the experimental frontier, tireless efforts are underway to detect CDM directly in underground low-background experiments; to produce CDM in particle accelerators; to make measurements to determine the nature of the dark energy (its sound speed, equation of state, and evolution); and to test inflation and determine what happened in the earliest moments of our universe.

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REVIEW

# Inflationary Cosmology: Exploring the Universe from the Smallest to the Largest Scales

**Alan H. Guth* and David I. Kaiser***

**Understanding the behavior of the universe at large depends critically on insights about the smallest units of matter and their fundamental interactions. Inflationary cosmology is a highly successful framework for exploring these interconnections between particle physics and gravitation. Inflation makes several predictions about the present state of the universe—such as its overall shape, large-scale smoothness, and smaller scale structure—which are being tested to unprecedented accuracy by a new generation of astronomical measurements. The agreement between these predictions and the latest observations is extremely promising. Meanwhile, physicists are busy trying to understand inflation's ultimate implications for the nature of matter, energy, and spacetime.**

The scientific community is celebrating the International Year of Physics in 2005, honoring the centennial of Albert Einstein's most important year of scientific innovation.

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In the span of just a few months during 1905 Einstein introduced key notions that would dramatically change our understanding of matter and energy as well as the nature of space and time. The centennial of these seminal developments offers an enticing opportunity to take stock of how scientists think about these issues today. We focus in particular on recent developments in the field of inflationary cosmology, which draws on a blend of concepts from particle physics and gravitation. The last few years have been a remarkably exciting time for cosmology, with new observations of unprecedented accuracy yielding many surprises. Einstein's legacy is flourishing in the early 21st century.

Inflation was invented a quarter of a century ago, and has become a central ingredient of current cosmological research. Describing dramatic events in the earliest history of our universe, inflationary models generically predict that our universe today should have several distinct features—features that are currently being tested by the new generation of high-precision astronomical measurements. Even as inflation passes more and more stringent empirical tests, theorists continue to explore broader features and implications, such as what might have come before an inflationary epoch, how inflation might have ended within our observable universe, and how inflation might arise in the context of our latest understanding of the structure of space, time, and matter.

Particle theory has been changing rapidly, and these theoretical developments have provided just as important a spur to inflationary cosmology as have the new observations. During the 1960s and 70s, particle physicists discovered that if they neglected gravity, they could construct highly successful descriptions of three out of the four basic forces in the universe: electromagnetism and the strong and weak nuclear forces. The "standard model of particle physics," describing these three forces, was formulated within the framework of quantum field theory, the physicist's quantum-mechanical description of subatomic matter. Inflationary cosmology was likewise first formulated in terms of quantum field theory. Now, however, despite (or perhaps because of) the spectacular experimental success of the standard model, the major thrust of particle physics research is aimed at moving beyond it.

For all its successes, the standard model says nothing at all about the fourth force: gravity. For more than 50 years physicists have sought ways to incorporate gravity within a quantum-mechanical framework, initially with no success. But for the past 25 or more years, an ever-growing group of theoretical physicists has been pursuing superstring theory as the bright hope for solving this problem. To accomplish this task, however, string theorists have been forced to introduce many novel departures from conventional ideas about fundamental forces and the nature of the universe. For one thing, string theory stipulates that the basic units of matter are not pointlike particles (as treated by quantum field theory), but rather one-dimensional extended objects, or strings. Moreover, in order to be mathematically self-consistent, string theories require the existence of several additional spatial dimensions. Whereas our observable universe seems to contain one timelike dimension and three spatial dimensions—height, width, and depth—string theory postulates that our universe actually contains at least six additional spatial dimensions, each at right angles to the others and yet somehow hidden from view.

For measurements at low energies, string theory should behave effectively like a quantum field theory, reproducing the successes of the standard model of particle physics. Yet the interface between cosmology and string theory has been a lively frontier. For example, some theorists have been constructing inflationary models for our universe that make use of the extra dimensions that string theory introduces. Others have been studying the string theory underpinnings for inflationary models, exploring such topics as the nature of vacuum states and the question of their uniqueness. As we will see, inflation continues to occupy a central place in cosmological research, even as its relation to fundamental particle physics continues to evolve.

## Inflationary Basics

According to inflationary cosmology (*1–3*), the universe expanded exponentially quickly for a fraction of a second very early in its history—growing from a patch as small as $10^{-26}$ m, one hundred billion times smaller than a proton, to macroscopic scales on the order of a meter, all within about $10^{-35}$ s—before slowing down to the more stately rate of expansion that has characterized the universe's behavior ever since. The driving force behind this dramatic growth, strangely enough, was gravity. [For technical introductions to inflationary cosmology, see (*4–6*); a more popular description may be found in (*7*).] Although this might sound like hopeless (or, depending on one's inclinations, interesting) speculation, in fact inflationary cosmology leads to several quantitative predictions about the present behavior of our universe—predictions that are being tested to unprecedented accuracy by a new generation of observational techniques. So far the agreement has been excellent.

