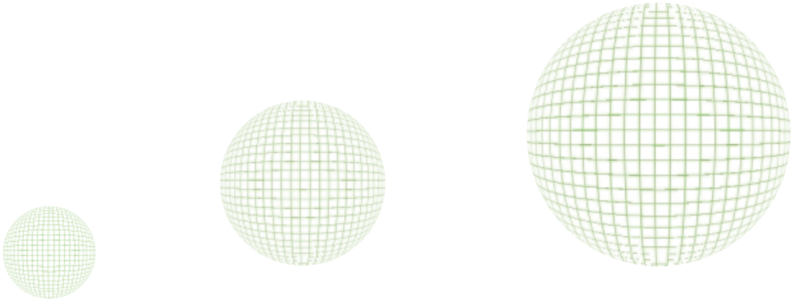
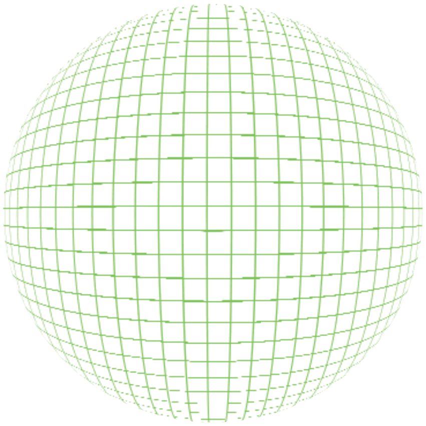
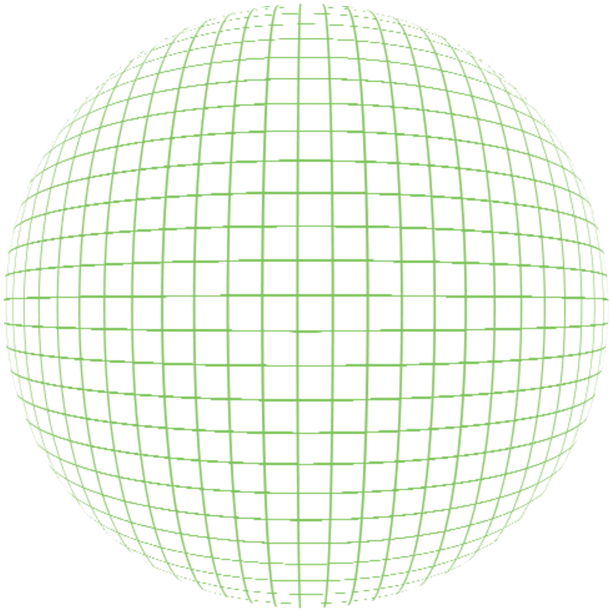


