to 39	stars (sun = 33.6)
+44	Milky Way galaxy
+54	"observable" Universe

have a reasonable grasp of what stars do for a living as a function of mass and time. The sun is about half way through using up its available hydrogen via the proton-proton chain of fusion reactions to form helium; Betelgeuse has used all its hydrogen and is not long for this galaxy; and FG Sge has probably just had the last gasping flash of nuclear reactions (turning helium to carbon and oxygen) that it will ever be allowed. Stellar lifetimes are proportional to M^{-x}, where x = 1–4, because large mass means high central temperature (so that pressure can balance gravity) and so rapid reactions and very large luminosity.

Most of the dots of light you see in the sky are actually gravitationally bound pairs or binary stars. It is not entirely true that having a stellar companion and having habitable planets are mutually exclusive, but almost. That we orbit a single star is not, therefore, improbable.

Star clusters are the main or only sites of star formation (at least here and now, and probably also there and then). The process of a large cloud of cold gas collapsing and fragmenting into stellar mass cores is a collective one, some times triggered by encounters with other clouds, expanding supernova remnants, or other shocks. The majority of clusters so formed dissipate (because only 1 percent or so of the gas actually ends up in stars). Thus we see a good many young clusters (like the Pleiades, the Hyades, the Jewel Box, and other favorite objects for small telescopes) of various masses, but only big, compact old clusters (called globular clusters) are still around. It would be fun to be able to point to other stars in the sky and say that they formed in the same cluster with our sun. But the sibship has orbited the galactic center dozens of times since birth, and the members have strayed beyond recovery.

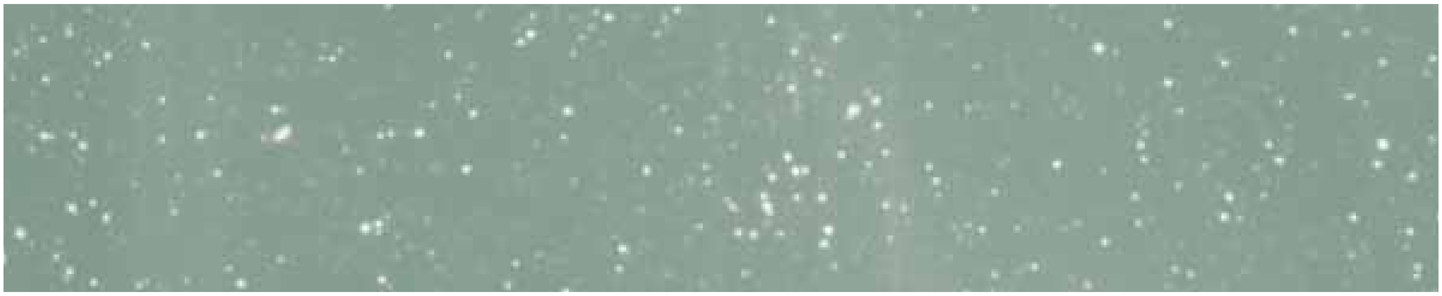
The Milky Way is a galaxy, consisting of something like 10^{11} stars, the majority in a fairly thin disk, rotating every 200,000,000 years or so, and the rest in a more spheroidal non-rotating halo. We cannot draw very good pictures of it because of living inside, where the view is partly blocked by dust, and because some methods of measuring distances are not single-valued. Available evidence is, however, consistent with its being a fairly typical spiral galaxy (meaning not quite as pretty as the



Cosmic Inventory

What	Where		What Else
PLANETS (ours is called Earth)			
9 planets	live in (our) Solar System	with	The Sun, moons, comets, etc.
other planets	live in (other) solar systems or planetary systems	with	one star per system + stuff
STARS (ours is called the Sun)			
all stars	formed in clusters*	with	$10–10^6$ other stars
few stars	still live in clusters*	with	$10–10^6$ other stars
90% of all stars	live in binary (etc.) systems	with	1–5 other stars
most/all stars	formed in and still live in galaxies	with	$10^6–10^{12}$ other stars
GALAXIES (ours is called the Milky Way or The Galaxy)			
most galaxies	live in small groups	with	a few to a few dozen other galaxies + intracluster gas
a few galaxies	live in rich clusters*	with	1000 or more other galaxies + very hot gas
GROUPS OF GALAXIES (ours is called the Local Group)			
most small groups	are part of more extended structures	with	other groups and clusters
RICH CLUSTERS* OF GALAXIES (the nearest is called the Virgo Cluster)			
rich clusters	are easy to see and so used as tracers		
LARGER SCALE STRUCTURES (ours is called the Virgo Supercluster)			
small groups and rich clusters	define more or less the same density inhomogeneities, often in sheets or filaments	with	other groups and clusters up to 100 Mpc away
UNIVERSES (ours is called the Universe)			
4-d universes	may live in higher dimension spaces	with	other universes