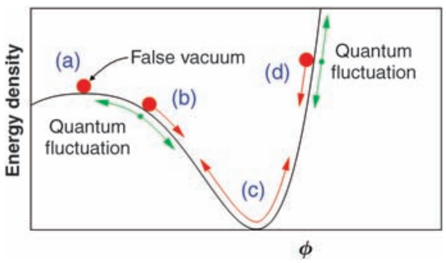


**Fig. 1.** In simple inflationary models, the universe at early times is dominated by the potential energy density of a scalar field, $\phi$. Red arrows show the classical motion of $\phi$. When $\phi$ is near region (a), the energy density will remain nearly constant, $\rho \cong \rho_f$, even as the universe expands. Moreover, cosmic expansion acts like a frictional drag, slowing the motion of $\phi$: Even near regions (b) and (d), $\phi$ behaves more like a marble moving in a bowl of molasses, slowly creeping down the side of its potential, rather than like a marble sliding down the inside of a polished bowl. During this period of "slow roll," $\rho$ remains nearly constant. Only after $\phi$ has slid most of the way down its potential will it begin to oscillate around its minimum, as in region (c), ending inflation.

How could gravity drive the universal repulsion during inflation? The key to this rapid expansion is that in Einstein's general relativity (physicists' reigning description of gravity), the gravitational field couples both to mass-energy (where mass and energy are interchangeable thanks to Einstein's $E = mc^2$) and to pressure, rather than to mass alone. In the simplest scenario, in which at least the observable portion of our universe can be approximated as being homogeneous and isotropic—that is, having no preferred locations or directions—Einstein's gravitational equations give a particularly simple result. The expansion of the universe may be described by introducing a time-dependent "scale factor," $a(t)$, with the separation between any two objects in the universe being proportional to $a(t)$. Einstein's equations prescribe how this scale factor will evolve over time, $t$. The rate of acceleration is proportional to the density of mass-energy in the universe, $\rho$, plus three times its pressure, $p$: $d^2a/dt^2 = -4\pi G\,(\rho + 3p)a/3$, where $G$ is Newton's gravitational constant (and we use units for which the speed of light $c = 1$). The minus sign is important: Ordinary matter under ordinary circumstances has both positive mass-energy density and positive (or zero) pressure, so that $(\rho + 3p) > 0$. In this case, gravity acts as we would expect it to: All of the matter in the universe tends to attract all of the other matter, causing the expansion of the universe as a whole to slow down.

The crucial idea behind inflation is that matter can behave rather differently from this familiar pattern. Ideas from particle physics suggest that the universe is permeated by scalar fields, such as the Higgs field of the standard model of particle physics, or its more exotic generalizations. (A scalar field takes exactly one value at every point in space and time. For example, one could measure the temperature at every position in a room and repeat the measurements over time, and represent the measurements by a scalar field, $T$, of temperature. Electric and magnetic fields are vector fields, which carry three distinct components at every point in space and time: the field in the $x$ direction, in the $y$ direction, and in the $z$ direction. Scalar fields are introduced in particle physics to describe certain kinds of particles, just as photons are described in quantum field theories in terms of electromagnetic fields.) These scalar fields can exist in a special state, having a high energy density that cannot be rapidly lowered, such as the arrangement labeled (a) in Fig. 1. Such a state is called a "false vacuum." Particle physicists use the word "vacuum" to denote the state of lowest energy. "False vacua" are only metastable, not the true states of lowest possible energy.

In the early universe, a scalar field in such a false vacuum state can dominate all the contributions to the total mass-energy density, $\rho$. During this period, $\rho$ remains nearly constant, even as the volume of the universe expands rapidly: $\rho \cong \rho_f =$ constant. This is quite different from the density of ordinary matter, which decreases when the volume of its container increases. Moreover, the first law of thermodynamics, in the context of general relativity, implies that if $\rho \cong \rho_f$ while the universe expands, then the equation of state for this special state of matter must be $p \cong -\rho_f$, a negative pressure. This yields $d^2a/dt^2 = 8\pi G\rho_f\, a/3$: Rather than slowing down, the cosmic expansion rate will grow rapidly, driven by the negative pressure created by this special state of matter. Under these circumstances, the scale factor grows as $a \propto e^{Ht}$, where the Hubble parameter, $H \equiv a^{-1}da/dt$, which measures the universe's rate of expansion, assumes the constant value, $H \cong (8\pi G\rho_f/3)^{1/2}$. The universe expands exponentially until the scalar field rolls to near the bottom of the hill in the potential energy diagram.

What supplies the energy for this gigantic expansion? The answer, surprisingly, is that no energy is needed (*7*). Physicists have known since the 1930s (*8*) that the gravitational field carries *negative* potential energy density. As vast quantities of matter are produced during inflation, a vast amount of negative potential energy materializes in the gravitational field that fills the ever-enlarging region of space. The total energy remains constant, and very small, and possibly exactly equal to zero.

