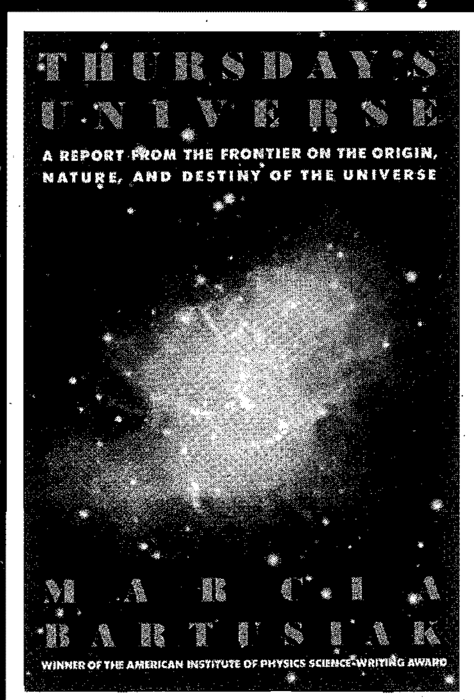
The Cosmic Burp:

The Genesis of the Inflationa



Editor's Note: One of the most fruitful scientific collaborations of recent times has been the joining of particle physics and *cosmology*, the study of the large-scale properties of the universe. Somewhat unexpectedly, the study of the smallest structures of the cosmos has illuminated our understanding of the largest, and *vice versa*. Perhaps the best-known idea to emerge from this collaboration has been the inspired suggestion that a period of dramatic *inflation* took place during the very earliest history of the universe. In the article below, award-winning science journalist Marcia Bartusiak explains the inflationary universe scenario and profiles the young physicist whose idea it was.

This article has been adapted from Ms. Bartusiak's intriguing new book *Thursday's Universe*, just published by Times Books. In clear nontechnical language it chronicles some of the most exciting developments in modern astronomy, including research on black holes, quasars, the birth and evolution of stars, and cosmology. Combining her interviews of prominent scientists with her trained journalist's perspective, she has managed to explain those developments in a most accessible and appealing style. We commend her book to our readers' attention.

About the Author

Marcia Bartusiak, a nationally published science writer, holds an advanced degree in physics. Her articles on subjects ranging from relativity to plate tectonics, have appeared in *Omni, Popular Science, Science News, Science Digest, Science 86,* and *Mosaic,* the magazine of the National Science Foundation.

In 1982, while a staff writer for *Discover* magazine, she was awarded the American Institute of Physics science-writing award in recognition of her ability to present complex ideas with clarity and style. She is a member of the A.S.P. and lives in Norfolk, Virginia.

Marcia Bartusiak

Universe Hypothesis

Introduction

"All roads lead to Rome," it was proudly proclaimed during the tempestuous reign of the Caesars. Likewise in astronomy, all inquiries and discussions seem to lead to *cosmology:* the branch of astronomy that strives to explain the origin, evolution, and overall structure of the universe. Cosmologists are anxious to know how the universe began and how it concocted the vast amounts of matter that eventually condensed into the billions and billions of galaxies we now observe.

By the 1980's, cosmologists came to realize that one vital key to cosmology, the science of the very large, actually lies in the science of the very small: particle physics. Possible answers to some cosmological riddles are arriving as theoretical physicists close in on a long-sought goal: the unification of the four basic forces that control the actions of everything from galaxies asteroids to raindrops and silicon chips. On the macroscopic level, there are the familiar forces of gravity and electromagnetism; on the microscopic level, the less familiar strong and weak nuclear forces. Each force acts very differently at the low temperatures of our normal surroundings, but, say theoreticians, they all become identical when energies are high enough. Because these energies, though, are far beyond the reach of any foreseeable particle accelerator, particle physicists have had to turn (grudgingly at first, but then more eagerly) to the field of cosmology. Many are now convinced that the forces of nature were assuredly one during the first hellish moments of the universe's creation. The Big Bang has become to them the ultimate particle accelerator — a cosmic-sized test lab for their newest and most challenging theories.

Cosmologists in turn have come to understand that by observing how particle physicists piece together their theoretical jigsaw puzzle, they will be offered a tantalizing peek at the cosmic soup that existed an infinitesimal fraction of a second after the Big Bang. To best comprehend this fascinating new marriage between cosmology and particle physics, though, we must first identify the plethora of particles that make up the subatomic world and the forces that reign over them.

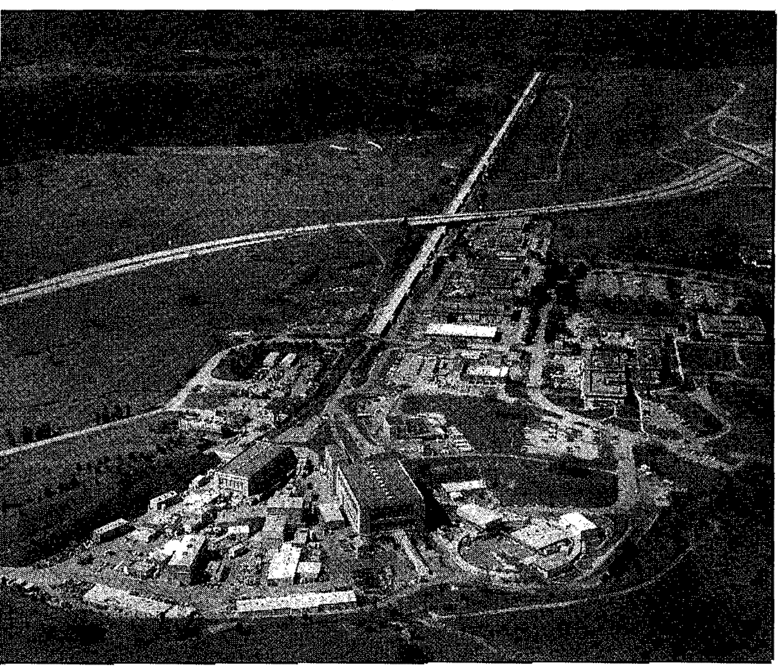
The Four Forces

Although science novices gazing at the arcane formulae in a physics textbook may have their doubts, the job of physicists can be summed up very easily: to describe the workings of the universe and all its complex and various phenomena in the simplest way possible. When Newton realized that the set of equations describing the trajectory of a rock thrown into the

Marcia Bartusiak. (Photograph by K. Keeny from Thursday's Universe.)

air could equally be applied to plotting the orbit of a planet or comet around the Sun, complexity gave way to simplicity. He had discovered that the motions of these two disparate objects, a small earthbound rock and an entire planet, were controlled by one, all-encompassing force — gravity. Gravity is the most far-reaching of the forces, capable of wielding its tugs over trillions of miles, yet it is also the feeblest interaction. As physicist James Trefil notes, "An ordinary magnet can lift a nail, even though the entire Earth is on the other side exerting a gravitational attraction."

A magnet exhibits one of the three interactions added to the roster of forces since Newton's day. Electromagnetism, the most conspicuous force on the human scale whether displayed in a lightning bolt or a dime-store compass, keeps electrons buzzing around a compact knot of protons and neutrons, thereby enabling atoms to exist. Without atoms, there would be no chemical elements, and without chemical elements there would be no life. And by discerning an even deeper structure within the nuclei of atoms during the first few decades of this century, physicists came to recognize the "strong" and "weak" forces. The strong force keeps every atomic nucleus, a packed assembly of protons and neutrons, from flying apart in the face of electromagnetic repulsion, while the weak force controls the way in which certain subatomic particles will disintegrate, causing a nucleus to decay radioactively. The weak force is also involved in nuclear fusion, so vital in powering the stars. (Could there be other forces? Possibly. Physicists would not be too surprised if new, very short-range forces, cousins to the strong and weak nuclear forces, are uncovered as particle accelerators increase their energies.)