**It is entirely possible (but undesirable) to confuse clusters of stars with clusters of galaxies (verbally, not if you are looking at one). The phrase "star cluster" is OK (and there are two types, called globular clusters and galactic or open clusters). The phrase "galaxy cluster" will almost always cause confusion. "Cluster of galaxies" is safe.*



ones most often shown in elementary text books). Its spiral arms are clearly present but do not extend continuously all the way around. Virtually all known spiral galaxies have masses within a factor 10 of that of the Milky Way. In all cases 90 percent or so of the mass is not normal stars or gas. We call it dark matter and discuss it constantly at conferences and in books and papers. Atlases of galaxies are dominated by spirals partly because they are pretty and partly because they are both brighter than the commonest kind and found preferentially in our (relatively low density) part of space.

Giant elliptical galaxies, especially the ones at the centers of rich clusters, can include as many as 10^{13} stars plus dark matter. Dwarf ellipticals and dwarf spheroidals have only a million or a billion stars. They are the commonest sort, but, being so small, contribute rather little to the mass and luminosity of the Universe as a whole. Irregular galaxies include low-mass ones with lots of gas and current star formation (like the Large and Small Magellanic Clouds), but also everything else that doesn't look like a spiral or an elliptical, for whatever reason. In general, we find ellipticals near the centers of rich clusters, while spirals prefer the outskirts or homes in small groups. The correlations of mass, morphology, location, chemical composition, and other properties of galaxies are understood by a number of astronomers. Unfortunately they understand somewhat different things.

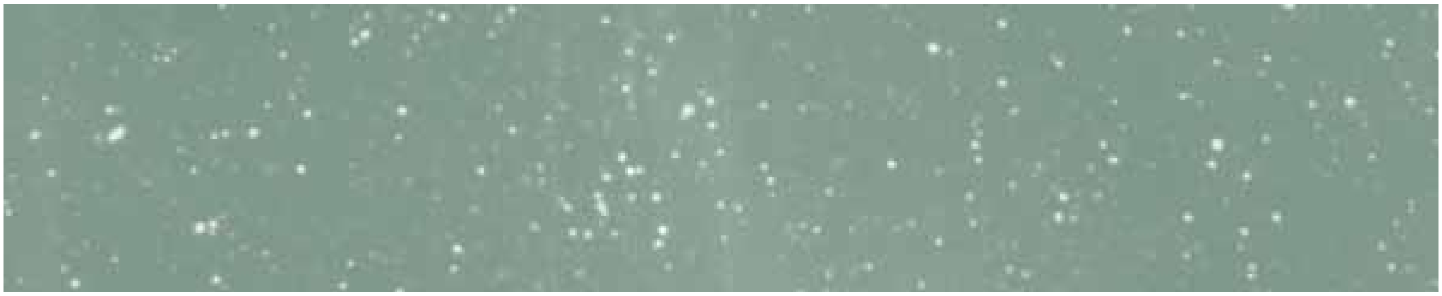
Truly isolated galaxies may never exist. Certainly as a rule we find them to be clustered on a wide range of scales, from pairs and small groups up to rich clusters and superclusters. Understanding how the galaxies formed and got into their present heirarchical structures is probably the most important unsolved problem of modern astrophysics.

The Local Group is a small group of galaxies. It includes two large spirals, us and the Andromeda Nebula (and would look like a binary galaxy from far enough away). The other members are a moderate-sized spiral (M33) and more than two dozen irregulars and dwarf spheroidal galaxies. We are currently finding new, small, obscure members of the Local Group at a rate of about one per year.

The Virgo Cluster is the nearest of the relatively rich clusters of galaxies. Its name indicates merely that you look past the stars of the constellation Virgo to see it, and the distance is anything from 10 to 25 million parsecs, depending on who you ask. A still richer cluster, further away, is called Coma (for the same reason). We live on the outskirts of the region of space where the motions of galaxies are seriously perturbed by the mass of the Virgo cluster and so can claim to be members of the Virgo supercluster. One implication is that our velocity of recession from the Virgo cluster (or conversely its from us) is smaller by 100–250 km/sec than would be the case if the cluster weren't there.