There are now dozens of models that lead to this generic inflationary behavior, featuring an equation of state, $p \cong -\rho$, during the early universe (*4*, *9*). This entire family of models, moreover, leads to several main predictions about today's universe. First, our observable universe should be spatially flat. Einstein's general relativity allows for all kinds of curved (or "non-Euclidean") spacetimes. Homogeneous and isotropic spacetimes fall into three classes (Fig. 2), depending on the value of the mass-energy density, ρ. If $\rho > \rho_c$, where $\rho_c \equiv 3H^2/(8\pi G)$, then Einstein's equations imply that the spacetime will be positively curved, or closed (akin to the two-dimensional surface of a sphere); parallel lines will intersect, and the interior angles of a triangle will always add up to more than 180°. If $\rho < \rho_c$, the spacetime will be negatively curved, or open (akin to the two-dimensional surface of a saddle); parallel lines will diverge and triangles will sum to less than 180°. Only if $\rho = \rho_c$ will spacetime be spatially flat (akin to an ordinary two-dimensional flat surface); in this case, all of the usual rules of Euclidean geometry apply. Cosmologists use the letter Ω to designate the ratio of the actual mass-energy density in the universe to this critical value: $\Omega \equiv \rho/\rho_c$. Although general relativity allows any value for this ratio, inflation predicts that Ω = 1 within our observable universe to extremely high accuracy. Until recently, uncertainties in the measurement of Ω allowed any value in the wide range, $0.1 \le \Omega \le 2$, with many observations seeming to favor $\Omega \cong 0.3$. A new generation of detectors, however, has dramatically changed the situation. The latest observations, combining data from the Wilkinson Microwave Anisotropy Probe (WMAP), the Sloan Digital Sky Survey (SDSS), and observations of type Ia supernovae, have measured $\Omega = 1.012^{+0.018}_{-0.022}$ (*10*)—an amazing match between prediction and observation.

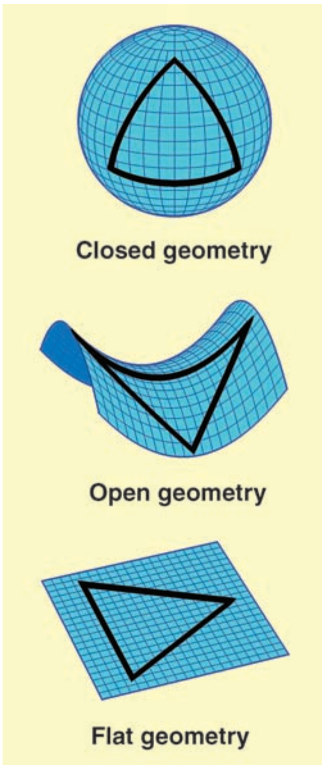


**Fig. 2.** According to general relativity, spacetime may be warped or curved, depending on the density of mass-energy. Inflation predicts that our observable universe should be spatially flat to very high accuracy.

In fact, inflation offers a simple explanation for why the universe should be so flat today. In the standard big bang cosmology (without inflation), Ω = 1 is an *unstable* solution: If Ω were ever-so-slightly less than 1 at an early time, then it would rapidly slide toward 0. For example, if Ω were 0.9 at 1 s after the big bang, it would be only $10^{-14}$ today. If Ω were 1.1 at $t$ = 1 s, then it would have grown so quickly that the universe would have recollapsed just 45 s later. In inflationary models, on the other hand, any original curvature of the early universe would have been stretched out to near-flatness as the universe underwent its rapid expansion (Fig. 3). Quantitatively, $|\Omega - 1| \propto 1/(aH)^2$, so that while $H \cong$ constant and $a \propto e^{Ht}$ during the inflationary epoch, Ω gets driven rapidly to 1.

The second main prediction of inflation is that the presently observed universe should be remarkably smooth and homogeneous on the largest astronomical scales. This, too, has been measured to extraordinary accuracy during the past decades. Starting in the 1960s, Earth-bound, balloon-borne, and now satellite detectors have measured the cosmic microwave background (CMB) radiation, a thermal bath of photons that fills the sky. The photons today have a frequency that corresponds to a temperature of 2.728 K (*11*). These photons were released ~400,000 years after the inflationary epoch, when the universe had cooled to a low enough temperature that would allow stable (and electrically neutral) atoms to form. Before that time, the ambient temperature of matter in the universe was so high that would-be atoms were broken up by high-energy photons as soon as they formed, so that the photons were effectively trapped, constantly colliding into electrically charged matter. Since stable atoms formed, however, the CMB photons have been streaming freely. Their temperature today is terrifically uniform: After adjusting for the Earth's motion, CMB photons measured from any direction in the sky have the same temperature to one part in $10^5$ (*12*).