The Stanford Linear Accelerator Center (SLAC) of Stanford University near San Francisco, California. In this device, charged subatomic particles are boosted to speeds near that of light in the mile-long, straight tunnel (which passes under the Interstate 280 freeway). Analysis of the microscopic "fragments" (subatomic particles) produced by impact of the speeding particles on their targets is a major tool in modern investigations of the nature of matter. (Photograph courtesy of SLAC.)

Just as the number of forces acknowledged by physicists grew from one to two to four, so, too, did the so-called "elementary" particles proliferate. In the 1930s, physicists confidently thought of electrons, protons, and neutrons as the sole units of matter. But as atom smashers grew over the intervening decades from crude room-size mechanisms to instruments with miles-long tunnels, myriads of ephemeral particles appeared in the debris spewed forth as protons and electrons crashed into stationary targets at near-light speeds. For a while, it was hard to keep track of all the new species. Such variety was bewildering to the scientists who were seeking simple truths, not intricate conundrums, from their energetic probes into the heart of the atomic nucleus.

A theoretical breakthrough in organizing the vast particle array was made in 1963 when Murray Gell-Man and George Zweig independently suggested that many of the puzzling particles might actually be composites, each a different combination of smaller, more fundamental constituents. Gell-Mann called these basic building blocks *quarks*, alluding to a line from James Joyce's *Finnegans Wake:* "Three quarks for Muster Mark." In the lexicon of physicists, so noted for their quirky labels, these quark types, now numbering six, are identified as *up, down, charm, strange, top,* and *bottom* (although more poetically minded physicists prefer to call the last two *truth* and *beauty*). Using this scheme, the proton turns out to be composed of two "up" quarks and one "down" quark. The neutron, the proton's near-twin except for a lack of electric charge, is a composite of two "downs" and an "up." While no one has indisputably observed a naked isolated quark, a number of accelerator experiments have strongly hinted that protons, neutrons, and a host of short-lived nuclear particles are indeed made out of such smaller components. Physicists call such particles *baryons*, from a Greek word meaning heavy.

Aside from quarks, the only other structureless and indivisible bits of matter currently thought to exist are the electron, the electron's close relatives the muon and tau particles, and three kinds of neutrinos. Collectively, these six related particles are known as *leptons*, from a Greek word meaning small. Nature contrives diverse constructs from its fundamental constituents. Particles of matter, it turns out, are either leptons or quark composites, and this simplification was a tremendous boost to certain cosmological inquiries. Additional strides were made as theorists conducted a parallel search for an underlying order among the four forces of nature.

Unification

Theoretical physicists have come to believe that the four interactions — gravity, electromagnetism, and the strong and weak nuclear forces — are just different manifestations of one ancestral force. It's analogous to the way that diamond, charcoal, and graphite are different expressions of a single substance. A sparkling gem, a blackish clump, and a greasy lubricant certainly look and feel different to us, but at some

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level they are essentially the same: all of them are carbon. Likewise, it is theorized that the four forces once exhibited a basic similarity within the fiery kiln of the early universe.

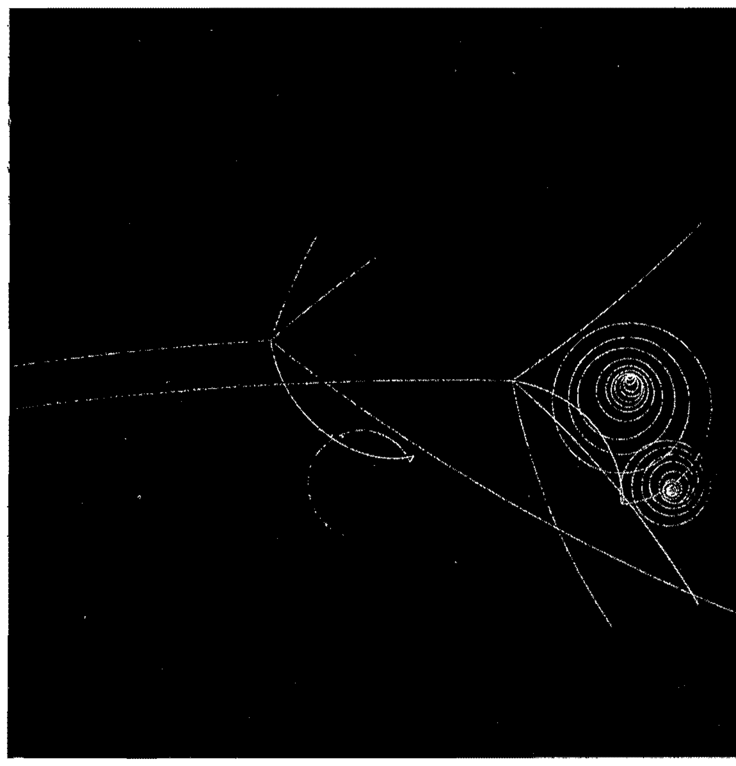
This process of theoretically unifying the forces actually began in the 1860s when James Clerk Maxwell, a Scottish physicist known as Daffy to his school chums, consolidated electricity (the force that governs an ordinary lightbulb) and magnetism (the force that gently swings a compass needle northward). Maxwell, by putting the experiments of Michael Faraday in mathematical form, saw that the two forces were merely different sides of the same coin, each unable to exist in isolation. Electric currents are always accompanied by a magnetic field, and conversely a variable magnetic field generates electricity. Maxwell's equations even predicted that electromagnetic energy could travel through space as an undulating wave, a realization that by the twentieth century led to radio, television, and microwave ovens.

Einstein had high hopes of continuing this process of unification by joining electromagnetism with gravity in one mathematical construct. He devoted a good part of his life to this quixotic pursuit, but, alas, to no avail. In some ways, he jumped the gun, for the two other fundamental forces, the strong and the weak, first needed to be better understood.

But where Einstein stumbled, a new generation of physicists were able to push forward. By the late 1960s, Harvard's Sheldon Glashow, Steven Weinberg, now with the University of Texas at Austin, and Abdus Salam of the Imperial College of Science and Technology in London all made (future Nobel-prize-winning) contributions to showing that there was a fundamental and intimate link between electromagnetism and the weak nuclear force. We certainly don't perceive this "electroweak" interaction in our relatively frigid environs; the unification of electromagnetism with the weak force occurs only at very high energies. Within the framework of the Big Bang, the electroweak force exerted its influence directly on the cosmos when the primeval fireball was no more than a ten-billionth of a second old. After that infinitesimally short stroke of time, electromagnetism and the weak force took on their separate guises: the weak force limited in its reach to the dimensions of an atom, while electromagnetism had a much longer range.

Many years had to go by, however, before the Weinberg-Salam-Glashow model could be fully accepted (initially, in fact, the theory was virtually ignored). Particle accelerators first had to become powerful enough to reach directly the high-energy domain — around a hundred billion electron-volts[1] or an equivalent temperature of 1,000 trillion degrees — wherein the electromagnetic and weak forces join up. Definitive proof came during the closing months of 1982 when a pencil-thin beam of protons, racing clockwise within a four-mile-long under-ground accelerator ring at CERN, the European Center for Nuclear Research near Geneva, slammed head-on into a focused beam of anti-protons traveling in the opposite direction. Whenever a proton and antiproton happened to crash into one another and completely annihilate each other, a monstrous state-of-the-art detector, weighing some 2,000 tons and as big as a house, recorded the resultant shower of debris — the newborn energy readily coalescing into a fresh batch of particles. More than one hundred physicists from thirteen laboratories around the world were involved in the endeavor. By 1983 the head of the CERN team, Harvard's Carlo Rubbia, was able to announce that a couple of handfuls of their observed collisions, which numbered in the tens of millions, generated the distinctive signatures of the W^+, W^-, and Z particles, the predicted "carriers" of the electroweak force. "There's now such a sense of confidence. It doesn't seem as if we are making it up as we go along," said theorist Weinberg at the time of the discovery.

