

New inflationary universe: an alternative to Big Bang?

Ever since the Big Bang, the universe has been growing at a rate proportional to a fractional power of time—or has it been? Could there have been an instant, in the earliest moments of time, when the expansion was far more rapid, producing in this brief instant a radial increase 25 orders of magnitude greater than that which would otherwise have occurred? If such an inflationary period did occur, it could account for some features of our observable universe hitherto unexplained by the standard theory of the Big Bang. These features include the remarkable homogeneity of the universe, its sparse population of magnetic monopoles (if there are any at all) and the pinpoint balance it maintains between an infinitely expanding and an eventually collapsing condition. In short, inflation may be far better news for cosmology than it is for the economy.

Alan Guth (MIT) originated¹ the concept of an inflationary universe in 1981. In his model, an exponential expansion is associated with a first-order phase transition that takes the universe from a symmetrical state, in which three forces of nature behave as

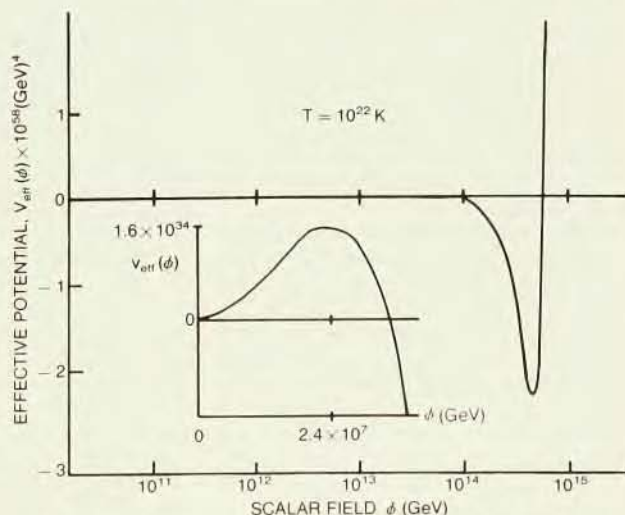
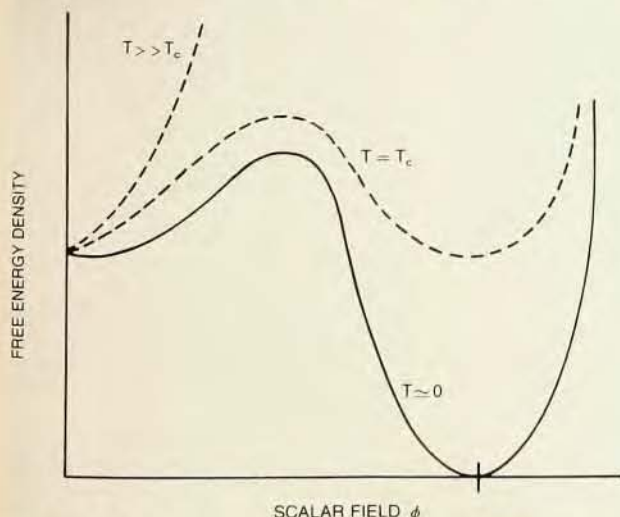
one, to a state of broken symmetry, in which leptons and quarks are differentiated by their interactions. A key ingredient of Guth's model is that a form of supercooling prolongs the phase transition long enough for it to affect the subsequent development of the universe.

Unfortunately, Guth's theory did not totally succeed. The phase transition is initiated on many nucleation sites through the formation of bubbles of the asymmetric phase, but these are prevented from subsequently coalescing by the simultaneous expansion of the intervening space. The resulting configuration looks more like a sponge than the cohesive universe we occupy today. Early last year A. D. Linde of the Lebedev Institute in Moscow² and, independently, Andreas Albrecht and Paul J. Steinhardt of the University of Pennsylvania³ proposed a modification to Guth's approach that retained all its positive aspects but circumvented its fatal flaw. In their picture of the "new" inflationary universe, the present observable universe grows from a single region and could even be part of but one expanded bubble in an unimaginably larger universe of similar bub-

bles. A. Starobinskii has also proposed a period of inflationary expansion but one that occurred at the much earlier Planck time when the effects of quantum gravity dominated.

Interest in the inflationary universe was clearly evident at the Eleventh Texas Symposium on Relativistic Astrophysics in Austin last December. Just five months earlier, the inflationary universe had been a major focus of effort at a three-week workshop in Cambridge, England, sponsored by the Nuffield Foundation. Although—as that workshop concluded—even the "new" inflationary universe is not yet right in every detail, no one has yet deflated the bubble of excitement that the new concept has generated.

The link with particle physics. The universe at birth is characterized by very small scales of length and time and very high values of temperature, and so it is a promising "laboratory" for testing phenomena that occur at energies beyond the reach of any conceivable accelerators. Of particular interest to particle physicists are the predictions of the grand unified theories (GUTs) that attempt to merge into one the separate gauge theories of the



Inflationary universe results when curve of free energy density vs. scalar field has two minima. In Guth's model (left) the universe expands exponentially while trapped in the local minimum before

tunneling into the stable state. In new models (right) the barrier becomes negligible and exponential expansion occurs as the universe rolls slowly along the nearly flat curve towards the stable state.

strong, weak and electromagnetic interactions. In such theories, complete symmetry among the three forces prevails at high energies. The symmetry is spontaneously broken in the lowest energy state of the system (termed the vacuum), which is a particular solution to the equations that does not share their symmetry. For GUTs the transition to this vacuum state occurs at energies of about 10^{14} GeV, corresponding to temperatures of approximately 10^{27} K.