Without inflation, this large-scale smoothness appears quite puzzling. According to ordinary (noninflationary) big bang cosmology, these photons should never have had a chance to come to thermal equilibrium: The regions in the sky from which they were released would have been about 100 times farther apart than even light could have traveled between the time of the big bang and the time of the photons' release (*1*, *4*–*6*). Much like the flatness problem, inflation provides a simple and generic reason for the observed homogeneity of the CMB: Today's observable universe originated from a *much* smaller region than that in the noninflationary scenarios. This much-smaller patch could easily have become smooth before inflation began. Inflation would then stretch this small homogeneous region to encompass the entire observable universe.

A third major prediction of inflationary cosmology is that there should be tiny departures from this strict large-scale smoothness and that these ripples (or "perturbations") should have a characteristic spectrum. Today these ripples can be seen directly as fluctuations in the CMB. Although the ripples are believed to be responsible for the grandest structures of the universe—galaxies, superclusters, and giant voids—in inflationary models they arise from quantum fluctuations, usually important only on atomic scales or smaller. The field ϕ that drives inflation, like all quantum fields, undergoes quantum fluctuations in accord with the Heisenberg uncertainty principle. During inflation these quantum fluctuations are stretched proportionally to $a(t)$, rapidly growing to macroscopic scales. The result: a set of nearly scale-invariant perturbations extending over a huge range of wavelengths (*13*). Cosmologists parameterize the spectrum of primordial perturbations by a spectral index, $n_s$. A scale-invariant spectrum would have $n_s = 1.00$; inflationary models generically predict $n_s = 1$ to within ~10%. The latest measurements of these perturbations by WMAP and SDSS reveal $n_s = 0.977^{+0.039}_{-0.025}$ (*10*).

Until recently, astronomers were aware of several cosmological models that were consistent with the known data: an open universe, with $\Omega \cong 0.3$; an inflationary universe with considerable dark energy (Λ); an inflationary universe without Λ; and a universe in which the primordial perturbations arose from topological defects such as cosmic strings. Dark energy (*14*) is a form of matter with negative pressure that is currently believed to contribute about 70% of the total energy of the observed universe. Cosmic strings are long, narrow filaments hypothesized to be scattered throughout space, remnants of a symmetry-breaking phase transition in the early universe (*15*, *16*). [Cosmic strings are topologically nontrivial configurations of fields, which should not be confused with the fundamental strings of superstring theory. The latter are usually believed to have lengths on the order of $10^{-35}$ m, although for some compactifications these strings might also have astronomical lengths (*17*).] Each of these models leads to a distinctive pattern of resonant oscillations in the early universe, which can be probed today through its imprint on the CMB. As can be seen in Fig. 4 (*18*), three of the models are now definitively ruled out. The full class of inflationary models can make a variety of predictions, but the prediction of the simplest inflationary models with large Λ, shown on the graph, fits the data beautifully.

## Before and After Inflation

Research in recent years has included investigations of what might have preceded inflation and how an inflationary epoch might have ended.

Soon after the first inflationary models were introduced, several physicists (*19–21*) realized that once inflation began, it would in all likelihood never stop. Regions of space would stop inflating, forming what can be called "pocket universes," one of which would contain the observed universe. Nonetheless, at any given moment *some* portion of the universe would still be undergoing exponential expansion, in a process called "eternal inflation." In the model depicted in Fig. 1, for example, quantum-mechanical effects compete with the classical motion to produce eternal inflation. Consider a region of size $H^{-1}$, in which the average value of ϕ is near (b) or (d) in the diagram. Call the average energy density $\rho_0$. Whereas the classical tendency of ϕ is to roll slowly downward (red arrow) toward the minimum of its potential, the field will also be subject to quantum fluctuations (green arrows) similar to those described above. The quantum fluctuations will give the field a certain likelihood of hopping up the wall of potential energy rather than down it. Over a time period $H^{-1}$, this region will grow $e^3 \cong 20$ times its original size. If the probability that the field will roll up the potential hill during this period is greater than 1/20, then on average the volume of space in which $\rho > \rho_0$ increases with time (*4*, *21*, *22*). The probability of upward fluctuations tends to become large when the initial value of ϕ is near the peak at (a) or high on the hill near (d), so for most potential energy functions the condition for eternal inflation is attainable. In that case the volume of the inflating region grows exponentially, and forever: Inflation would produce an infinity of pocket universes.

An interesting question is whether or not eternal inflation makes the big bang unnecessary: Might eternal inflation have been truly "eternal," existing more or less the same way for all time, or is it only "eternal" to the future once it gets started? Borde and Vilenkin have analyzed this question (most recently, with Guth), and have concluded that eternal inflation could not have been past-eternal: Using kinematic arguments, they showed (*23*) that the inflating region must have had a past boundary, before which some alternative description must have applied. One possibility would be the creation of the universe by some kind of quantum process.

Another major area of research centers on the mechanisms by which inflation might have ended within our observable universe. The means by which inflation ends have major consequences for the subsequent history of our universe. For one thing, the colossal expansion during inflation causes the temperature of the universe to plummet nearly to zero, and dilutes the density of ordinary matter to negligible quantities. Some mechanism must therefore convert the energy of the scalar field, ϕ, into a hot soup of garden-variety matter.