That an atomic particle can be conceived of as the conveyor of a force was once of the revolutionary outcomes of modern physics. When walking about on the Earth's surface, we often get the impression that a force is some kind of invisible entity that pushes or pulls us around. But on the level of atoms, physicists prefer to describe forces as a kind of tennis game: A force between two particles arises from their continually exchanging another, identifiable particle (a subatomic tennis ball, so to speak). For electromagnetic interactions, the "tennis ball" is the photon. The Z and W particles, meanwhile, are responsible for transmitting the weak force. And, as an expression of the strong force, something called a gluon constantly bounces between quarks to bind them into protons and neutrons. In keeping with this stratagem, a particle called the graviton, not yet detected, is thought to convey the force of gravity.



Subatomic particles in collision. A proton's path and fate are chronicled in this "bubble chamber" photograph, which records the paths of subatomic particles. In the pictured event, a speeding proton (longer straight track from the left) collides with a particle called a "pion", creating an electron and its antimatter counterpart, a positron. The electron spirals clockwise here under the influence of the chamber's magnetic field; the positron spirals in the opposite direction. (Photograph from Thursday's Universe courtesy of the Lawrence Berkeley Laboratory.)

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1. Particle physicists traditionally describe accelerator energies in terms of *electron-volts*. One electron-volt is the energy an electron picks up as it crosses a one-volt electric field, the voltage in a penlight battery.

GUTs

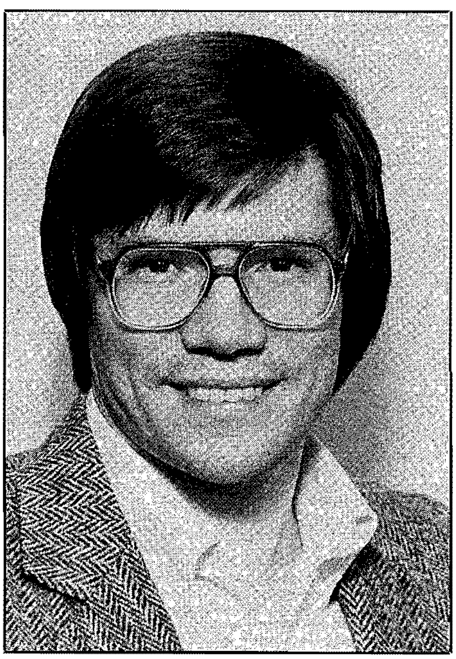
The success of the electroweak theory gave physicists, Howard Georgi and Glashow among them, the courage to push their unification schemes to energies as high as a trillion trillion electron-volts, a realm where the electroweak force at last merges with the strong force. Altogether, the various mathematical models that attempt to describe this unification are referred to as *Grand Unified Theories*, or GUTs for short (although some think it a pretentious name, since gravity is not included). Leon Lederman, director of the Fermi National Laboratory, a facility which operates the United States' most powerful atom smasher, the Tevatron, says that their ultimate goal is "to explain the entire universe in a single, simple formula that you can wear on your T-shirt." When the weak and strong nuclear interactions are united with electromagnetism in a single force, it is believed that quarks and leptons, such as electrons and neutrinos, become virtually indistinguishable, quickly and easily changing from one form to the other. It is a capability which, at one crucial moment in the universe's history, may have resulted in some cosmos-shaking consequences.

Unfortunately, unlike the electroweak merger, the GUT unification occurs at such high energies that it is technologically impossible to duplicate the effect on Earth. "Energies as high as those involved in GUTs are far beyond what we can get in terrestrial laboratories," points out University of Chicago astrophysicist (and A.S.P. Trumpler Award winner) David Schramm. "It would require an accelerator that stretches from here to Alpha Centauri, which would ease vacuum leak problems but would make data analysis difficult — not to mention problems with the gross national product."

But luckily, physicists have access to this high-energy arena through a convenient back door. "There was at least one event that took place at these energies: the Big Bang itself," continues Schramm. "The first 10^{-35} second of the universe's history provides our best testing ground for the grand unifying ideas."

The new cosmologists often describe the embryonic universe as swiftly proceeding through a series of "phase transitions," each stage altering the early universe's basic physical properties (analogous to the way that water is physically transformed as it cools from vapor to liquid to solid ice). During the first searing flash of creation, it is believed that the four forces of nature were united. But then, as the universe coursed outward and cooled, the individual forces (and their associated collections of particles) broke away one by one, each force eventually assuming its own identity.

Under the rules of this theoretical game, physicists came to see that the force of gravity was the first to part company, 10^{-43} second after the initial explosion. Though vastly important on cosmological scales, it ultimately became the weakest of the forces; the gravitational force between an electron and proton is 10,000 trillion trillion trillion times feebler than the electrical force binding those same two particles in an atom. By the time the universe was about 10^{-35} second old, the GUT unification was shattered, allowing the strong force to develop its own characteristics. A fleeting instant later, the electroweak force divided into its two separate components. All the while, the various particles out of which we are composed congealed, like crystals of ice in a cooling pond of water. Verifying this fascinating tale of creation can be tricky, because the Big Bang laboratory shut down more than 10 billion years ago. Unable to construct a particle accelerator from here to Alpha Centauri, Big Bang specialists must be content to search for supporting evidence in the many fossils that remain behind from that most ancient of epochs.



Dr. Alan Guth in 1985. (Photograph courtesy of the Massachusetts Institute of Technology.)

Alan Guth

As regular readers of *Mercury* know, the Big Bang scenario — aided and abetted by the new results from particle physics — has had remarkable success in explaining many of the observed properties of the cosmos. But while the overall picture of an explosive beginning fit the observations well, a number of specific features of the universe's makeup remained, to everyone's frustration, unexplained. As one example, cosmologists could only guess at the reasons for the universe being so amazingly smooth over very large scales. By some means — no one knew exactly how — the universe got filled with a nearly uniform and intensely hot gas, which stayed relatively homogeneous as the universe evolved. Inexplicably, the cosmos seems to be as finely tuned as a precision toolmaking machine. It was not until 1979 that a possible explanation for this curious initial condition arrived, and ironically the solution was introduced by a physicist with absolutely no background in astrophysics.

Alan Guth was a most unlikely candidate to alter our understanding of the universe in one night. He was one of the many gypsies of physics, an intrepid "post-doc" who wandered from university to university filling temporary lectureships and research positions after obtaining a Ph.D from the Massachusetts Institute of Technology in 1972. His first stop was Princeton, where he served as an instructor in particle physics for three years. From there, he went on to Columbia University and then Cornell, all in all an eight-year trek from the woodlands of central New Jersey to the Finger Lakes region of western New York.

During this time, Guth was oblivious to cosmology, almost as unacquainted with its basic tenets as a college freshman. "Frankly," he says with the bright smile that often crosses his face, "I thought it was too speculative." Instead, Guth was immersed in studying the many and varied forces of nature, not experimentally by the side of a giant particle accelerator but rather from a theorist's perspective. Guth was one of that legion of theoretical physicists who attempt to describe the forces of nature in the most elegant mathematical language possible. His graduate thesis attempted to show how quarks, those basic units of matter, might be joining up to become protons and neutrons, the core ingredients of an atomic nucleus. He had no interest in hazy conjectures on the universe's emergence from a vantage point fifteen eons down the road. Mathematical rigor was his passion.

Yet, serendipity — three times over — would eventually nudge him toward the study of cosmology. Two lectures, a chance collaboration with a colleague, and an off-the-cuff remark would lead him to a late-night revelation that dramatically revised the whole "industry's" model of our cosmic birth. Guth's calculations reveal that our universe may have begun, not only with a bang, but with a sort of cosmic *burp* — a brief moment of superaccelerated expansion that transformed a subatomic smudge of energy into a celestial cornucopia of galaxies, stars, and planets.

If Guth's fundamental concept is correct, it also means that the universe astronomers have long studied through their telescopes is only a miniscule mot immersed in a much larger domain of spacetime. In the sixteenth century, Copernicus displaced humanity from the center of the universe by suggesting that the Earth revolved around the Sun. Nearly four centuries later, Edwin Hubble continued the process by proving that our beloved Milky Way is but one in a myriad of galaxies rushing through the vast gulfs of outer space. Now Guth was moving us one more step into obscurity by suggesting that the cosmos visible to astronomy's mighty array of instrumentation is only a speck when measured against a larger stage of spacetime.