The evidence for deviations from homogeneity and smooth expansion in the Universe becomes less persuasive when we look at still larger scales but does not vanish. The largest-scale structures seem to be sheets and filaments of galaxies and clusters outlining voids with density well below the cosmic average. Voids of 30–50 Mpc are common, and one can probably trace coherent structures of 100–200 million parsecs. Streaming velocities of at least a few hundred km/sec around smooth Hubble expansion are found over comparable size regions, and we are in the process of trying to associate particular velocity perturbations seen among the galaxies with the masses that cause them and with the velocity-induced dipole we find for the 3K microwave background radiation. This last is some 600 km/sec (after allowance for the earth's orbit speed, rotation of the Milky Way, our orbit around the Andromeda galaxy, and a few other things) and also requires explanation in terms of a scenario for the formation and clustering of galaxies.

The Universe is a universe whether capitalized or not. A convenient definition is "all of the four-dimensional space-time that we can ever communicate with and the contents thereof." It is convenient because it will equally offend the beginning student (who does not understand the words, at least in that order) and the advanced theoretical physicist (who does not agree with the words, at least in that order). It is older than a breadbox (by 10–20 Gyr), bigger than a breadbox (probably infinitely so), and not a good source of ground truth.



Key Events from the Big Bang to the Birth of Richard Nixon

- early, hot, dense phase (comprising baryogenesis, big bang nucleosynthesis and probably other things)
- *formation of galaxies and large scale structure
- *first generation of stars (pure hydrogen + helium) initial nucleosynthesis and distribution by supernovae
- second and later generations of stars
- additional nucleosynthesis, including secondary products, distribution by supernovae, novae, planetary nebulae, etc.
- formation of planetary systems with terrestrial planets
- chemical evolution
- origin of life (self-replicating systems with information storage capacity)
- biological evolution
- tool-making, radioastronomy, etc.

**It is possible that these two stages were more or less simultaneous or even inverted.*

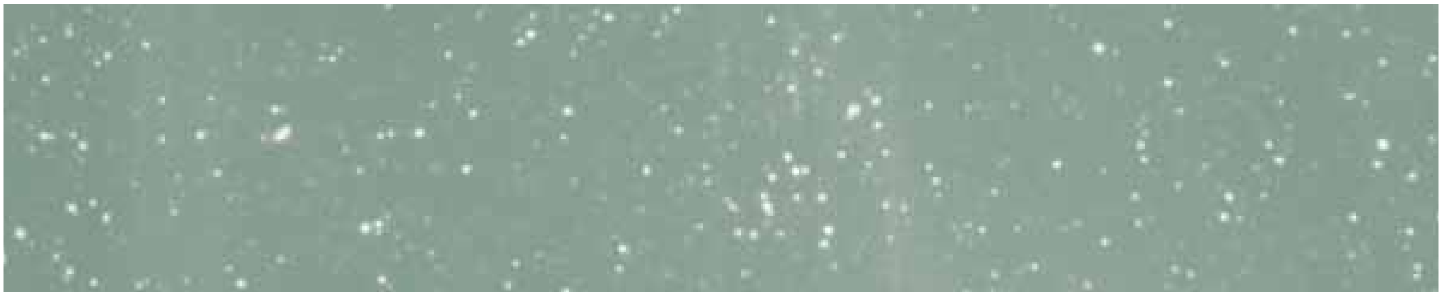
AN OUTLINE OF HISTORY

First came the *Big Bang*, meaning that the entire Universe (in the sense just undefined) passed through a state of nearly homogeneous thermodynamic equilibrium at a temperature in excess of 10^{10} K, out of which it has been expanding ever since. (Evidence that there was such a state is discussed in the *Beam Line* Vol. 25, No. 1, p. 25.)* Early in the expansion, the baryonic material gradually transformed itself from a soup of interacting protons, neutrons and electrons to hydrogen and helium nuclei in a ratio of about 10:1, with much smaller numbers of deuterium and lithium-7 nuclei also forming. We suppose that there is a sea of cosmic neutrinos sent freely on their way at this time, though it has yet to be seen.