In the standard model of the Big Bang, the universe cools to 10^{27} K after the first 10^{-35} second and passes through this transition so rapidly that the expansion rate is unaffected. Guth used SU(5) models in which the energy density has two minima, with the higher of the two being a local minimum termed the "false vacuum." (See the figure at left on page 17.) As the universe cools below the critical temperature it can become trapped in this metastable, symmetric state, much as a liquid can be supercooled below the temperature at which a solid state is thermodynamically more favorable. As the universe expands, the false vacuum still maintains a constant energy density. Under these conditions, the equations of general relativity dictate that the expansion goes exponentially. The Dutch astronomer Willem deSitter first studied such an exponentially expanding universe for other reasons, and it is now known as a deSitter universe.

Several field theorists in the mid-1970s, particularly T. D. Lee and Gian Carlo Wick (Columbia University), discussed the formation of bubbles in metastable vacuum states. M. B. Voloshin, I. Yu. Kobzarev and L. B. Okun (Institute for Theoretical Physics, Moscow) recognized⁴ the cosmological implications of such a metastable state but did not know how to calculate its decay rate. Paul Frampton (University of North Carolina)⁵ and Sidney Coleman (Harvard) and Curtis Callan (Princeton)⁶ developed the formalism that allowed explicit calculation of the tunneling probability out of this false vacuum and into the true vacuum.

In Guth's model this tunneling out of the false vacuum state occurs at many nucleation sites, and the problem arises because the bubbles begun on these nucleation sites subsequently fail to coalesce. The modifications proposed by Linde and by Albrecht and Steinhardt essentially replace the metastable region with an unstable one but still in such a way as to prolong the transition to the asymmetric state. One form of the energy-density curve that would result in this behavior is one that is nearly flat over a wide range of values of the scalar field before it finally dips to the vacuum state. (See the figure at

right on page 17.) In the "new" inflationary scenario, the universe cools in a metastable state to temperatures of about 10^{22} K, at which point the temperature is stabilized by the quantum effects of curved space-time, first discovered⁷ by Gary W. Gibbons and Stephen W. Hawking (Cambridge University). The barrier becomes negligible, and fluctuations drive regions of the universe over this barrier. The system rolls slowly but inexorably towards the vacuum state, expanding exponentially all the while. The observable universe would exist within one such region, and other regions beyond our horizon may have been driven by fluctuations towards different minima.

The "new" inflationary models are less generic than that of Guth. They achieve the nearly flat form of the energy-density curve by choosing particular values for some of the free parameters. The desired form of the potential was first formulated by Coleman and by Erick Weinberg (Columbia). Many physicists are now examining a variety of models in which one obtains the desired form of energy density without any special choice of parameters.

In both the original and the new inflationary scenarios, the energy difference between the false and true vacuums is sufficiently large that the latent heat released in the transition can reheat the universe back to 10^{27} K. From there the evolution of the universe proceeds as described by the standard hot Big Bang theory.

Triumphs and stumbling blocks. The inflationary universe can resolve three problems that have plagued the standard picture of the Big Bang. The first puzzle is how the universe became so homogeneous. For example, the 3-K microwave background radiation reaches us from every corner of the universe, even from parts of it that were apparently not causally connected when the photons were emitted. However, if the universe underwent an exponential expansion, the observable universe must have grown from a much smaller region (with linear dimensions on the order of 10^{-28} cm) than that implied by the standard model (about 10^{-4} cm). This region is sufficiently minute for all parts of it to have initially been in causal contact.

A second problem for the standard Big Bang is that, when combined with GUTs, it predicts copious production of magnetic monopoles—experimentally, however, only one candidate has actually been observed. In the current gauge theories, magnetic monopoles correspond to point-like topological defects, or "knots," in the expectation value of the Higgs scalar field. In the "new" inflationary model, the Higgs field is correlated over the entire obser-

vable universe so that magnetic monopoles are not expected to be formed in large numbers. Similarly the surface-like topological defects called domain walls are expected to be formed only at the edges of the fluctuation region and should be unobservable to us from deep within that region.

The third mystery unsolved by the standard Big Bang is why the energy density of the universe is so close to the critical value below which the universe would expand forever and above which it would be closed. The present ratio of the energy density to the critical energy density is estimated to be within an order of magnitude of 1. This value implies that the universe began with a value of this ratio extraordinarily close to unity, because any deviations from unity grow with time. In geometric terms, a universe so precisely perched corresponds to one that is exceptionally flat—because mass density affects the curvature of space. A flat universe arises quite naturally from an exponentially expanding universe much as a small area on the surface of a balloon becomes increasingly flat as the balloon enlarges.

Ironically, the inflationary universe may explain the flatness almost too well: Most estimates of the energy density ratio tend to fall on the low side of 1. This discrepancy may create additional interest in searches already under way for possible sources of "missing" mass in the universe. Some candidates include heavy neutrinos, axions or particles such as the photino or gravitino that are associated with supersymmetries.

The inflationary scenario has not been a complete panacea. One notable feature that it cannot explain is the formation of galaxies and clusters. At the Nuffield Conference, four separate groups attempted to calculate the density inhomogeneities that might arise from spatial fluctuations in the Higgs field. These four groups consisted of James Bardeen (University of Washington), Steinhardt and Michael Turner (University of Chicago), Starobinski, Hawking, and Guth. These fluctuations could be the nucleus for galaxy formation. Traveling different paths, the four groups arrived at the same conclusion—that the density fluctuations were too large by five or six orders of magnitude. The amplitude of the density fluctuations depends on the details of the particular GUTs model. Many theorists are now examining alternative models.

On a more positive note, the workshop participants did establish that the magnitude of density fluctuations is essentially independent of their linear size. Such a scale-invariant spectrum is an important prerequisite for the pancake model of galaxy formation