Guth's ideas have had a considerable impact on the astrophysics community because they appear to solve several cosmological mysteries that have plagued theorists for years and to answer some very basic questions about our explosive beginnings: Why the universe was once so hot, why it keeps expanding, and where it obtained its supply of mass and energy.

A Lecture and a Question

Guth's unplanned scientific odyssey began on the afternoon of November 13, 1978, with the young researcher sitting in an auditorium on the Cornell campus listening to a visiting lecturer, Princeton theorist Robert Dicke, expound on cosmological paradoxes. Why, Dicke asked his audience, raising one of cosmology's thorniest puzzles, is the universe so geometrically flat? There's another way of viewing this problem: Why is the universe virtually poised, like a ballerina *en pointe,* between open and closed?

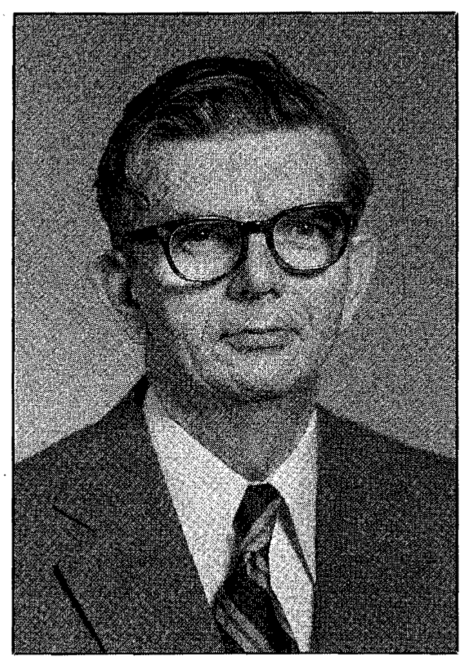
It was Einstein who first taught cosmologists of the intimate relationship between matter, gravity, and the curvature of spacetime: Matter, as it's since been proved many times, causes space to warp and bend. If there is not enough matter in the cosmos to exert the gravitational muscle needed to halt the expansion of spacetime, then our universe will remain *open,* destined to expand for all eternity. With too little mass, space never turns inward, closing back upon itself. Instead, a mass-poor space curves out like a saddle whose edges go off to infinity, fated never to meet.

On the other hand, a higher density would provide enough gravity to lasso the speeding galaxies — slowing them down at first, then drawing them inward until spacetime curls back up in a "Big Crunch" and re-forms the brilliant fireball from which we were spawned. Here, in this *closed* model, spacetime would encompass a finite volume and yet have no boundaries. The two-dimensional analogy would be the surface of a sphere like our Earth which, as sailors discovered hundreds of years ago, has no edges. If a space voyager traveled a straight-line course through a closed universe long enough, she'd eventually return to her starting point (not unlike a round-the-world cruise here on our own planet).[2]

But astronomers cannot yet predict with absolute certainty which fate, eternal expansion or fiery collapse, will befall us; indeed, the density of matter now measured in our universe lies relatively close to the threshold, a notable juncture called "critical density." Here, spacetime looks neither open nor closed, but flat as a pancake. Adding up all the luminous material we are aware of in the universe plus the dark, unseen matter for whose existence we have indirect evidence[3] takes the cosmos to within one-tenth of critical density. (In cosmology, being within ten percent, at the very least, is close.) Working with the standard model of Big Bang, Dicke, in collaboration with Princeton University physicist P. James E. Peebles, realized that this was a bewildering situation. Since any deviation

2. For more on models of the universe, see the article by the late George Abell in the May/June 1978 issue of *Mercury.* — *Ed.*

3. For more on the "missing mass" question, see the articles by George Field in our May/June 1982 issue and Wallace Tucker in our Jul/Aug 1981 issue. — *Ed.*



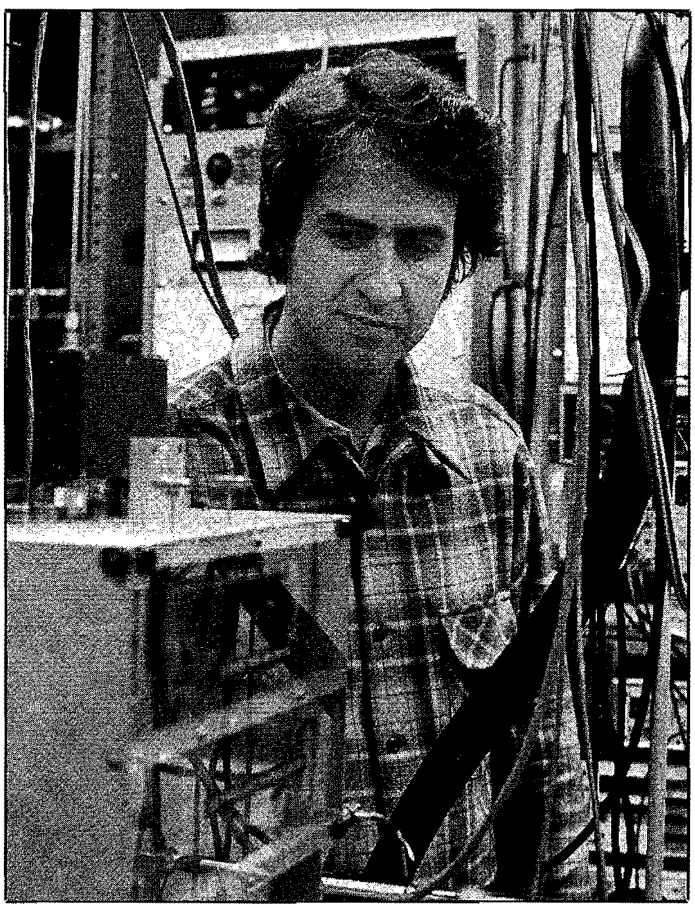
Dr. Robert H. Dicke. A lecture by Dicke at Cornell in 1978 piqued Alan Guth's curiosity about modern cosmological puzzles, and started his "unplanned scientific odyssey" into theories of the early universe. (Photograph courtesy of Princeton University.)

from critical density at the moment of creation would grow quite rapidly with time, Dicke explained that to be within ten percent of critical density today means that the density of the universe at the age of one second had to differ from critical density by less than one trillionth of one percent. At the time of Dicke's talk, there was simply no explanation for this incredible fine-tuning, as difficult a task as throwing a dart from New York City and hitting a bull's-eye on a dart board held over Washington D.C. "I didn't understand the basis for Dicke's statement at the time," admits Guth. "But it did stike me as an amazing fact."

Around this same time, a friend and colleague at Cornell, Henry Tye, began asking Guth whether he thought grand unified theories or GUTs, the theoretical attempts to unite the force of electromagnetism with the strong and weak nuclear forces, would give rise to magnetic monopoles. "I had heard the words 'grand unified theories,' before, but I knew nothing about them, absolutely nothing," recalls Guth. "Henry explained to me what they were, and I went home one night to think about whether monopoles would be a natural outcome from this theory."

Guth was familiar with the concept of a monopole; he had studied it before on an abstract, mathematical level. The great physicist Paul Dirac first predicted the monopole's existence more than half a century ago when he was contemplating nature's many symmetries. If the universe has provided us with separate units of electric charge — the positively charged proton and the negatively charged electron, for example — then it's likely, Dirac surmised, that it also cooked up separate particles of only one magnetic pole.

