The New Inflationary Universe

A series on particle physics in the early universe begins with the origin of the Big Bang; next: the large-scale structure of the universe

The "Inflationary Scenario" sounds at first like another jeremiad on economics. In fact it is pure astrophysics—the first plausible and compelling model for the origin of the Big Bang.

It is not quite a model for the origin of the universe. That much, at least, is still beyond the ken of science. But it is an audacious extrapolation of modern particle physics and gravitation theory into very early times. It suggests how the Big Bang expansion might have begun. It explains how a universe of extraordinary uniformity and flatness could have emerged from primeval chaos. It explains why the universe seems devoid of magnetic monopoles. It explains in a fairly natural way how and why galaxies and clusters of galaxies began to form. And it even suggests how all the matter, energy, and entropy in the universe could have emerged from empty space.

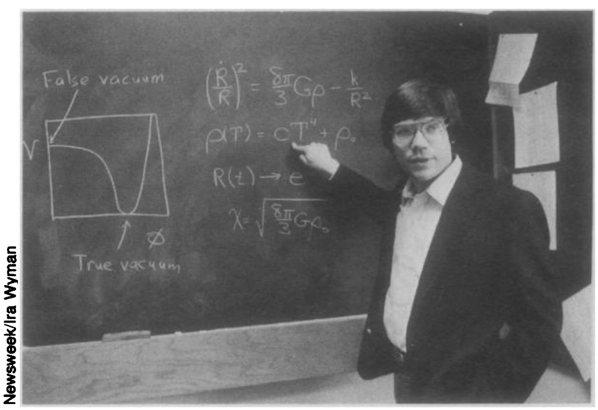
The model was originated in 1980 by particle theorist Alan H. Guth of the Massachusetts Institute of Technology. Guth realized that a universe controlled by the so-called grand unified theories of particle physics (GUT's)* might be forced to undergo a period of what he called "inflation": exceedingly rapid expansion, far faster than anything predicted in the standard models of the Big Bang. This was an intriguing idea and it drew a lot of favorable comment at the time, especially since Guth was able to show that such an episode in the first instants of our own universe would have produced all the properties of homogeneity and flatness just mentioned. Unfortunately, as Guth and his co-workers also pointed out, his mathematically inflating universe would eventually evolve into a grossly inhomogeneous hodge-podge bearing no resemblance to the world we actually live in. Thus, the researchers were forced to conclude that inflation was an intriguing idea, but fatally flawed (*Science*, 3 July 1981, p. 121).

They were wrong. Within the last year or so two groups of physicists have independently found a way out. Their "New Inflationary Universe" is quite realistic and, as Guth recently explained to a gathering of astrophysicists in Texas,† people are taking it very seriously indeed.

Guth began with the standard, noninflationary model of the Big Bang. This model assumes first that the equations of general relativity—Einstein's theory of gravity—have governed the evolution of the universe since the first instant of creation; second, that the universe is homogeneous and symmetric; and third, that the properties of matter were essentially the same then as they are now. It then follows that the universe began as an infinitely hot point of infinite density—the "initial singularity"—and exploded outward, diffusing and cooling into the tenuous immensity we live in today.

Alan H. Guth

The equations of general relativity, plus a generous infusion of particle theory, show how matter, energy, entropy, and the Big Bang itself might have emerged from primeval chaos.



A straightforward application of nuclear and atomic physics to these early times has allowed theorists to understand such phenomena as the 3 K microwave background radiation (the "afterglow" of the Big Bang) and the cosmic abundance of helium (roughly 22 percent by weight, virtually all created by nuclear reactions in the first 3 minutes.) But despite the successes of the standard model, says Guth, there are problems.

The horizon problem, first discussed by Wolfgang Rindler in 1956, is simply another name for the astounding uniformity of the universe. On the largest scales the clumpiness of matter seems to average out: galaxies and clusters of galaxies are scattered across the cosmos like dust motes in a sunbeam; the ubiquitous 3 K background varies across the sky by no more than a few parts in ten thousand. This condition seems natural enough. Why should the universe be anything but symmetrical? But in fact, says Guth, it is very unnatural. There are many more ways for widely separated regions to be different than for them to be the same.