In most models, inflation ends when ϕ oscillates around the minimum of its potential, as in region (c) of Fig. 1. Quantum-mechanically, these field oscillations correspond to a collection of ϕ particles approximately at rest. Early studies of postinflation "reheating" assumed that individual ϕ particles would decay during these oscillations like radioactive nuclei. More recently, it has been discovered (*24–28*) that these oscillations would drive resonances in ϕ's interactions with other quantum fields. Instead of individual ϕ particles decaying independently, these resonances would set up collective behavior—ϕ would release its energy more like a laser than an ordinary light bulb, pouring it extremely rapidly into a sea of newly created particles. Large numbers of particles would be created very quickly within specific energy-bands, corresponding to the frequency of ϕ's oscillations and its higher harmonics.

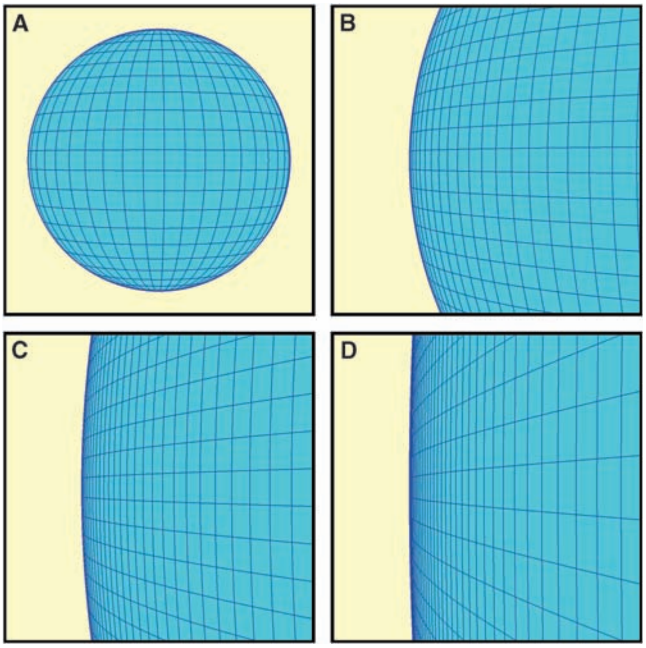


**Fig. 3.** (**A** to **D**) The expanding sphere illustrates the solution to the flatness problem in inflationary cosmology. As the sphere becomes larger, its surface becomes more and more flat. In the same way, the exponential expansion of spacetime during inflation causes it to become spatially flat.

This dramatic burst of particle creation would affect spacetime itself, as it responded to changes in the arrangement of matter and energy. The rapid transfer of energy would excite gravitational perturbations, of which the most strongly amplified would be those with frequencies within the resonance bands of the decaying ϕ field. In some extreme cases, very long-wavelength perturbations can be amplified during reheating, which could in principle even leave an imprint on the CMB (*29*).

## Brane Cosmology: Sticking Close to Home

Although superstring theory promises to synthesize general relativity with the other fundamental forces of nature, it introduces a number of surprising features—such as the existence of microscopic strings, rather than particles, as the fundamental units of matter, along with the existence of several extra spatial dimensions in the universe. Could our observable universe really be built from such a bizarre collection of ingredients?

Naïvely, one might expect the extra dimensions to conflict with the observed behavior of gravity. To be successful, string theory, like general relativity, must reduce to Newton's law of gravity in the appropriate limit. In

Newton's formulation, gravity can be described by force lines that always begin and end on masses. If the force lines could spread in $n$ spatial dimensions, then at a radius $r$ from the center, they would intersect a hypersphere with surface area proportional to $r^{n-1}$. An equal number of force lines would cross the hypersphere at each radius, which means that the density of force lines would be proportional to $1/r^{n-1}$. For $n = 3$, this reproduces the familiar Newtonian force law, $F \propto 1/r^2$, which has been tested (along with its Einsteinian generalization) to remarkable accuracy over a huge range of distances, from astronomical scales down to less than a millimeter (*30*, *31*).

An early response to this difficulty was to assume that the extra spatial dimensions are curled up into tiny closed circles rather than extending to macroscopic distances. Because gravity has a natural scale, known as the Planck length, $l_P \equiv (\hbar G/c^3)^{1/2} \cong 10^{-35}$ m (where $\hbar$ is Planck's constant divided by $2\pi$), physicists assumed that $l_P$ sets the scale for these extra dimensions. Just as the surface of a soda straw would appear one-dimensional when viewed from a large distance—even though it is really two-dimensional—our space would appear three-dimensional if the extra dimensions were "compactified" in this way. On scales much larger than the radii of the extra dimensions, $r_c$, we would fail to notice them: The strength of gravity would fall off in its usual $1/r^2$ manner for distances $r \gg r_c$, but would fall off as $1/r^{n-1}$ for scales $r \ll r_c$ (*32*). The question remained, however, what caused this compactification, and why this special behavior affected only some but not all dimensions.