This is a concept that goes against the grain of our daily experience. Every magnet on Earth is composed of an inseparable duo: a north and south pole. Break the bar in two and you only end up with two new magnets, each with its own north and south pole. This would be true even if you continued to break each piece down to its very last atom. But *mono*poles, as the name implies, would be elementary particles that have only one pole, either north or south. In 1982, the entire physics community was abuzz when a sophisticated detector, set up by Blas Cabrera in a tiny basement lab at Stanford University, appeared to see a monopole passing through its supercooled coil. As of this writing, the signal has not been repeated, so the jury is still conferring on whether such alleged magnetic debris from the Big Bang is truly coursing through the universe. Many hope it is but more evidence is the only way to settle this case. "Roses are red, violets are blue, the time has come for monopole two," a playful group of Harvard theoretical particle physicists once wrote Cabrera.[4]



Blas Cabrera amid equipment for his magnetic monopole detector at Stanford University. The experiment seemed to have made an unprecedented detection of a monopole in 1982. However, it has not done so again since, and whether magnetic monopoles even exist remains an open question — a question whose eventual answer will have a profound impact on cosmology. (Photograph courtesy of Stanford University.)

However, it was 1979, and Guth was not concerned with the experimental evidence but rather the latest theoretical grounds for justifying a monopole's existence. From the perspective of GUTs, monopoles turn out to be infinitesimally small spots in space where the amazing conditions of grand unification continue to prevail. Put another way, they are cosmological "flaws" in the topology of spacetime that arose as the universe expanded and cooled, reminiscent of the faults that crop up as a body of water freezes. "Once I understood the rules, it didn't take too long to realize that grand unified theories would give rise to magnetic monopoles. In fact, monopoles with ridiculously high masses." To reach that conclusion, Guth used methods developed by Dutch physicist Gerard 't Hooft and Moscow physicist Alexander Polyakov, who a few years earlier had worked out a theory of monopoles with a simpler model. According to the calculations, each bit of "magnetic charge" would weigh more than a million billion protons. This was the mass of an amoeba squeezed into a volume that was smaller than a proton, making a magnetic monopole the superheavyweight champ of all the elementary atomic particles.

From Monopoles to Supercooling

Tye was quite pleased by the finding and eager to figure out how many of these goliaths would have come spewing from the Big Bang. Guth, however, was more than a little reluctant. "In all honesty," he confesses, "I thought it was a sort of silly thing to work on." But again, a visiting lecturer, this time soon-to-be Nobel laureate Steven Weinberg, opened Guth's mind to the formidable possibilities to be found in combining particle-physics theory with cosmology. "Steve was one of the first to use grand unified theories to see how baryons [whose best-known examples are protons and neutrons] were produced in the Big Bang, and his talk left me with the distinct impression that the Big Bang was indeed a tractable mathematical problem."

4. For an account of Blas Cabrera's experiment, see the article by Wallace and Karen Tucker in the March/April 1983 issue of *Mercury*. — *Ed.*

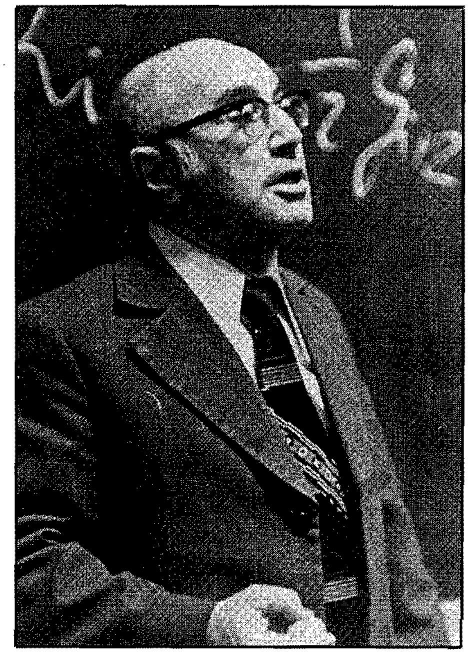
Once on track, Tye and Guth saw rather quickly that the Big Bang would be quite prolific in its monopole production. In fact, a little too prolific. (This was a result independently reached and first published by Caltech's John Preskill, a Harvard graduate student at the time.) "So many of these heavy monopoles should have been produced that we began to wonder why the universe was here at all," remembers Guth. "Their tremendous weight would have closed the universe back up eons ago." What happened to prevent the universe's early demise?

With the arrival of autumn, Guth traveled west to fill yet another postdoctoral position, this one at the Stanford Linear Accelerator Laboratory in California. But his collaboration with Tye would continue through phone calls and correspondence. They concluded that there was only one way the Big Bang could have avoided flooding the universe with heavy magnetic monopoles: It must have experienced a period of "supercooling," a sort of stall in the break-up of the grand unified force. In the mid-1970s Harvard theoretical physicist Sidney Coleman, among others, had already pointed out that this was a distinct possibility.

If you could somehow have done the impossible and sneaked a detector into the universe during the GUT era, you'd have found that quarks, electrons, and neutrinos, distinct entities at the low temperatures of our everyday life, looked and acted virtually alike. The universe was wondrously symmetric. As we discussed earlier, each force broke out of this cocoon of uniformity only as the universe expanded and cooled. Some like to think of this process as a sort of crystallization, as water crystallizes when it becomes ice. But maybe, posed Tye and Guth, the cosmos maintained its symmetry for a while as the temperature plunged, just as water can sometimes supercool and thus remain liquid below its freezing point. This would prevent too many monopoles, or pointlike imperfections, from arising in the "crystal" that was freezing out to become our universe.

Guth, sitting in an office whose neatly shelved books and organized papers reflect the order so often sought by the theoretical physicist, explains: "When you cool water it forms ice, and this ice forms along axes which are chosen at random. So, you have the possibility that one part of the ice will start forming with the crystal axis pointed a certain way, while another piece nearby points a different way. An imperfection in the crystal arises where these two pieces join. In particle physics, the creation of monopoles is the analogy of that process." Supercooling provided the time to smooth out these many misalignments and keep the number of monopoles to a minimum — at least few enough not to squish us down in a Big Crunch anytime soon.

Left at that, Tye and Guth's finding would have provided an interesting, though not momentous, footnote in the developing marriage of cosmology and particle physics. But Guth went one step further, spurred, he believes, by a casual reminder by Tye to check how this supercooling might have affected the expansion of the infant universe, the development of spacetime itself. At the time, Guth little realized the import of that remark. In fact, he didn't get around to the job for quite a while. The spark may have been a long chat on grand unified theories that he had one Thursday afternoon with Harvard's Coleman, who was on sabbatical at the Stanford laboratory that year. Whatever the reason, the varied pieces of the cosmological puzzle that had been gathering in Guth's mind over the previous six months finally fell into place later that night, December 6, 1979.



Soviet astrophysical theoretician Yakov Borisovich Zel'dovich. Zel'dovich, among others, published early papers which included speculation about what Guth would later call the "inflationary" era of the early universe. (Photograph from the A.S.P. archives.)

An Idea is Born

Around eleven o'clock, Guth sat down in his makeshift office at his rented home in Menlo Park, a town near the Stanford campus, and began to work on a series of calculations that within a couple of hours would cover four pages. The title at the top of the first page records his ambititious intentions: The small precise black letters announced that he was tackling no less than the EVOLUTION OF THE UNIVERSE. What follows is a potent blend of particle physics theory and general relativity, which has long served as the very backbone of all cosmological ponderings. "Actually, it's an easy calculation once you know the question to ask yourself," Guth modestly professes. "I'm surprised it wasn't done earlier."

In actuality, there were some foreshocks. Once a revolutionary idea has caught on, a search through the scientific literature will often point out precursors — the germ of the theory sprouting in earlier forms. In the 1970s, for instance, the noted Soviet theorists Yakov Zel'dovich[5] and A.D. Linde each wrote on the possibility of an early universe that wildly raced outward for a short time. However, they offered no special mechanism for this to occur. And at the very moment that Guth was formulating his model, others were deriving it independently. Theoretical astrophysicist Demosthenes Kazanas of the NASA Goddard Space Flight Center in Maryland would write in the *Astrophysical Journal* three months before Guth's paper was published in the *Physical Review* that "the presence of a phase transition early in the history of the universe, associated with spontaneous symmetry breaking . . . significantly modifies its dynamics and evolution

5. Zel'dovich won the A.S.P.'s coveted Bruce Medal in 1984. — *Ed.*

. . . The expansion law of the universe then differs substantially . . ." This same point would also be made by a Japanese researcher named Katsuhiko Sato and University of Michigan physicist Martin Einhorn. But Guth's paper, with its greater detail, would serve as the definitive catalyst to this new line of research. "It's an interesting example of the sociology of science," points out Princeton's Peebles. "There are preliminary quakes, and then one paper catches your attention." Guth himself helped the process along by becoming a scientific barnstormer, widely lecturing on the idea before he even published to convince the doubting Thomases that his scheme was a powerful tonic for many of cosmology's ills. As Tye jokes, Gut had become a "born-again cosmologist."