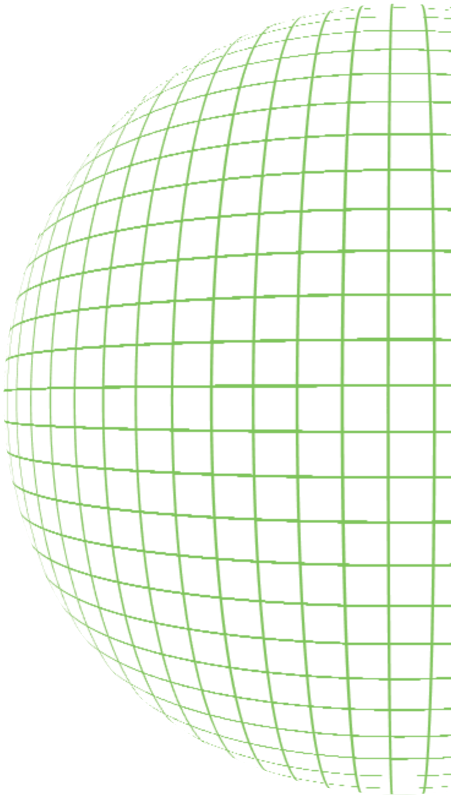
Alan H. Guth

Inflation and the New Era of High-Precision Cosmology

During the past five years our view of the universe has been jolted by several new and surprising observations. On March 3, 1998, a *New York Times* headline announced quite accurately that "Shocked Cosmologists Find Universe Expanding Faster." Instead of slowing due to gravitational attraction, the expansion of the universe was found to be speeding up! By December of that year, *Science* magazine proclaimed the accelerating universe the "breakthrough of the year," and the next month the cover of *Scientific American* heralded a "Revolution in Cosmology." Shortly afterward new measurements of the cosmic background radiation overturned the prevailing beliefs about the geometry and total mass density of the universe. According to the *New York Times* of November 26, 1999, "Like the great navigators who first sailed around the world, establishing its size and the curvature of







its surface, astronomers have made new observations that show with startling directness the large-scale geometry of the universe and the total amount of matter and energy that it contains. … All the data are consistent with a flat universe, said scientists on the projects and others who have read the teams' reports." The combined results of these observations have led to a new picture of our universe, in which the dominant ingredient is a mysterious substance dubbed "dark energy." The second most abundant material is "dark matter," and the ordinary matter that we are made of has been relegated to third place. Although substantially different from what was believed just a few years before, the new picture is beautifully consistent with the predictions of inflationary cosmology. In May 2001 a headline in *Astronomy* announced that "Universal Music Sings of Inflation," and two months later *Physics Today* referred to the latest measurements of the cosmic background radiation as "another triumph for inflation."

In this article I will try to describe the meaning of these new developments, but to put them in context we should begin by discussing the big bang theory and cosmic inflation.

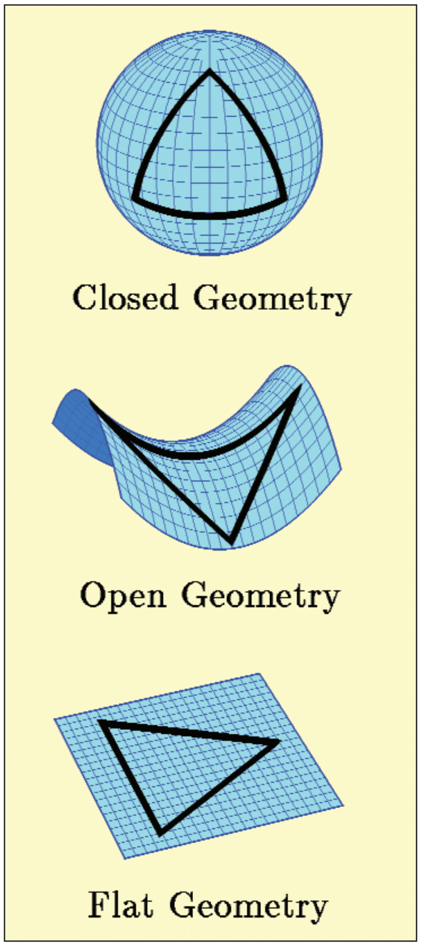


Figure 1

Possible Geometries for the Cosmos

The three possible geometries can be illustrated as the surface of a sphere (closed universe), the surface of a saddle (open universe), and a flat surface.

THE BIG BANG THEORY traces its roots to the calculations of Alexander Friedmann, who showed in 1922 that the equations of general relativity allow an expanding solution that starts from a singularity. The evidence for the big bang is now overwhelming. The expansion of the universe was first observed in the early 1920s by Vesto Melvin Slipher, and in 1929 was codified by Edwin Hubble into what we now know as "Hubble's Law": on average, each distant galaxy is receding from us with a velocity that is proportional to its distance. In 1965 Arno Penzias and Robert Wilson detected a background of microwave radiation arriving at Earth from all directions—radiation believed to be the afterglow of the primordial hot dense fireball. Today we know, based on data from the *Cosmic Background Explorer* (COBE) satellite, that the spectrum of this background radiation agrees with exquisite precision—to 50 parts per million—with the thermal spectrum expected for the glow of hot matter in the early universe. In addition, calculations of nucleosynthesis in the early universe show that the big bang theory can correctly account for the cosmic abundances of the light nuclear isotopes: hydrogen, deuterium, helium-3, helium-4, and lithium-7. (Heavier elements, we believe, were synthesized much later, in the interior of stars, and were then explosively ejected into interstellar space.)