The background radiation, for example, was emitted from the cooling cosmic plasma only 100,000 years after the Big Bang. But photons that are now arriving from opposite sides of the sky were emitted from regions that were much more than 100,000 light years apart. Since no physical interaction can propagate faster than light, there is no way those regions could have come into thermal equilibrium with each other. Each lay beyond the others "horizon." Yet they are in equilibrium, and the only way theorists can account for that fact in the standard model is to postulate it, impose it as an initial condition. And that, of course, does not explain anything.

The flatness problem, first discussed by Robert H. Dicke and P. James E. Peebles in 1979 can be thought of as a question of balance. Einstein's theory of gravity holds that the fate of the universe is determined by the amount of matter and energy it contains. If the density is greater than a certain critical value, then the universe is a closed space of finite volume and the mutual gravitation of its stars and nebulae must someday bring its expansion to a halt. Eventually the universe will collapse back into a point—the "Big Crunch."

If the density is less than the critical

*There is a whole family of GUT's, each one a slightly different approach to unifying the strong, weak, and electromagnetic forces in a single mathematical framework. No one believes that they represent a complete theory of nature. The framework is not unique, and even within a single scheme there are far too many arbitrary parameters; moreover, the fourth fundamental force, gravity, is left out completely. But nonetheless, there are indications that the GUT's are on the right track. They constrain the charge of the electron to be equal and opposite to the charge on the proton, for example, a balance that is otherwise incomprehensible. They also offer a plausible explanation for the virtual absence of antimatter in the universe (*Science*, 20 February 1981, p. 803).

†The Eleventh Texas Symposium on Relativistic Astrophysics, 12–17 December 1982, Austin, Texas.

value, however, the universe will be infinite and it will expand forever. And if the density is precisely critical, the universe will be infinite but "flat" in a certain geometrical sense.

The actual density of the universe is not well known, says Guth, but virtually all astronomers would agree that it lies somewhere between 0.01 and 10 times the critical density. This may not seem remarkable. In fact it is astonishing.

A mathematical universe starting out precisely at the critical density is balanced like a pencil on its point, says Guth: the slightest deviation and it quickly falls to either side, into the Big Crunch or the infinite expansion. For the real universe to be so close to criticality now, some 10 billion to 20 billion years after the Big Bang, it must have differed from criticality in the earliest instants by less than one part in 10^{49}. An initial condition so exquisitely precise cries out for an explanation, says Guth, especially since the known laws of physics are consistent with any value of the initial density whatsoever.

Finally, there is the monopole problem. Central to the dynamics of the grand unified theories are certain quantum fields known, for historical reasons, as Higgs fields. Shortly after the GUT's were invented in the mid-1970's, Guth explains, it was realized that the Higgs fields had the ability to tie themselves into a knot. From the outside such a knot would look like a stable, enormously heavy particle having some 10^{16} times the mass of the proton, or about the mass of an amoeba. Moreover, this particle would be an isolated north or south magnetic pole: a monopole.

Until about a year ago, physicists could assert that no one had ever seen a monopole. All the magnetic fields in nature seem to arise from electric currents or spinning electrons. (Break a bar magnet and there are two bar magnets, not two isolated poles.) On 14 February 1982, however, that faith was shaken when a monopole-like signal appeared in a superconducting detector designed by Stanford physicist Blas Cabrera (*Science*, 4 June 1982, p. 1086).

Cabrera is highly regarded as a cautious and careful experimenter, and neither he nor anyone else has been able to explain his event away. On the other hand, no other events have been forthcoming. Moreover, there is strong evidence from astronomy that monopoles must be very rare in the universe. Otherwise, for example, they would short out the galaxy's magnetic field or cause neutron stars to be copious emitters of x-rays (*Science*, 15 October 1982, p. 274). Since observations show that they are doing neither, many physicists now assume that Cabrera's result was somehow an artifact and that monopoles are either rare or nonexistent.

But even if Cabrera's result is correct, says Guth, there is still a problem. The standard model, expanded to include the GUT's, seems to predict a universe where monopoles are ubiquitous—roughly as abundant as protons. Yet monopoles are 10 quadrillion times more massive than protons, and putting that many of them into our own universe would give it roughly a trillion times the critical density. It would have recollapsed into the Big Crunch long ago. Since this has clearly not happened, where are all the monopoles?