The Inflationary Scenario

Guth's four pages of equations look deceptively easy, yet any practicing theorist reading over the pages, now inconspicuously ensconced in one of many cherry-red binders lined up on Guth's book shelf, would see immediately that Guth was dealing with the arcane tools of their trade — things called gauges, Higgs fields, and false vacuum states. Often it is difficult for physicists to explain, in everyday language, what those technical words mean. But, as Guth put down his pen around 1 AM, the bottom line was undeniable. If his equations were valid, the universe did not just expand at the moment of its birth, it tore outward like a fanciful science-fiction spaceship in warp drive. Perhaps inspired by the double-digit rises in the cost of living at the time, Guth soon came up with an appropriate name for this period of hyperacceleration — he called it inflation.

At first glance, this may seem to be a subtle change, a mere alteration in the mechanics of the Big Bang. Why does it really matter that the universe once expanded at a much faster rate, you might ask? But it was much more than that. Guth's inflationary universe rewrote the script of our cosmic beginnings, giving us the first hint as to the origins of the matter and light that fill the universe.

The scenario begins 10^{-35} second into the birth, when the universe as we know it was only one trillionth the size of a proton (about 10^{-25} centimeter across). This unimaginably hot seed was expanding and thus starting to cool below 10^{27} degrees. That's more than a million million million times hotter than our Sun, whose core temperature is practically absolute zero in comparison with such energies. Under the standard model of the Big Bang, this is the stage at which the unified symmetry should have started to fragment into separate, distinct forces and differentiated subatomic particles. But, as Guth and Tye suggested earlier with the monopoles, this did not happen right away.

Instead, the little knot of space and time became supercooled as the temperature plunged — again, just as water can sometimes remain liquid below 32° Fahrenheit before freezing into ice. This delay in its "crystallization" endowed the universe with a tremendous potential energy, not unlike a rock about to fall from a precarious perch on the edge of a precipice. What Guth realized late that night was that there would be peculiar side effects of this supercooling, most importantly on gravity. A pressure contribution to gravity, a term usually ignored in everyday computations, became very important in the early universe. In this bizarre supercooled state, the pressure term actually reversed the effect of gravity. In other words, gravity, normally a force that draws things together, did a turnabout and became repulsive, causing space to balloon outward at a superaccelerted rate. Within an infinitesimal fraction of a second (about 1/100,000,000,000,000,000,000,000,000,000,000 of a second) our observable cosmos doubled its size a hundred times over (2, 4, 8, 16,. . .) until it was the size of a softball, or maybe even larger.

This momentary inflationary epoch at last ended quite climactically when the supercooled symmetry (using the jargon of physics) began to break spontaneously. At this point, the analogy to supercooled water can be taken one step further. When water freezes, it radiates a certain amount of energy into its environment. This is its so-called *latent heat* and represents the difference in thermal energy between the solid and liquid states. A jostling drop of liquid water, it is readily apparent, contains more energy than an immobile piece of ice, and this extra energy is released during the transition. This energy is not minuscule. If the water in an Olympic-sized swimming pool were to freeze, from the surface to the bottom, it would give off enough energy to heat a large house for a couple of years.

A similar energy difference exists between the inflationary and noninflationary phases. Guth surmised that, upon "freezing," the inflationary universe converted all its latent energy into an awesome cascade of extremely hot matter — in fact, *all* the particles and radiation that surround us today. It would be

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DYNAMICS OF THE UNIVERSE AND SPONTANEOUS SYMMETRY BREAKING

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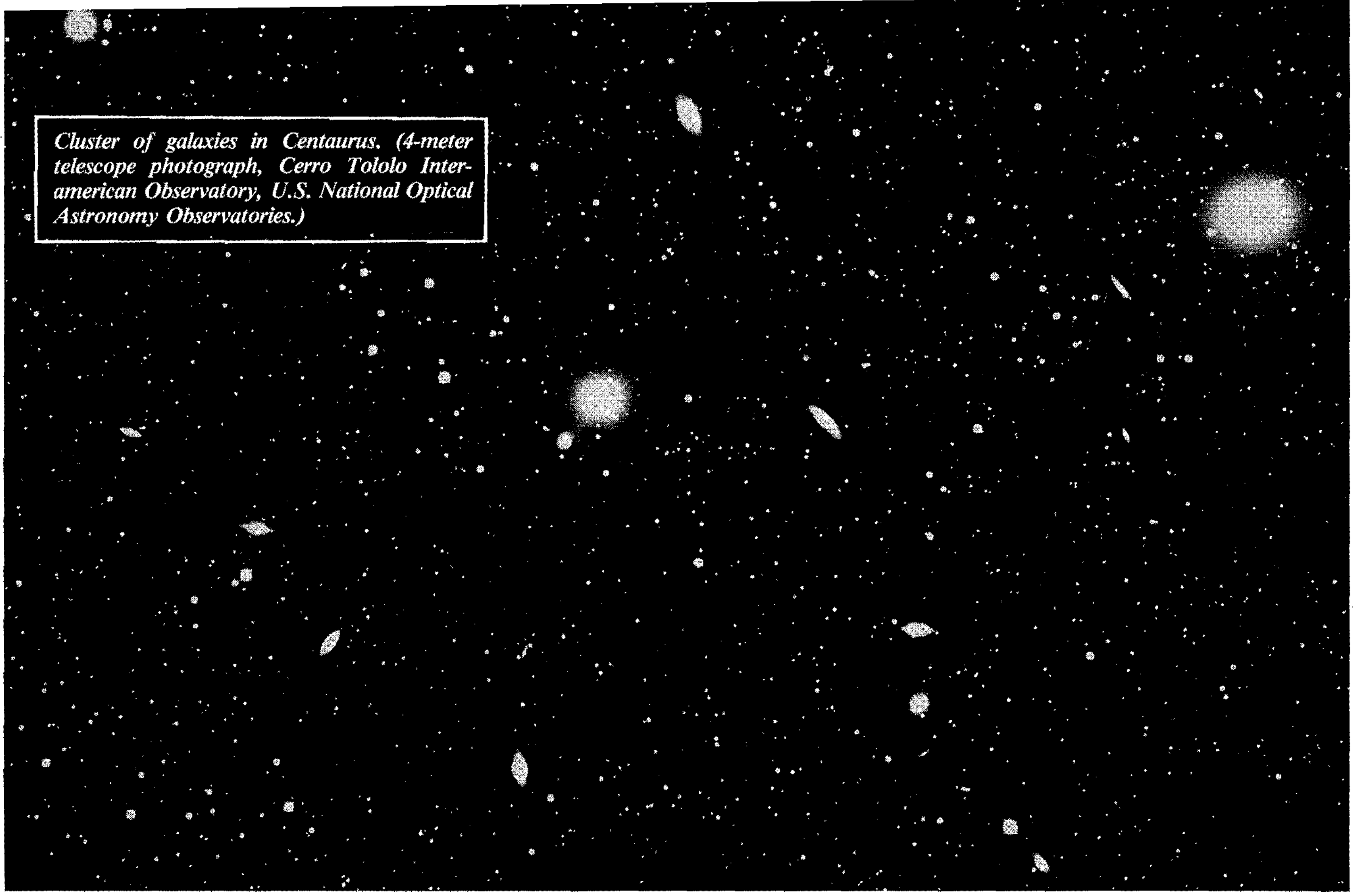
ABSTRACT