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

A Very Special Bang

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

In fact, none of these scenarios can plausibly account for the big bang that started our universe, which had two very special features which distinguish it from any typical explosion.

First, the big bang was far more homogeneous, on large scales, than can be explained by an ordinary explosion. If we imagine dividing space into cubes of 300 million light-years or more on a side, we would find that each such cube closely resembles the others in all its average properties, such as mass density, galaxy density, light output, etc. This large-scale uniformity can be seen in galaxy surveys, but the most dramatic evidence comes from the cosmic background radiation. Data from the COBE satellite, confirmed by subsequent ground-based observations, show that this radiation has the same temperature in all directions (after correcting for the motion of the Earth) to an accuracy of one part in 100,000.

To see how difficult it is to account for this uniformity in the context of an ordinary explosion, we need to know a little about the history of the cosmic background radiation. The early universe was so hot that the gas would have been ionized, filling space with a plasma so opaque that photons could not travel. After about 300,000 years, however, the universe cooled enough for the plasma to form a highly transparent gas of neutral atoms. The photons of the cosmic background radiation have traveled on straight lines ever since, so they provide today an image of the universe at an age of 300,000 years, just as the photons reaching your eye at this moment provide an image of the page in front of you. Thus, the observations of the cosmic background radiation show that the universe was uniform in temperature, to one part in 100,000, at an age of several hundred thousand years.

Under many circumstances such uniformity would be easy to understand, since anything will come to a uniform temperature if left undisturbed for a long enough time. In the traditional form of the big bang theory, however, the universe evolves so quickly that there is no time for the uniformity to be established. Calculations show that energy and information would have to be transported at about 100 times the speed of light in order to achieve uniformity by 300,000 years after the big bang. Thus, the traditional big bang theory requires us to postulate, without explanation, that the primordial fireball filled space from the beginning. The temperature was the same everywhere by *assumption*, but not as a consequence of any physical process. This shortcoming is known as the *horizon problem*, since cosmologists use the word "horizon" to indicate the largest distance that information or energy could have traversed, since the instant of the big bang, given the restriction of the speed of light.

The second special feature of the big bang is a remarkable coincidence called the *flatness problem*. This problem concerns the pinpoint precision with which the mass density of the early universe must be specified for the big bang theory to agree with reality.

To understand the problem, we must bear in mind that general relativity implies that 3-dimensional space can be curved, and that the curvature is determined by the mass density. If we adopt the idealization that our universe is homogeneous (the same at all places) and isotropic (looks the same in all directions), then there are exactly three cases *(see figure 1)*. If the total mass density exceeds a value called the *critical density*, which is determined by the expansion rate, then the universe curves back on itself to form a space of finite volume but without boundary. In such a space, called a *closed universe*, a starship traveling on what appears to be a straight line would eventually return to its point of origin. The sum of the angles in a triangle would exceed 180°, and lines which appear to be parallel would eventually meet

The Critical Density

According to Hubble's law, the recession velocity of any distant galaxy is given approximately by

$$v = Hr$$

where r is the distance to the galaxy and H is a measure of the expansion rate called the Hubble constant (or Hubble parameter). The critical mass density is determined by the expansion rate, and is given by

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

where G is Newton's gravitational constant. The critical density is defined to be that density which leads to a geometrically flat universe. (In the past cosmologists often said that a closed universe ($\rho > \rho_c$) will recollapse and an open universe ($\rho < \rho_c$) will expand forever, but these statements are invalidated by the possibility of a cosmological constant. A positive cosmological constant can allow a closed universe to expand forever, and a negative one can cause an open universe to collapse.)