The photons slip out of thermal equilibrium with the baryons at the epoch called *recombination or decoupling*, at a temperature near 3000 K (corresponding to a redshift of about 1000), after which atoms are mostly neutral for a while and photons can stream freely through space. At about the same time, the energy density in radiation falls below that in matter.

Next comes *structure formation or galaxy formation*. The idea is that the low-amplitude density fluctuations that have been present since (before) the Big Bang grow more or less linearly with redshift (as fast as they can in an expanding substrate) until they approach non-linearity, and can start doing things that are too difficult to calculate analytically. It is almost impossible to make this happen in a pure-baryon universe without ruffling up the background photons by a factor 10 or so more than is observed ($\Delta T/T$ = something $\times 10^{-4}$ vs something $\times 10^{-5}$). Non-baryonic dark matter is an enormous help, because its fluctuations can start amplifying toward superclusters

**As for what came before the Big Bang, the short (polite) answer is that the state of thermodynamic equilibrium washed out nearly all the evidence. Probable exceptions include (a) a spectrum of low-amplitude density fluctuations required if we are eventually to get galaxies; (b) the amount of excess of baryons over anti-baryons relative to the number of photons; and perhaps (c) the dark matter, whatever it is.*



and voids before $T = 3000$ K without distorting the photons except gravitationally. Then, after decoupling, baryonic gas flows into existing potential wells to start becoming galaxies (etc.). Structure formation is an essential early step, because the average baryonic density of the Universe is about one atom per cubic meter, and, in the absence of density fluctuations, no committee could ever have more than one member (possibly not such a bad state of affairs).

Astronomers have been asking for more than 30 years whether structure arose in a "bottom-up" (little things form first and heirarchically cluster) or "topdown" (big things form first and fragment) fashion. The answer appears to be "no." That is, neither sort of scenario in its pure form does a good job of matching the patterns of clusters and voids that we see in both real and redshift space. Neither, truthfully, do the more complex scenarios, however much you multiply entities in the form of hot + cold dark matter, topological and non-topological defects, non-zero cosmological constant, tilted spectrum of the initial-perturbations, or whatever.

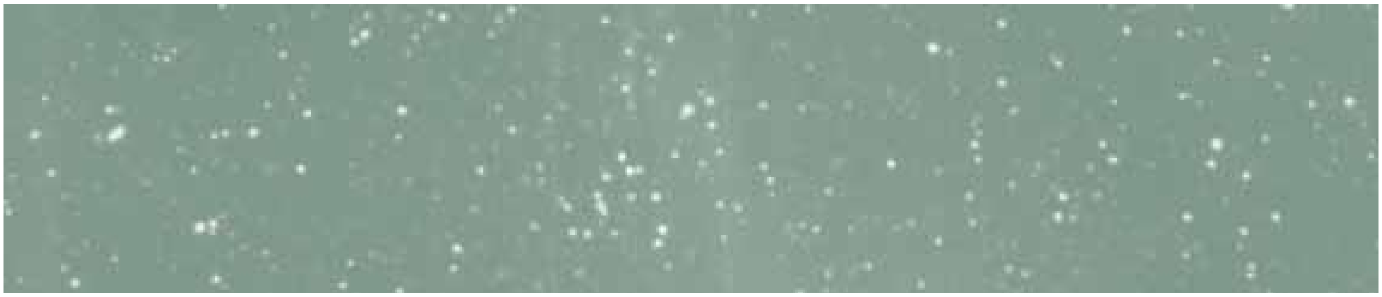
Next come *stars*. In fact, the earliest ones may well precede most of the large scale structure we now see. They must have been pure hydrogen and helium, and none are left. Either they were all massive and died long ago, or they have painted themselves with a concealing thin coat of heavy elements by passing through interstellar gas over the years.

Nucleosynthesis is the process of building up heavy elements from lighter ones and occurs in all stars. Massive stars live only millions of years and ones like the sun billions of years). Thus we expect chemical enrichment to begin with elements (like oxygen) that can be made from scratch in the most massive stars and liberated in core-collapse supernovae, to be followed by things like iron (made in other kinds of supernovae) and carbon (made and liberated mostly by intermediate mass stars). Still later appear the elements which can be made only in second-generation stars with some initial heavy elements present at their birth. These included nitrogen (much of which comes from proton captures on previously-existing carbon and oxygen) and the products of slow neutron capture on iron-group seeds (the *s*-process), including barium and yttrium. The detailed abundance patterns both of old stars in our galaxy and of gas in galaxies where star formation has been slow are a reasonable match to what you would expect from these theoretical considerations.