It is shown that the presence of a phase transition early in the history of the universe, associated with spontaneous symmetry breaking (believed to take place at very high temperatures at which the various fundamental interactions unify), significantly modifies its dynamics and evolution. This is due to the energy "pumping" during the phase transition from the vacuum to the substance, rather than the gravitating effects of the vacuum. The expansion law of the universe then differs substantially from the $R \propto t^{1/2}$ relation considered so far for the very early time expansion. In particular it is shown that under certain conditions this expansion law is exponential. It is further argued that under reasonable assumptions for the mass of the associated Higgs boson this expansion stage could last long enough to potentially account for the observed isotropy of the universe.
Subject heading: cosmology

*The abstract of an article containing ideas about an inflationary phase of the universe. This paper predated Guth's more greatly-detailed, definitive work by only three months; in 1980, several theorists were independently pursuing lines of thought in this direction. (Courtesy of **The Astrophysical Journal** and the American Astronomical Society.)*



Cluster of galaxies in Centaurus. (4-meter telescope photograph, Cerro Tololo Inter-american Observatory, U.S. National Optical Astronomy Observatories.)

this fireball, not the earlier expanding seed, whose glowing embers appear today throughout space as a cool wash of microwave radiation. Whatever mass-energy was contained in the pre-inflationary seed was simply overwhelmed by the fiery flood tide.

Surprisingly, Guth figures that only about twenty pounds of hot, symmetric mass-energy is needed to get the process going. Thus, it was inflation's demise that put the *bang* into the Big Bang and provided our cosmos with all its necessary building materials. According to this scheme, every galaxy, dust cloud, and photon — some 10^{87} particles in all — is only the resultant mass-energy from that brief but frenzied inflationary era. As Guth likes to put it, "Our universe is the ultimate free lunch." Mountains and asteroids, pulsars and nebulae, people and pine trees, every material entity in the universe is simply the residual afterglow of inflation.

After the release of inflation's pent-up energy, the superacceleration stopped, gravity went back to being an attractive force, and expansion of the heavens continued at a more sedate pace as spacetime coasted outward on the sheer momentum left over from that initial, hyperexplosive thrust. With this theory physicists could understand, better than ever before, why the early universe was so hot and how it got so big.

Guth didn't comprehend these features all at once that balmy December night, but he did smell the air of truth about his initial calculations, quite an accomplishment for someone unacquainted with cosmology only the year before. The next day, after a record bicycle ride back to work, the very first words the excited researcher wrote in his notebook were: "SPECTACULAR REALIZATION: This kind of supercooling can explain why the universe today is so incredibly flat — and therefore resolve the fine-tuning paradox pointed out by Bob Dicke in his . . . lectures." As if to back up his judgment, he drew a double box around the paragraph.

Inflation and Flatness

How inflation solves the flatness problem is quite intuitive. Just imagine the surface of a balloon as it's being blown up. As the balloon gets larger and larger and larger, its curvature gets flatter and flatter and flatter. And a universe doubling its size every 10^{-35} second only magnifies this effect in a preposterous manner. By the end of the inflationary period, the universe's curvature was greatly suppressed, taking it to the very brink between open and closed. Since the geometry and density of the universe are intimately linked, Guth's result also implies that there should be a *hundred* times more matter wandering through the cosmos than currently viewed through telescopes. Motions of galaxies within clusters and the unusual spins of spiral disks do suggest there is additional stuff filling the universe — dark and hidden material ten times more plentiful than luminous matter. But, if Guth is right, and the universe is just balanced between open and closed, the cosmic density must be greater still: another tenfold increase is required to flatten the universe out. This is one reason cosmologists today are speculating, with great excitement, that the universe might be filled with exotic elementary particles that have not yet been detected in particle accelerators.

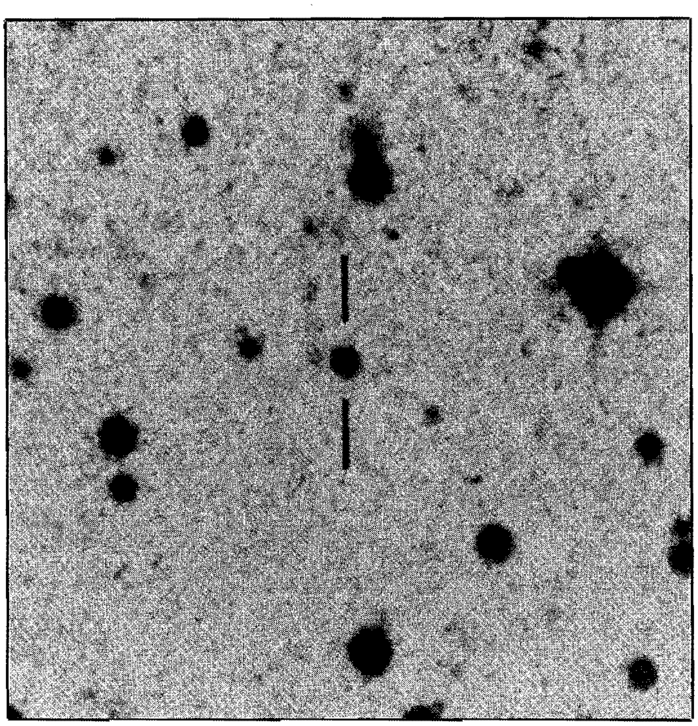
Inflation and Uniformity

By the start of the new year — 1980 — Guth experienced another stroke of luck. While having lunch at the accelerator laboratory's cafeteria, he heard a colleague, physicist Marvin Weinstein, mention another longstanding cosmological mystery: astronomy's difficulty in explaining the incredible uniformity of the universe. Guth, the cosmology novice, had been unaware of this problem, but after listening to the lunch-time discourse he soon realized that inflation could easily provide an explanation.

It may seem odd to describe the universe as uniform. The presence of stars and galaxies makes it appear quite the opposite. From our earthly perspective, the cosmos looks rather lumpy. We're not only circling the outer perimeter of a clump known as the Milky Way, we're also perched at the edge of a disklike assemblage of galaxies called the Local Supercluster. Even farther out, galaxies now appear to be arranged on the surfaces of immense bubbles, surrounding immense voids of almost empty space. But if you could look down at the universe over scales of billions of light years, you'd see that the galaxies are fairly smoothly distributed, not unlike the way the foamy texture of a sponge would look increasingly uniform as you stepped away from it.

Under the standard model of the Big Bang, there is no easy way to explain this smoothness. There is not enough time during the early stages of the explosion to get all bits of matter "well blended" before they shoot off. Yet, somehow, the galaxies in the northern part of the sky went on to form and develop in exactly the same way that they evolved in the south. And that background hum of microwaves in our universe, the echo of the Big Bang, varies from place to place in the sky by only one part in ten thousand. The problem is that all regions of our ever-expanding cosmos could not possibly have communicated with one another (in a sense, gotten their story straight) at the time that radiation was emitted. Then, why is each corner of the universe putting out precisely the same hum?

Inflation could be the reason. Recall that right before inflation took off, the region that was going to evolve into our observable universe was a trillion times smaller than a proton. Thus, it was quite easy for all corners of this infinitesimal speck to readily mix, attaining the same temperature and density. Inflation then stepped in to spread and maintain this uniform mixture throughout a growing bubble of spacetime.



Quasar Parkes 2000-330 (indicated), one of the most distant objects detected from Earth thus far. It is roughly twelve billion light years away — but, according to some interpretations of "inflationary universe" theories, the "boundaries" of our universe may be a hundred billion billion times more distant. (Photograph courtesy of NASA.)

A New, Improved Theory

Like any new scientific venture, though, Guth's original idea was not without its shortcomings. For one, he could not provide a graceful exit from the inflationary spurt. At first, he thought the hyperacceleration might end suddenly, like a runaway car slamming into a brick wall. But that, in theory, left him with a chaotic mess of tiny "bubble" universes, none of which could grow and evolve into the universe we see around us. The crystallization, in a sense, was patchy. Guth joined forces with Columbia University's Erick Weinberg to see if they could come up with a way to get those bubbles of "normal space" to coalesce somehow and form one big universe, but to no avail.