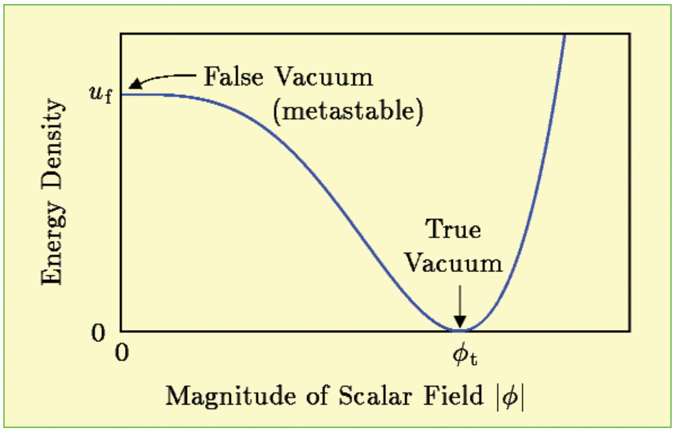
if they are extended. If the average mass density is less than the critical density, then the space curves in the opposite way, forming an infinite space called an *open universe*, in which triangles contain less than 180° and lines that appear to be parallel would diverge if they are extended. If the mass density is exactly equal to the critical density, then the space is a *flat universe*, obeying the rules of Euclidean geometry that we all learned in high school.

The ratio of the actual mass density to the critical value is known to cosmologists by the Greek letter Ω (Omega). Ω is very difficult to determine. Five years ago the observationally preferred value was 0.2–0.3, but the new observations suggest that to within 5% it is equal to 1. For either range, however, one finds a very surprising situation when one extrapolates backwards to ask about the early universe. $\Omega = 1$ is an *unstable equilibrium point* of cosmological evolution, which means that it resembles the situation of a pencil balancing on its sharpened tip. The phrase *equilibrium point* implies that if Ω is ever exactly equal to one, it will remain exactly equal to one forever—just as a pencil balanced precisely on end will, according to the laws of classical physics, remain forever vertical. The word *unstable* means that any deviation from the equilibrium point, in either direction, will rapidly grow. If the value of Ω in the early universe was just a little above one, it would have rapidly risen toward infinity; if it was just a smidgen below one, it would have rapidly fallen toward zero. For Ω to be anywhere near one today, it must have been extraordinarily close to one at early times. For example, consider one second after the big bang, the time at which the processes related to big bang nucleosynthesis were just beginning. Even if Ω differed from unity today by a factor of 10, at one second after the big bang it must have equalled one to an accuracy of 15 decimal places!

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

Physics of the False Vacuum (FIGURE 2)

A false vacuum arises naturally in any theory that contains scalar fields, i.e., fields that resemble electric or magnetic fields except that they have no direction. The Higgs fields of the Standard Model of Particle Physics or the more speculative grand unified theories are examples of scalar fields. It is typical of Higgs fields that the energy density is minimized not when the field vanishes, but instead at some nonzero value of the field. For example, the energy density diagram might look like:



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

The Inflationary Universe

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

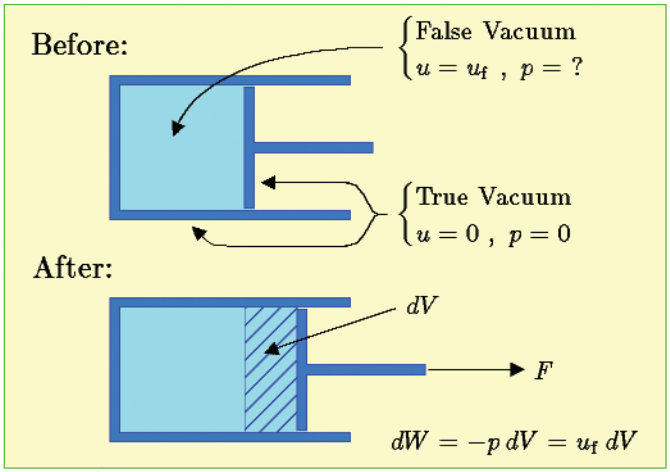
The crucial property of physical law that makes inflation possible is the existence of states of matter which have a high energy density that cannot be rapidly lowered. Such a state is called a *false vacuum*, where the word *vacuum* indicates a state of lowest possible energy density, and the word *false* is used to mean *temporary*. For a period that can be long by the standards of the early universe, the false vacuum acts as if the energy density cannot be lowered, since the lowering of the energy is a slow process. The underlying physics of the false vacuum state is described in *Figure 2*.

The peculiar properties of the false vacuum stem from its pressure, which is large and *negative (see Figure 3)*. Mechanically such a negative pressure corresponds to a suction, which does not sound like something that would drive the universe into a period of rapid expansion. The mechanical effects of pressure, however, depend on pressure differences, so they are unimportant if the pressure is reasonably uniform. According to general relativity, however, there is a gravitational effect which is very important under these circumstances. Pressures, like energy densities, create gravitational fields, and in particular a positive pressure creates an attractive gravitational field. The negative pressure of the false vacuum, therefore, creates a repulsive gravitational field, which is the driving force behind inflation.

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

Pressure of the False Vacuum (FIGURE 3)

The pressure of the false vacuum can be determined by a simple energy-conservation argument. Imagine a chamber filled with false vacuum, as shown in the following figure:



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

$$p = -u_f$$

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

$$\tau = \sqrt{3c^2/(8\pi G u_f)}$$

where c is the speed of light.

Once a patch of the early universe is in the false vacuum state, the repulsive gravitational effect drives the patch into an inflationary period of exponential expansion. To produce a universe with the special features of the big bang discussed above, the universe must expand during the inflationary period by at least a factor of 10^{25}. There is no upper limit to the amount of expansion. If the energy scale of the false vacuum is characteristic of the 10^{16} GeV scale of grand unified theories, then the time constant of the exponential expansion would be about 10^{-37} seconds. Eventually the false vacuum decays, and the energy that had been locked in the false vacuum is released. This energy produces a hot, uniform soup of particles, which is exactly the assumed starting point of the traditional big bang theory. At this point the inflationary theory joins onto the older theory, maintaining all of its successes.

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

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

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

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

Inflation and the Very Special Bang

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

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

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

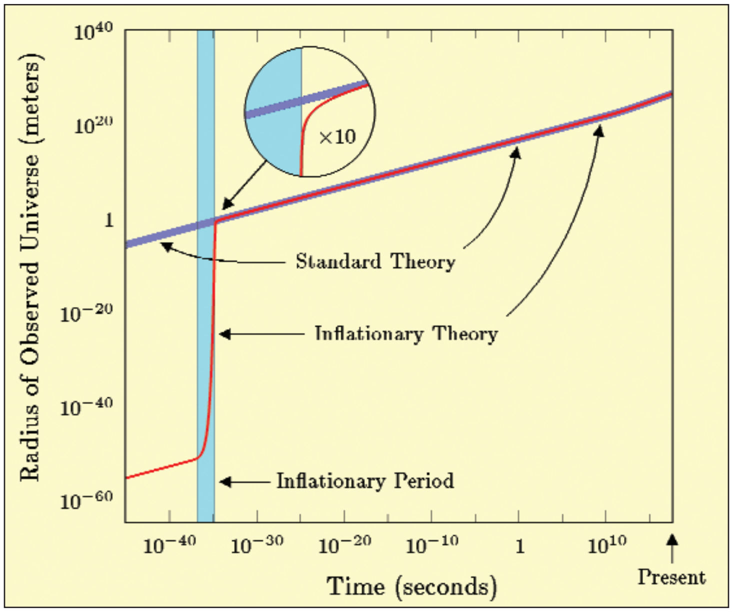


FIGURE 4

The Solution to the Horizon Problem

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

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

During the inflationary era, however, the peculiar nature of the false vacuum state results in some important sign changes in the equations that describe the evolution of the universe. During this period, as we have discussed, the force of gravity acts to accelerate the expansion of the universe rather than to retard it. It turns out that the equation governing the evolution of Ω also has a crucial change of sign:

during the inflationary period the universe is driven very quickly and very powerfully *towards* a critical mass density. This effect can be understood if one accepts from general relativity the fact that Ω must equal one if the space of the universe is geometrically flat. The huge expansion factor of inflation drives the universe toward flatness for the same reason that the Earth appears flat, even though it is really round. A small piece of any curved space, if magnified sufficiently, will appear flat.

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

Furthermore, there is a prediction that arises from this behavior. The mechanism that drives Ω to one almost always overshoots, which means that even today the mass density should be equal to the critical value to a high degree of accuracy. Thus, until recently inflation was somewhat at odds with astronomical observations, which pointed strongly towards low values of Ω. All this has reversed, however, in the revolution of the past five years.

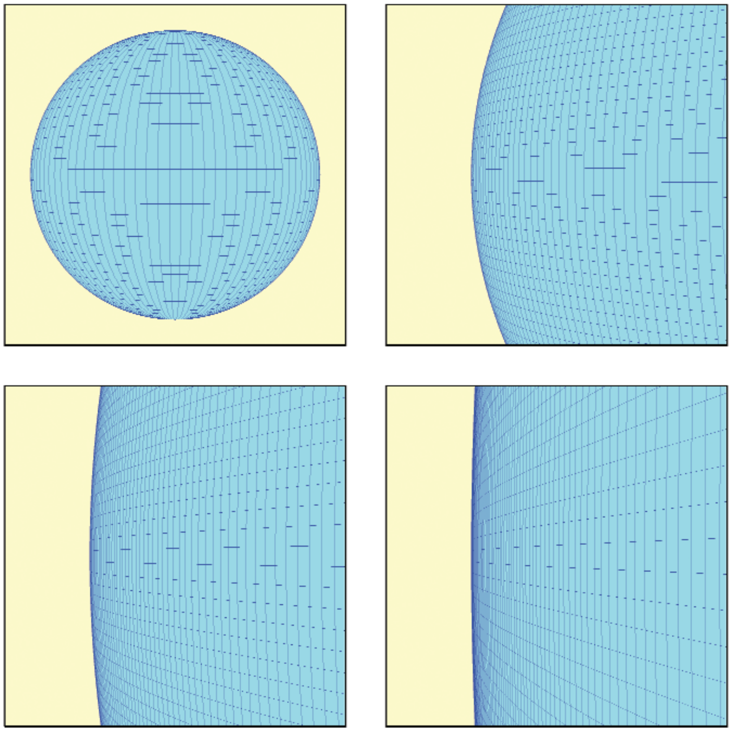


FIGURE 5

The Solution to the Flatness Problem

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

The Current Revolution in Cosmology

The revolution can be said to have begun on January 9, 1998, when the Supernova Cosmology Project, based at Lawrence Berkeley Laboratory under the leadership of Saul Perlmutter, announced at a meeting of the American Astronomical Society that they had found evidence suggesting that the separation velocity between galaxies had not been slowing down over the past 5 billion years as had been expected, but in fact has been speeding up. The following month, the High-Z Supernova Search Team, an international collaboration led by Brian Schmidt of the Mount Stromlo and Siding Spring Observatory in Australia, announced at a meeting in California that they had also found evidence for cosmic acceleration.