Recently, Arkani-Hamed, Dimopoulos, and Dvali (*33*) realized that there is no necessary relation between $\ell_P$ and $r_c$, and that experiments only require $r_c \leq 1$ mm. Shortly afterward, Randall and Sundrum (*34*, *35*) discovered that the extra dimensions could even be infinite in extent! In the Randall-Sundrum model, our observable universe lies on a membrane, or "brane" for short, of three spatial dimensions, embedded within some larger multidimensional space. The key insight is that the energy carried by the brane will sharply affect the way the gravitational field behaves. For certain spacetime configurations, the behavior of gravity along the brane can appear four-dimensional (three space and one time), even in the presence of extra dimensions. Gravitational force lines would tend to "hug" the brane, rather than spill out into the "bulk"—the spatial volume in which our brane is embedded. Along the brane, therefore, the dominant behavior of the gravitational force would still be $1/r^2$.

In simple models, in which the spacetime geometry along our brane is highly symmetric, such as the Minkowski spacetime of special relativity, the effective gravitational field along our brane is found to mimic the usual Einsteinian results to high accuracy (*36*, *37*). At very short distances there are calculable (and testable) deviations from standard gravity, and there may also be deviations for very strong gravitational fields, such as those near black holes. There are also modifications to the cosmological predictions of gravity. In the usual case, when Einstein's equations are applied to a homogeneous and isotropic spacetime, one finds $H^2 \propto \rho - k/a^2$, where $k$ is a constant connected to the curvature of the universe. If instead we lived on a brane embedded within one large extra dimension, then $H^2 \propto \rho + \alpha\rho^2 - k/a^2$, where $\alpha$ is a constant (*38*).

Under ordinary conditions, $\rho$ decreases as the universe expands, and so the new term in the effective Einstein equations should have minimal effects at late times in our observable universe. But we saw above that during an inflationary epoch, $\rho \cong$ constant, and in these early moments the departures from the ordinary Einsteinian case can be dramatic. In particular, the $\rho^2$ term would allow inflation to occur at lower energies than are usually assumed in ordinary (nonembedded) models, with potential energy functions that are less flat than are ordinarily needed to sustain inflation. Moreover, the spectrum of primordial perturbations would get driven even closer to the scale-invariant shape, with $n_s = 1.00$ (*39*, *40*). Brane cosmology thus leads to some interesting effects during the early universe, making inflation even more robust than in ordinary scenarios.

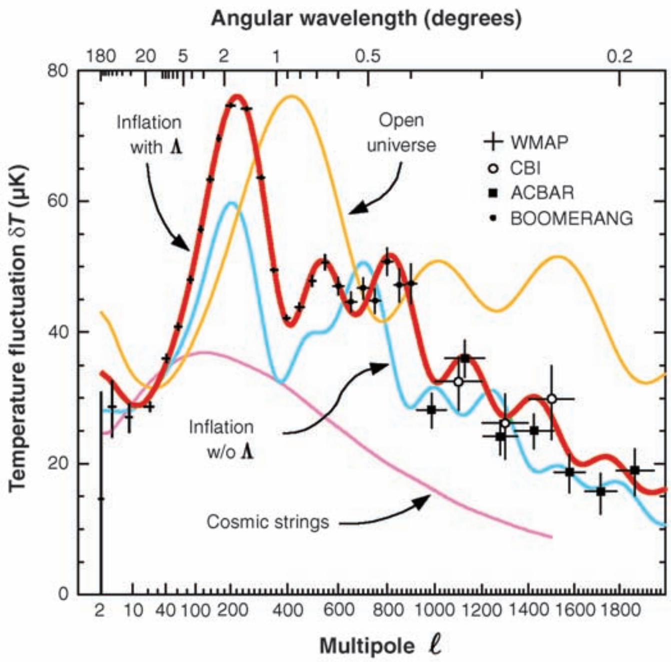


**Fig. 4.** Comparison of the latest observational measurements of the temperature fluctuations in the CMB with several theoretical models, as described in the text. The temperature pattern on the sky is expanded in multipoles (i.e., spherical harmonics), and the intensity is plotted as a function of the multipole number $\ell$. Roughly speaking, each multipole $\ell$ corresponds to ripples with an angular wavelength of $360°/\ell$.

## String Cosmology

Although theories of extra dimensions establish a connection between string theory and cosmology, the developments of the past few years have pushed the connection much further. [For reviews, see (*41–43*).] The union of string theory and cosmology is barely past its honeymoon, but so far the marriage appears to be a happy one. Inflation, from its inception, was a phenomenologically very successful idea that has been in need of a fundamental theory to constrain its many variations. String theory, from its inception, has been a very well-constrained mathematical theory in need of a phenomenology to provide contact with observation. The match seems perfect, but time will be needed before we know for sure whether either marriage partner can fulfill the needs of the other. In the meantime, ideas are stirring that have the potential to radically alter our ideas about fundamental laws of physics.