Planets co-form with stars. But the advent of terrestrial planets must await the increase of heavy elements to some critical value. This value is not known (and is of some importance if you want to estimate the number of habitable planets in the Milky Way). We currently have no information on the composition of any other stars with terrestrial mass planets, nor have the theorists done much exploring of how the evolution of proto-planetary disks depends on composition. Thus we do not know whether it is interesting that the sun is one of the most metal-rich stars in its neighborhood.

Chemical evolution, in this context, is the build-up from simple molecules like water, carbon dioxide, and ammonia to complex ones like amino acids, phosphates, and bases. It has gone some ways already in interstellar gas, where we see many dozens of compounds, including methyl and ethyl alcohol, HC_7N (no, you can't buy that one at the drug store), and formic acid.* Carbon-rich meteorites harbor a wide range of amino acids (including ones we don't use) and other macromolecules. One would very much like to answer the question: Where did chemical evolution go from there? Life on earth has long ago eaten the traces of its own birth. Places we might look for hints of the later history include comets that have not yet been much exposed to sunlight and sub-surface layers on Mars. It is perhaps a little difficult to make this latter sound like an exciting reason for multiple Martian expeditions. Luckily the search strategy is essentially similar to that for actual life, present or past.

**The UCI campus animal is the anteater (basically because we are a relatively young university and all the good animals were taken), and it is left as an exercise for the reader to supply some appropriate pun or other witticism. For extra credit, have a go at the UC Santa Cruz animal, the banana slug.*



Life can be defined however you wish. If you allow me to describe it as the appearance of molecules that can both store information and reproduce themselves accurately (using much less than their rest mass energy), then it becomes obvious that evolution from slime molds to politicians is practically inevitable. In a truly infinite Universe, this must have happened an infinite number of times. It has happened at least once even in our own parochial little Local Group. But, since astronomy handed over to chemistry and biology a paragraph or two back, it is time for me to tiptoe away and leave you to study for the quiz. It will be open book, and the main questions will require you to order astronomical objects by their sizes and ages.

Suggestions for Further Reading

The Origin and Evolution of the Universe (ed. B. Zuckerman and M. A. Malkan, 1996, Jones and Bartlett) has chapters devoted to each of the major events in cosmic history.

The Anthropic Cosmological Principle (by J. D. Barrow and F. J. Tipler, 1985, Oxford University Press) is the standard dlscussion emphasizing why the Universe might be so hospitable to complex, intelligent life.

CONTRIBUTORS


Barbara Ahlberg


Donna Coveney, MIT

MICHAEL S. TURNER is the proud father of future theoretical physicist Rachel Mary, age 6, and budding venture capitalist Joseph Lucien, age 4, pictured above. In his spare time he is married to architect Barbara Ahlberg and is Professor in the Physics and Astronomy & Astrophysics Departments (Chair of the latter) at The University of Chicago and Scientist in the Theoretical Astrophysics Group at Fermi National Accelerator Laboratory.

Turner received his undergraduate training at Caltech and began his graduate career in the SLAC theory group, finishing his PhD work on the Stanford campus with Robert Wagoner. He went to Chicago as an Enrico Fermi Fellow in 1978 and joined the faculty in 1980. His research focuses on the interface of elementary particle physics with astrophysics and cosmology.

ALAN H. GUTH is the Victor F. Weisskopf Professor of Physics at the Massachusetts Institute of Technology. Trained in particle theory at MIT, Guth held postdoctoral positions at Princeton, Columbia, Cornell, and SLAC before returning to MIT as a faculty member in 1980. His work in cosmology began at Cornell, when Henry Tye persuaded him to study the production of magnetic monopoles in the early Universe. Using standard assumptions, they found that far too many would be produced.