"The universe," notes Guth, "could be the ultimate free lunch."

The answer—and the key to the inflationary universe—lies within the GUT's themselves. Among their many predictions is the possibility that the hot matter in the early universe did *not* behave as matter does now. Instead, the universe as a whole underwent one or more phase transitions.

Mathematically, at least, these transitions were a kind of crystallization, like water vapor condensing into frost on a windowpane. So long as the temperature of the universe remained high, matter was essentially undifferentiated. Elementary particles such as quarks, leptons, and neutrinos behaved identically. But as the expanding universe cooled below some 10^{27} degrees Kelvin—in the standard model about 10^{35} seconds after the Big Bang—the same Higgs field encountered in the monopole problem "froze" and became rigid, giving each point in space a kind of internal structure. The frozen field altered the particle masses and subtly began to differentiate their mutual interactions. Eventually, as the universe cooled even further, the quarks bound themselves into composites known as protons, neutrons, or mesons and became virtually unrecognizable, while electrons and neutrinos remained free as we see them today.

Now in some versions of GUT's this phase transition occurs quickly, says Guth, in which case the cosmological consequences are unimportant. The standard model still holds. But in other versions the transition occurs slowly, in which case the consequences are profound. During the changeover the universe is suspended in a state of anomalously high energy, energy that in turn influences the gravitational field and creates an enormous outward push. Until the changeover is complete, says Guth, the universe expands exponentially with time—the phenomenon he dubbed inflation in 1980. (In the standard model the universe expands only as the square root of time.)

To see how this inflationary episode cures the ills of the standard model, says Guth, imagine that the world begins in a primeval, chaotic super-universe (origin unspecified). Assume that the equations of general relativity hold, and assume also that at least one region—the forerunner of what we now call the "universe"—is hot (more than 10^{27} degrees Kelvin) and expanding. The expanding region then cools, he said, and eventually the Higgs field starts to freeze out. An inflationary phase begins.

In his original formulation, says Guth, this inflation continued until the Higgs field suddenly froze into "bubbles" of normal space. Unfortunately, there turned out to be no way for the bubbles to coalesce: his model universe ended up looking more like a sponge than like the homogeneous space we live in.

However, in the "New" inflationary model pioneered last year by A. D. Linde of the Lebedev Institute in Moscow and, independently, by Andreas Albrecht and Paul J. Steinhardt of the University of Pennsylvania, the Higgs field does not freeze out so much as it slowly congeals like a mass of jelly. This is good. It not only eliminates the bubble problem, but it allows for an enormous inflation: our entire observable universe, from quasars to computer chips, could have grown from a patch of space roughly one trillionth the size of a single proton.

This solves the horizon, or uniformity, problem right away, Guth notes. Such an infinitesimal region is small enough to be in thermal equilibrium. The flatness problem is also solved because, intuitively, space flattens out during the inflation much as the surface of an expanding balloon flattens out. Rigorous calculations show that the difference between the real mass density and the critical mass density can easily decrease by 50 orders of magnitude or more during the inflation. In addition, it turns out that any irregularities in this exponentially inflating space will rapidly die out. The more the region inflates, the smoother it is.

The monopoles are virtually eliminated because, over a region only one trillionth the size of a proton, the Higgs field is essentially constant. It is simply not unruly enough to tie itself into a lot of knots.

Meanwhile, as the inflation continues the slowly freezing Higgs field is converting its anomalous energy into a hot, dense plasma of elementary particles, much as freezing water gives off latent heat. The heat and entropy generated is enormous, says Guth, easily overwhelming any matter that the universe might have contained initially. Thus, there is the philosophically appealing possibility—although a difficult one to prove—that the Higgs transition is the origin of *all* matter and energy. "The universe," notes Guth, "could be the ultimate free lunch."

In any case, by the time the Higgs field solidifies and the inflation stops the universe has expanded by at least 25 orders of magnitude, and the patch that will one day surround Earth—the 10 billion light year sphere accessible to present-day telescopes—is at least 10 centimeters across. Smooth, flat, devoid of monopoles, filled with a brand-new plasma at some 10^{27} degrees Kelvin, it is ready to settle down into normal expansion as described by the standard model. Looking back, we call it the Big Bang.