The death knell was about to sound for Guth's inflationary scheme when several other physicists, A.D. Linde of the Lebedev Physical Institute in Moscow and, independently, Andreas Albrecht and Paul Steinhardt of the University of Pennsylvania, came to the rescue. In a move that would make Madison Avenue proud, their revised model came to be called the "New Inflationary Universe." By tweaking some of the parameters in the equations, Linde, Albrecht, and Steinhardt were able to show how inflation could proceed in a subtly different manner, lasting long enough for any one of Guth's many bubbles to balloon into a suitable cosmos. In fact, the new inflationary model predicts that the visible universe we observe out to the farthest quasar is just a tiny fraction of the spacetime domain that burst forth to give birth to us. The equations can't tell just how much larger, but a good guess is that the entire region is billions and billions of times bigger than the observable universe. If true, astronomers will no longer be able to talk glibly about seeing out to the edge of the cosmos. The best telescopes today can observe quasars, the luminous cores of young, violent galaxies, out to a distance of some 12 billion light years. But the true boundaries of the spacetime domain that inflated may now lie more than 10^{30} light years away — 100 billion billion times more distant.

Did it happen just once? Maybe not. The new inflationary scheme also enables physicists to imagine a host of bubble universes frothing out of a primordial sea of symmetry. Some theorists envision these cosmic cousins nesting together like a string of suds blown out of a bubble blower; in other versions, they remain forever isolated from one another. The two views nicely parallel the debate astronomers had almost a century ago on whether our Milky Way was just one of many "island universes" floating in outer space. From a philosophical standpoint, it almost appears to be the next logical extension: We are but one of the many planets circling one of many stars that resides in one of many galaxies . . . in one of many universes. As Peebles would declare, "The inflationary universe allows the imagination to roam free. Perhaps you start matter roaring around, collapsing and expanding. Somewhere you enter an inflationary phase, and it all happens. From this chaos can pop up this and other universes."

Currently, theorists are attempting to wring one more useful function out of the inflationary universe theory: explaining the origin of galaxies. Inflation is quite successful in explaining the overall uniformity of the heavens, but astronomers can't easily forget that as they examine tinier and tinier slices, clumps like

The 1987 A.S.P. Awards

We are proud to announce the winners of the 1987 awards bestowed by the Astronomical Society of the Pacific. The recipients of these awards are selected by the A.S.P. Board of Directors on behalf of the Society's world-wide membership.

The Catherine Wolfe Bruce Medal (for a lifetime of outstanding achievement in astronomical research) goes to **Dr. Edwin E. Salpeter** of Cornell University.

The Robert J. Trumpler Award (for an outstanding dissertation in astronomy done at a university in North America) goes to **Dr. Stephen Schneider** of the University of Virginia.

The Muhlmann Prize (for outstanding research done at any of the Mauna Kea Observatories in Hawaii) goes to **Dr. Alan Stockton** of the University of Hawaii.

The Klumpke-Roberts Award (for outstanding contributions to the public understanding of astronomy) goes to the editors of ***Sky & Telescope*** magazine.

The Amateur Achievement Award (for outstanding contributions to astronomy by an amateur) goes to **Clinton Ford**, the secretary of the American Association of Variable Star Observers.

★ ★ ★

More about each award winner will appear in a future issue of *Mercury*. The awards will be presented by A.S.P. President James Hesser during the Society's 99th Annual Meeting this summer at Pomona College in Southern California.

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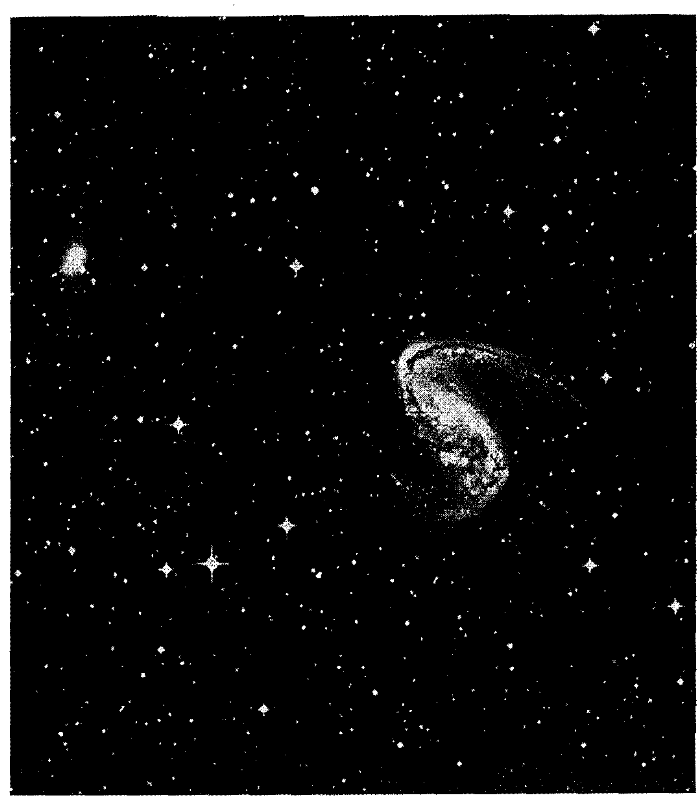
galaxies and clusters start emerging. How did a universe so uniform on the largest scale, they must ask themselves, get so mottled on the small scale? It has long been assumed that the Big Bang sent a series of waves coursing through the newly born sea of particles and that these density perturbations pressed and squeezed the gas into galaxies and clusters.

How did these waves originate? No one knows for sure. But inflation provides a good guess. It suggests that the ripples may have been born when tiny (quantum) fluctuations in that initial kernel about to inflate — submicroscopic disturbances in its sea of symmetry — were blown up to an astronomical scale as the universe ballooned outward. It would be these perturbations that eventually corralled the primordial gas into clumps. Unfortunately, the strength of this effect is very sensitive to the particle physics theory being plugged into the equations. When theorists used the simplest grand unified theory, galaxies tended to collapse into black holes at a rather early point in the universe's history, a result that soon sent everyone scurrying back to the blackboard. But the perfect grand unified theory has yet to be devised. Inserting the proper one into the inflationary scheme, it is hoped, will show how one can form galaxies just like our own. Some believe, in fact, that this requirement will be the key to developing the correct unified theory.

Predicting how our universe behaved at these incomprehensible times, the first trillionth of a trillionth of a trillionth of a second, seems an audacious endeavor. Guth himself thought so just a few years ago. But inflation's successful track record in solving those cosmic dilemmas — flatness, uniformity, and the dearth of monopoles — can easily change one's mind, and one's status. Guth was finally able to put his gypsy days behind him; he's now a tenured professor in the theoretical physics department at MIT, his alma mater. "Actually, predicting the early universe's behavior is a lot easier than you might expect," says Guth. "The more you heat a system and the hotter it gets, the simpler the interactions. And when you measure the temperature of the microwave background radiation, you find it's uniform to an extraordinary degree. Meteorologists could make terrific predictions if they could deal with climates that uniform. So, in a way, predicting the state of the early universe is a lot easier than predicting the weather!" ■



Galaxy NGC 2442 and companion. While matter in the universe is distributed very evenly and smoothly when one considers extremely large distance scales, it is "clumpy" on scales of "only" a few hundreds of millions of light years and smaller. The clusters of galaxies seen elsewhere in this article represent one level of "clumpiness"; individual galaxies like the ones in this photograph demonstrate localized concentrations on another, smaller level. (NGC 2442 is a peculiar barred spiral galaxy, sporting a complex central "bar" of stars from which two distorted spiral arms emerge. To its left is a smaller, companion galaxy whose gravitation may be responsible for NGC 2442's disturbed condition. Photograph by the U.K. Schmidt Telescope Unit, Australia, courtesy of and copyright © by the Royal Observatory, Edinburgh.)