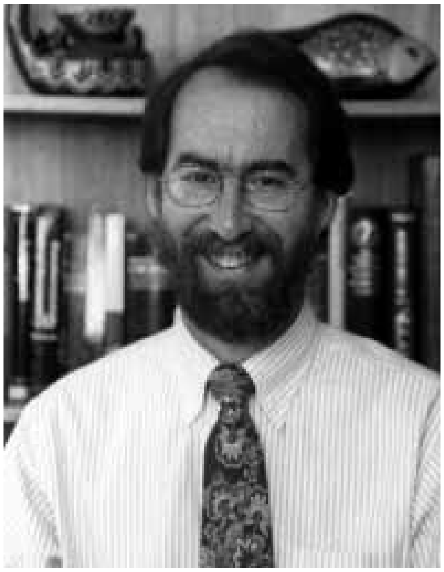
Continuing this work at SLAC, Guth discovered that the magnetic monopole glut could be avoided by a new proposal which he called the inflationary universe. Still busy exploring the consequences of inflation, Guth just finished a popular-level book called *The Inflationary Universe: The Quest for a New Theory of Cosmic Origins* (Addison-Wesley, 1997).

HEIDI NEWBERG received her PhD in physics in 1992 from the University of California at Berkeley, where she participated in both the Berkeley Automated Supernova Search and the High Redshift Supernova Search at Lawrence Berkeley National Laboratory.

She is currently applying her experience with automated imaging searches and software (as well as her lengthy exposure to the culture of high energy physics) as an Associate Scientist at Fermi National Accelerator Laboratory working on the Sloan Digital Sky Survey.

Newberg is also studying the statistics and colors of galactic stars, as well as color techniques to separate stars from QSOs. She plans to measure the large scale structure of QSOs which will be revealed in the data from the Sloan Digital Sky Survey.

CONTRIBUTORS



ANDREW PHILLIPS is a research astronomer at Lick Observatory, where he arrived as a postdoc in 1992. After receiving his MS from the University of Minnesota, he worked for four years at the Cerro Tololo Inter-American Observatory in Chile. He received his PhD from the University of Washington, where his dissertation researched star formation in nearby galaxies.

Since coming to work with the DEEP project, his research has shifted considerably deeper into space. He is closely involved in the planning and design of software for DEIMOS. When not working—a constant occupational hazard among astronomers—he enjoys music, backpacking, and camping with his family.

NICOLE P. VOGT is a research scientist at Lick Observatory, at the University of California, Santa Cruz. She completed her BS degree in physics at the California Institute of Technology in 1988. She obtained her PhD in astronomy from Cornell University in 1995, studying the effects of environment on mass and light in nearby spiral galaxies. She has studied cosmic rays in the earth's atmosphere, star formation in the center of the Galaxy, spiral galaxies in the local Universe, kinematics of galaxies out to a redshift of 1, and potential progenitor galaxies at a distant redshift of 3.

For the last two years she has been a member of the DEEP project, focusing upon the evolution of distant galaxies with the Hubble Space Telescope and the W. M. Keck Telescopes.

GERSON GOLDHABER is a Professor in the Graduate School, University of California at Berkeley and Faculty Staff Scientist emeritus at the Lawrence Berkeley National Laboratory. Since 1990 he has been working with Saul Perlmutter in a search for the most distant supernovae in order to measure the deceleration parameter of the Universe.

He received the 1977 California scientist of the year award for the discovery of charmed mesons, and in 1991 he shared the Panofsky Prize of the American Physical Society. He is a member of the National Academy of Science, the American Academy of Arts and Sciences, and a foreign member of the Royal Swedish Academy of Sciences. He also holds an honorary Doctorate degree from the University of Stockholm.

JUDITH GOLDHABER retired from the Lawrence Berkeley Laboratory after 35 years as a writer and editor in the public information department. Since then, she has been keeping busy writing the book and lyrics for a musical based on the life and ideas of Stephen Hawking. This work, “Falling Through a Hole in the Air,” had its premier in 1996 at San Francisco City College’s City Summer Opera; a second production is scheduled for May 1998.

LESLIE ROSENBERG is an Assistant Professor of Physics at the Massachusetts Institute of Technology. He received his BS at UCLA and his PhD from Stanford University. He did his graduate work with the MAC Collaboration at the SLAC PEP ring under Professor David Ritson. He then became an Enrico Fermi Fellow and later a Senior Research Associate at the University of Chicago before joining the faculty at MIT.

His research focuses on the intersection of particle physics, nuclear physics, and astrophysics. He is co-spokesman of the US effort to search for the axion, a hypothetical particle introduced to enforce CP conservation in QCD and later realized a good candidate for cold dark matter. He is the recipient of an Outstanding Junior Investigator award from the Department of Energy and a Career award from the National Science Foundation.