Both groups had made very similar observations, using supernovae of type 1A as *standard candles* to probe the expansion rate of the universe. A standard candle is an object, like a 100-watt light bulb, for which the light output is known. When such an object is found, astronomers can determine its distance by measuring how bright it looks. The recession velocity of the distant supernovae can be determined by the redshift of their spectra, so each supernova can be used as a measure of the expansion rate. Since looking far out into space is the equivalent of looking back in time, the supernovae allowed the astronomers to probe the expansion rate much further back than any previous measurement.

The precise explanation for the accelerated expansion remains a mystery, but apparently the universe is permeated with a material of negative pressure, creating a gravitational repulsion that is similar to the driving force of inflation, but with a much smaller magnitude. This negative pressure material has come to be called the *dark energy* of the universe. Dark energy is distinct from *dark matter*, since dark energy has negative pressure and is uniformly distributed throughout the universe, while dark matter has approximately zero pressure and is clumped into galaxies and clusters of galaxies.

One possibility is that the negative pressure is caused by the vacuum itself, which would be the case if the vacuum had a positive energy density. In this case the true vacuum would act like the false vacuum that is believed to have driven inflation, except that it is absolutely stable, and its energy density and negative pressure are much smaller in magnitude. A vacuum energy density would be precisely equivalent to what Einstein called a cosmological constant. (It may seem strange to attribute an energy density to the vacuum, but one should bear in mind that particle theorists see the vacuum as a complicated state in which "virtual" particles are constantly appearing and disappearing as quantum fluctuations. To the particle theorists, the big problem is to understand how the energy density of the vacuum could be so amazingly small.) The other possibility for the dark energy, dubbed *quintessence*, proposes a low-energy false vacuum state that closely parallels the mechanism behind inflation, except that it is much slower. In either case, the total mass density of the dark energy is about 70% of the critical density, with dark matter comprising about 25%. Ordinary matter, composed of protons, neutrons, and electrons, has fallen to third place in the cosmic hierarchy, contributing only about 5% of the critical density. With the addition of the dark energy, the total mass density is now believed to be equal to, or at least very close to, the critical density, as predicted by inflation.

The supernova data can be disputed, but the conclusions have been strongly bolstered by new measurements of the nonuniformities in the cosmic background radiation. Although this radiation is uniform to one part in 100,000, the measurements have become so precise that the study of the nonuniformities has become a minor industry. The nonuniformities allow us to measure the ripples in the mass density of the universe at the time when the plasma combined to form neutral atoms, about 300,000 years after the big bang. These ripples are crucial for understanding what happened later, since they are the seeds which led to the complicated tapestry of galaxies, clusters of galaxies, and voids. But they are also crucial for understanding what happened earlier, since they contain clues about the earliest moments of cosmic history.

In inflationary models, the enormous expansion smooths out any structure that might have been present before inflation. The cosmic ripples are generated, however, by quantum fluctuations that occur during inflation. While quantum effects are normally important only on the smallest distance scales, inflation has the unusual property of stretching these initially microscopic fluctuations to macroscopic and even astronomical proportions. Since there are many different versions of inflationary theory, there is no unique prediction for these quantum fluctuations. Nonetheless, the simplest versions of inflation all give very similar predictions for the *spectrum* of these ripples, where the word "spectrum" is used in a sense very similar to that of sound waves: it describes how the relative intensities of the ripples depend on their wavelengths.