Now in addition to all this, says Guth, the new inflationary model turns out to address yet another cosmic mystery: the large-scale "structure" of the universe. If the Big Bang plasma had been perfectly smooth, matter would never have been able to clump up into galaxies and clusters of galaxies. Cosmologists have simply had to assume that the density fluctuations were there at early times, without knowing where they came from.

But in the inflationary model, says Guth, the scale and magnitude of the fluctuations can be calculated. They arise from quantum and thermal fluctuations in the congealing Higgs field. These calculations were first made last summer at the Nuffield workshop in Cambridge, England, where a number of independent researchers obtained similar and very exciting results: the magnitude of the fluctuations is essentially independent of their linear size, which happens to be exactly what is required in the model of large-scale structure that is currently most favored by observation, the Zeldovitch "pancake" model (*Science*, 30 January 1981, p. 470).

True, the magnitude of the fluctuations calculated with the simplest GUT [the SU(5) model] are about 100,000 times too large, says Guth. But he regards this as an encouraging near-miss. Other GUT's do better, and anyway, no one has much faith in the details of any one GUT.

On the other hand, it must also be said that the all-important Higgs field is a weak link in the inflationary model. Linde, Albrecht, and Steinhardt had to make certain special assumptions about Higgs field dynamics before they could derive their model. And while the assumptions are not implausible, the fact remains that the Higgs is poorly understood in GUT's or in any other theory.

Nonetheless, the consensus now is that the basic idea of inflation is very good, a judgment echoed again and again by attendees at the Texas conference. "In its new form it is simple, it is natural, and it solves some fundamental cosmological problems," says Guth. It virtually eliminates the need to impose initial conditions on our theories and, assuming that the GUT's bear some relation to reality, it makes the universe as we know it seem almost inevitable.

—M. MITCHELL WALDROP

Is Tyrosine the Key to Growth Control?

Both tumor viruses, which cause uncontrolled growth, and growth factors, which stimulate controlled growth, phosphorylate tyrosines

The first tantalizing hints that an unusual chemical modification of proteins might have something to do with the way cells control growth were reported 3 years ago. Tony Hunter at the Salk Institute found, to his great surprise, that the transforming protein of Rous sarcoma virus, an RNA tumor virus, adds phosphate to tyrosines of certain proteins. "No one had ever detected tyrosine phosphorylation of proteins, and at first we thought it was an artifact."

But it was not an artifact and, 6 months after Hunter's discovery, Stanley Cohen of Vanderbilt University reported that when the cell-surface receptor for epidermal growth factor (EGF) binds EGF, the receptor starts phosphorylating tyrosines. Within a year, virologists learned that five different classes of RNA tumor viruses make transforming proteins that phosphorylate tyrosines (*Science*, 20 March 1981, p. 1336). These transforming proteins are essential for the conversion of normal cells into cancerous ones.

Now the connection between tyrosine phosphorylation and growth control looks even stronger. C. Ronald Kahn of the Joslin Clinic in Boston reports that when insulin binds to its receptor, the receptor starts phosphorylating tyrosines. One of the key actions of insulin is to stimulate cell growth. Carl-Henrik Heldin of the University of Uppsala in Sweden finds that when platelet-derived growth factor (PDGF) binds to its receptor, its receptor, too, phosphorylates tyrosines.

With these discoveries, investigators immediately began asking, Which cellular proteins are phosphorylated? Do the RNA tumor viruses, which cause uncontrolled growth, and the growth factors, which cause controlled growth, phosphorylate the same proteins? And how does tyrosine phosphorylation relate to growth control? The answers are not yet in, but researchers note that, with the data from both viruses and growth factors, they at least have a chance of answering the questions. Work with viruses has the advantage that the genetics is fairly well understood. With growth factors—particularly insulin—the biochemistry is well worked out.

Of course, just because no one had ever seen tyrosine phosphorylation before Hunter's discovery does not mean that it does not occur normally. Cells are known to contain enzymes, called kinases, that add phosphate groups to amino acids, although these kinases were thought to phosphorylate mainly serine and threonine—not tyrosine. In some cases, serine or threonine phosphorylations turn enzymes on or off.

One of the first things Hunter and his colleague Bartholomew Sefton did after finding that the sarcoma virus transforming protein phosphorylates tyrosines was to look in normal cells to see if somehow