For many years the possibility of describing inflation in terms of string theory seemed completely intractable, because the only string vacua that were understood were highly supersymmetric ones, with many massless scalar fields, called moduli, which have potential energy functions that vanish identically to all orders of perturbation theory. When the effects of gravity are included, the energy density of such supersymmetric states is never positive. Inflation, on the other hand, requires a positive energy density, and it requires a hill in the potential energy function. Inflation, therefore, could only be contemplated in the context of nonperturbative supersymmetry-breaking effects, of which there was very little understanding.

The situation changed dramatically with the realization that string theory contains not only strings, but also branes, and fluxes, which can be thought of as higher-dimensional generalizations of magnetic fields. The combination of these two ingredients makes it possible to construct string theory states that break supersymmetry and that give nontrivial potential energy functions to all the scalar fields.

One very attractive idea for incorporating inflation into string theory is to use the positions of branes to play the role of the scalar field that drives inflation. The earliest version of this theory was proposed in 1998 by Dvali and Tye (*44*), shortly after the possibility of large extra dimensions was proposed in (*33*). In the Dvali-Tye model, the observed universe is described not by a single three-dimensional brane, but instead by a number of three-dimensional branes, which in the vacuum state would sit on top of each other. If some of the branes were displaced, however, in a fourth spatial direction, then the energy would be increased. The brane separation would be a function of time and the three spatial coordinates along the branes, and so from the point of view of an observer on the brane, it would act like a scalar field that could drive inflation. At this stage, however, the authors needed to invoke unknown mechanisms to break supersymmetry and to give the moduli fields nonzero potential energy functions.

In 2003, Kachru, Kallosh, Linde, and Trivedi (*45*) showed how to construct complicated string theory states for which all the moduli have nontrivial potentials, for which the energy density is positive, and for which the approximations that were used in the calculations appeared justifiable. These states are only metastable, but their lifetimes can be vastly longer than the 14 billion years that have elapsed since the big bang. There was nothing elegant about this construction—the six extra dimensions implied by string theory are curled not into circles, but into complicated manifolds with a number of internal loops that can be threaded by several different types of flux, and populated by a hodgepodge of branes. Joined by Maldacena and McAllister, this group (*46*) went on to construct states that can describe inflation, in which a parameter corresponding to a brane position can roll down a hill in its potential energy diagram. Generically the potential energy function is not flat enough for successful inflation, but the authors argued that the number of possible constructions was so large that there may well be a large class of states for which sufficient inflation is achieved. Iizuka and Trivedi (*47*) showed that successful inflation can be attained by curling the extra dimensions into a manifold that has a special kind of symmetry.

A tantalizing feature of these models is that at the end of inflation, a network of strings would be produced (*17*). These could be fundamental strings, or branes with one spatial dimension. The CMB data of Fig. 4 rule out the possibility that these strings are major sources of density fluctuations, but they are still allowed if they are light enough so that they do not disturb the density fluctuations from inflation. String theorists are hoping that such strings may be able to provide an observational window on string physics.

A key feature of the constructions of inflating states or vacuumlike states in string theory is that they are far from unique. The number might be something like $10^{500}$ (*48–50*), forming what Susskind has dubbed the "landscape of string theory." Although the rules of string theory are unique, the low-energy laws that describe the physics that we can in practice observe would depend strongly on which vacuum state our universe was built upon. Other vacuum states could give rise to different values of "fundamental" constants, or even to altogether different types of "elementary" particles, and even different numbers of large spatial dimensions! Furthermore, because inflation is generically eternal, one would expect that the resulting eternally inflating spacetime would sample every one of these states, each an infinite number of times. Because all of these states are possible, the important problem is to learn which states are probable. This problem involves comparison of one infinity with another, which is in general not a well-defined question (*51*). Proposals have been made and arguments have been given to justify them (*52*), but no conclusive solution to this problem has been found.

What, then, determined the vacuum state for our observable universe? Although many physicists (including the authors) hope that some principle can be found to understand how this choice was determined, there are no persuasive ideas about what form such a principle might take. It is possible that inflation helps to control the choice of state, because perhaps one state or a subset of states expands faster than any others. Because inflation is generically eternal, the state that inflates the fastest, along with the states that it decays into, might dominate over any others by an infinite amount. Progress in implementing this idea, however, has so far been nil, in part because we cannot identify the state that inflates the fastest, and in part because we cannot calculate probabilities in any case. If we could calculate the decay chain of the most rapidly inflating state, we would have no guarantee that the number of states with significant probability would be much smaller than the total number of possible states.