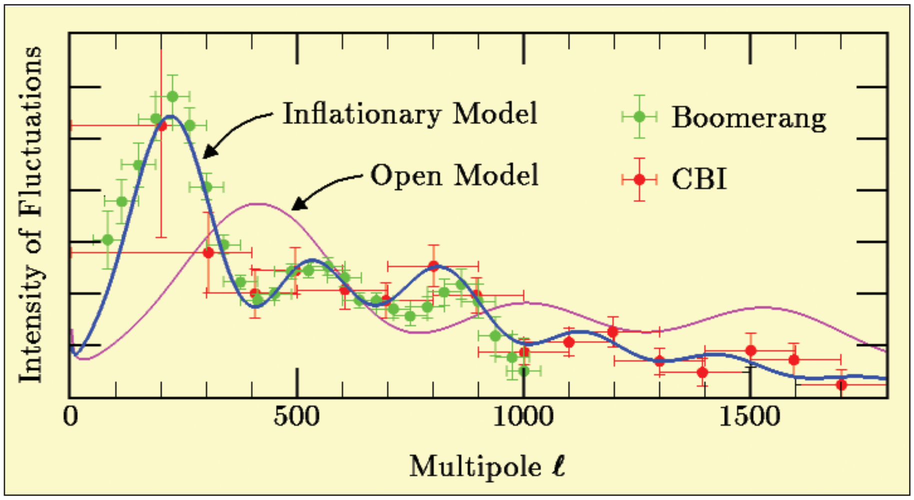


Figure 6

Nonuniformities of the Cosmic Background Radiation

Intensity of cosmic microwave background nonuniformities as a function of angular scale. 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 ℓ. Roughly speaking, each multipole ℓ corresponds to ripples with an angular wavelength of 180°/ℓ. The inflationary model curve represents a flat universe, with 70% of the mass in dark energy. The open model curve shows what would be expected for an $\Omega = 0.3$ universe with no dark energy, a possibility that seemed very likely a few years ago.

The initial ripples set up waves that oscillated as the universe evolved, producing a pattern of acoustic peaks in the spectrum that became imprinted on the cosmic background radiation. The positions and heights of these peaks reflect not only the initial fluctuations resulting from inflation, but also the properties of the universe in which they evolved. The nonuniformities of the cosmic background radiation were first detected by the COBE satellite in 1992, and the first of the acoustic peaks was mapped out in 1999 by balloon experiments called BOOMERANG and Maxima, and the mountain-top Microwave Anisotropy Telescope (MAT). These preliminary measurements of the first peak were sufficient to strongly indicate that the universe is flat, in agreement with the indications from the supernovae. The graph in *Figure 6* shows the latest data from the BOOMERANG experiment, along with the very recent data from the Cosmic Background Imager, which reached an angular resolution better than one tenth of a degree. There are now five peaks visible in the data, which continues to agree well with the inflation-based theoretical model.

While it may be too early to say that inflation is proved, the case for inflation is certainly compelling. It is hard to even conceive of an alternative theory that could explain the basic features of the observed universe. (The recently proposed cyclic model of Steinhardt and Turok claims to reproduce all the successes of inflation, but it does so by introducing a form of inflation, albeit a very novel one.) Not only does inflation produce just the kind of special bang that matches the qualitative properties of the observed universe, but its detailed predictions for the total mass density of the universe and for the form of the primordial density fluctuations are now in excellent agreement with observations.

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

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Ned Wright's Cosmology Tutorial *http://www.astro.ucla.edu/~wright/cosmolog.htm*

INDEX OF REVIEW ARTICLES

The Net Advance of Physics: Cosmology *http://web.mit.edu/redingtn/www/netadv/Xcosmology.html*

COSMIC MICROWAVE BACKGROUND EXPERIMENTS

Boomerang *http://www.physics.ucsb.edu/~boomerang/*

Cosmic Background Imager *http://www.astro.caltech.edu/~tjp/CBI/*

Microwave Anisotropy Probe *http://map.gsfc.nasa.gov/*

SUPERNOVA OBSERVATIONS

High-Z Supernova Search Team *http://cfa-www.harvard.edu/cfa/oir/Research/supernova/HighZ.html*

Supernova Cosmology Project *http://www-supernova.lbl.gov/*

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Guth is still busy exploring the consequences of inflation. He has also written a popular-level book called "The Inflationary Universe: The Quest for a New Theory of Cosmic Origins" (Addison-Wesley/Perseus Books, 1997).