A senior physicist at Lawrence Livermore National Laboratory since 1985, KARL VAN BIBBER is the project leader for LLNL’s PEP-II B Factory effort. He is also the group leader for high energy physics and accelerator technology.

He received his undergraduate and graduate degrees from the Massachusetts Institute of Technology and did postdoctoral work at Lawrence Berkeley National Laboratory. In 1980 he accepted an assistant professorship of physics at Stanford University, and during his five years there he received an Alfred P. Sloan Research Fellowship in 1982.

CONTRIBUTORS

FRED HAPGOOD is a freelance intellectual property provider based in Boston and specializing in text since 1970.

VIRGINIA TRIMBLE has taken the first vital step toward renewing her passport, so as to be able to attend the triennial general assembly of the International Astronomical Union (in August in Kyoto), of which she is one of the vice presidents. This picture is one of the rejects. It might also be taken as illustrating the advice of William A. Fowler that one should turn a blind eye, a deaf ear, and a cold shoulder to written, spoken, and implied criticism respectively.

She currently also holds offices (of very little power but remarkably large temporal absorptive capacity) in the American Astronomical Society, the American Physical Society, Sigma Xi, the American Association for the Advancement of Science, and the Astronomical Society of the Pacific. She has recently received, and is trying valiantly to make sense of, data obtained by the Hipparcos Astrometric Satellite under a 1982 announcement of opportunity.

DATES TO REMEMBER

Nov 3–7	International Conference on Accelerator and Large Experimental Physics Control Systems (ICALEPCS 97), Beijing, China (Mr. Rucheng Hou, ICALEPCS 97, Institute of High Energy Physics, 19 Yuquan Road, Beijing 100039, P. R. China or baribaud@cernvm.cern.ch)
Nov 6–9	Workshop on Physics at the First Muon Collider and at the Front End of the Muon Collider, Batavia, IL (Cynthia Sazama, Fermilab, MS 122, Box 500, Batavia, IL 60510-0500 or sazama@fnal.gov)
Nov 9–14	7th International Conference on Calorimetry in High-Energy Physics (ICCHEP 97), Tucson, AZ (T. Embry, Secretariat, University of Arizona, Department of Physics, PAS, Bldg. #81, Tucson, AZ 85721 or calor97@physics.arizona.edu)
Nov 9–15	Nuclear Science Symposium and Medical Imaging Conference, Albuquerque, NM (Roger Gearhart, SLAC, MS 20, Box 4349, Stanford, CA 94309 or nss97@quest.uoregon.edu or gearhart@slac.stanford.edu)
Nov 15–19	Conference on Nuclear and Particle Physics, Cairo, Egypt (Dr. M. N. H. Comasan, Chairman NUPPAC 97, NRC, AEA, Cairo 13759, Egypt)
Nov 16–21	Supercomputing 97, San Jose, CA (Donna Crawford, Sandia National Laboratories, MS 9003, Box 969, Livermore, CA 94551-0969 or dona@ca.sandia.gov)
Nov 17–21	International Conference on Highlights in X-Ray Synchrotron Radiation Research (on the occasion of the 50th anniversary of the discovery of synchrotron radiation 1947–1997), Grenoble, France (Conference Secretariat, ESRF, BP 220, F-38043 Grenoble, France or sr50@esrf.fr)
Dec 10–12	4th International Conference on Physics Potential and Development of $\mu^+\mu^-$ Colliders (MUMU 97), San Francisco, CA (MUMU 97, Department of Physics, UCLA, Box 951547, Los Angeles, CA 90095-1547 or mumu97@physics.ucla.edu)
Jan 4–9 1998	Advanced ICFA Beam Dynamics Workshop on Quantum Aspects of Beam Physics, Monterey, CA (Dr. Pisin Chen, SLAC, MS 26, Box 4349, Stanford, CA 94309 or chen@slac.stanford.edu)
Jan 19–30	US Particle Accelertor School, Austin, TX (US Particle Accelerator School, Fermilab, MS 125, Box 500, Batavia, IL 60510-0500 or uspas@fnal.gov)
Jan 28–30	HEP Visualization and Data Analysis Workshop (HEPVIS 98), Stanford, CA (hepvis98@slac.stanford.edu)
Feb 18–20	3rd International Symposium on Sources and Detection of Dark Matter in the Universe, Santa Monica, CA (www.physics.ucla.edu/dm98/ or email dm98@physics.ucla.edu)