Another possibility, now widely discussed, is that *nothing* determines the choice of vacuum for our universe; instead, the observable universe is viewed as a tiny speck within a multiverse that contains *every* possible type of vacuum. If this point of view is right, then a quantity such as the electron-to-proton mass ratio would be on the same footing as the distance between our planet and the sun. Neither is fixed by the fundamental laws, but instead both are determined by historical accidents, restricted only by the fact that if these quantities did not lie within a suitable range, we would not be here to make the observations. This idea—that the laws of physics that we observe are determined not by fundamental principles, but instead by the requirement that intelligent life can exist to observe them—is often called the anthropic principle. Although in some contexts this principle might sound patently religious, the combination of inflationary cosmology and the landscape of string theory gives the anthropic principle a scientifically viable framework.

A key reason why the anthropic approach is gaining attention is the observed fact that the expansion of the universe today is accelerating, rather than slowing down under the influence of normal gravity. In the context of general relativity, this requires that the energy of the observable universe is dominated by dark energy. The identity of the dark energy is unknown, but the simplest possibility is that it is the energy density of the vacuum, which is equivalent to what Einstein called the cosmological constant. To particle physicists it is not surprising that the vacuum has nonzero energy density, because the vacuum is known to be a very complicated state, in which particle-antiparticle pairs are constantly materializing and disappearing, and fields such as the electromagnetic field are constantly undergoing wild fluctuations. From the standpoint of the particle physicist, the shocking thing is that the energy density of the vacuum is so low. No one really knows how to calculate the energy density of the vacuum, but naïve estimates lead to numbers that are about $10^{120}$ times larger than the observational upper limit. There are both positive and negative contributions, but physicists have been trying for decades to find some reason why the positive and negative contributions should cancel, so far to no avail. It seems even more hopeless to find a reason why the net energy density should be nonzero, but 120 orders of magnitude smaller than its expected value. However, if one adopts the anthropic point of view, it was argued as early as 1987 by Weinberg (*53*) that an explanation is at hand: If the multiverse contained regions with all conceivable values of the cosmological constant, galaxies and hence life could appear only in those very rare regions where the value is small, because otherwise the huge gravitational repulsion would blow matter apart without allowing it to collect into galaxies.

The landscape of string theory and the evolution of the universe through the landscape are of course still not well understood, and some have argued (*54*) that the landscape might not even exist. It seems too early to draw any firm conclusions, but clearly the question of whether the laws of physics are uniquely determined, or whether they are environmental accidents, is an issue too fundamental to ignore.

## Conclusions

During the past decade, cosmology has unquestionably entered the domain of high-precision science. Just a few years ago several basic cosmological quantities, such as the expansion parameter, $H$, and the flatness parameter, $\Omega$, were known only to within a factor of 2. Now new observations using WMAP, SDSS, and the high-redshift type Ia supernovae measure these and other crucial quantities with percent-level accuracy. Several of inflation's most basic quantitative predictions, including $\Omega = 1$ and $n_s \cong 1$, may now be compared with data that are discriminating enough to distinguish inflation from many of its theoretical rivals. So far, every measure has been favorable to inflation.

Even with the evidence in favor of inflation now stronger than ever, much work remains. Inflationary cosmology has always been a framework for studying the interconnections between particle physics and gravitation—a collection of models rather than a unique theory. The next generation of astronomical detectors should be able to distinguish between competing inflationary models, whittling down the large number of options to a preferred few. One important goal is the high-precision measurement of polarization effects in the CMB, which allows the possibility of uncovering the traces of gravity waves originating from inflation. Gravity waves of the right pattern would be a striking test of inflation, and would allow us to determine the energy density of the ''false vacuum'' state that drove inflation. The new cosmological observations also offer physicists one of the best resources for evaluating the latest developments in idea-rich (but data-poor) particle theory, where much of the current research has been aimed at the high-energy frontier, well beyond the range of existing accelerators. Perhaps the interface between string theory and cosmology will lead to new predictions for the astronomers to test. Whether such tests are successful or not, physicists are certain to learn important lessons about the nature of space, time, and matter.

Meanwhile, several major puzzles persist. Now that physicists and astronomers are confident that $\Omega = 1$ to high accuracy, the question remains of just what type of matter and energy is filling the universe. Ordinary matter, such as the protons, neutrons, and electrons that make up atoms, contributes just 4% to this cosmic balance. Nearly one-quarter of the universe's mass-energy is some form of ''dark matter''—different in kind from the garden-variety matter we see around us, and yet exerting a measurable gravitational tug that shapes the way galaxies behave. Particle physicists have offered many candidates for this exotic dark matter, but to date no single contender has proved fully convincing (*55*).

Even more bizarre is the dark energy now known to contribute about 70% to $\Omega$. This dark energy is driving a mini-inflationary epoch today, billions of years after the initial round of inflation. Today's accelerated expansion is far less fast than the earlier inflationary rate had been, but the question remains why it is happening at all. Could the dark energy be an example of Einstein's cosmological constant? Or maybe it is a variation on an inflationary theme: Perhaps some scalar field has been sliding down its potential energy hill on a time scale of billions of years rather than fractions of a second (*14*). Whatever its origin, dark energy, much like dark matter, presents a fascinating puzzle that will keep cosmologists busy for years to come.

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