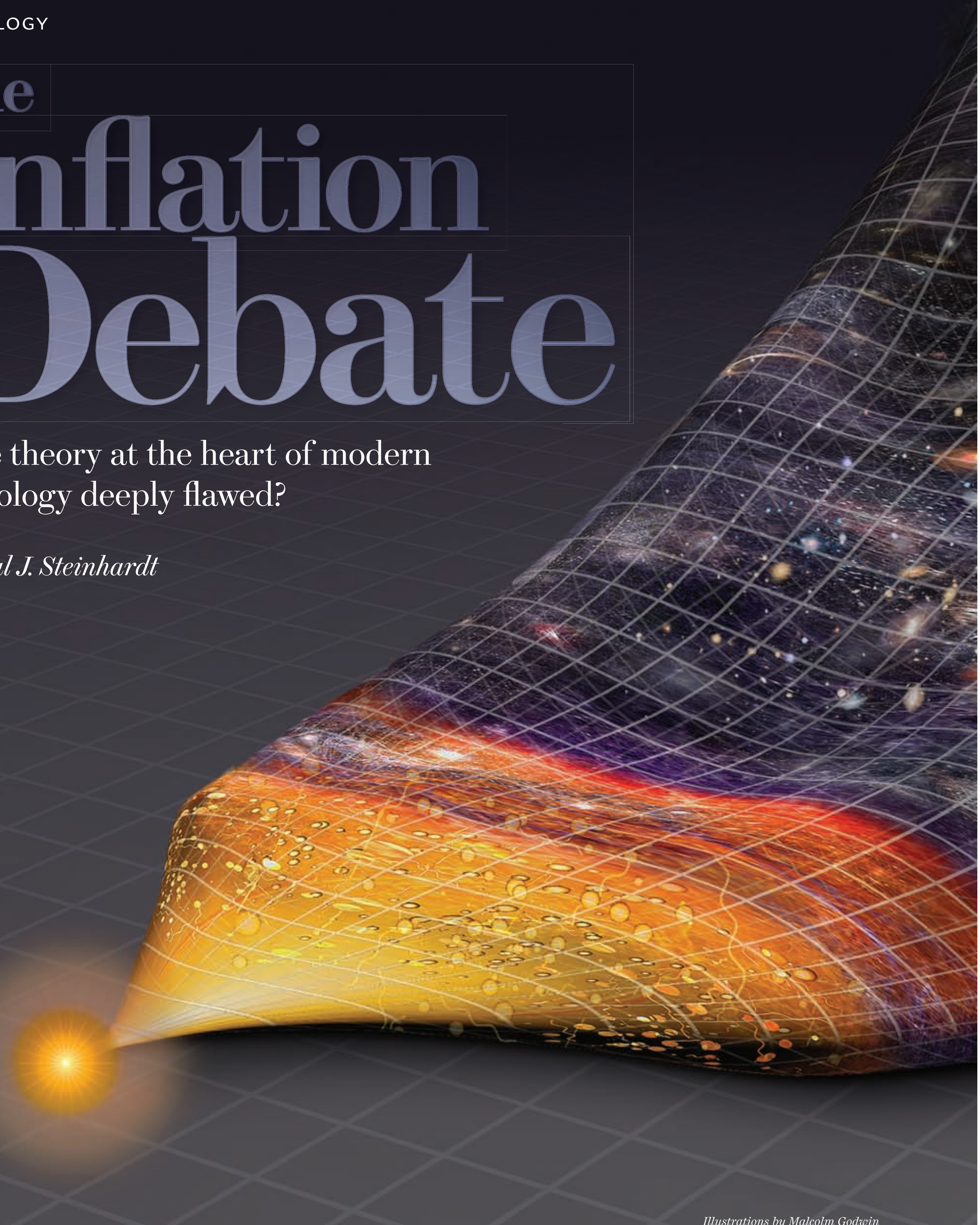
COSMOLOGY

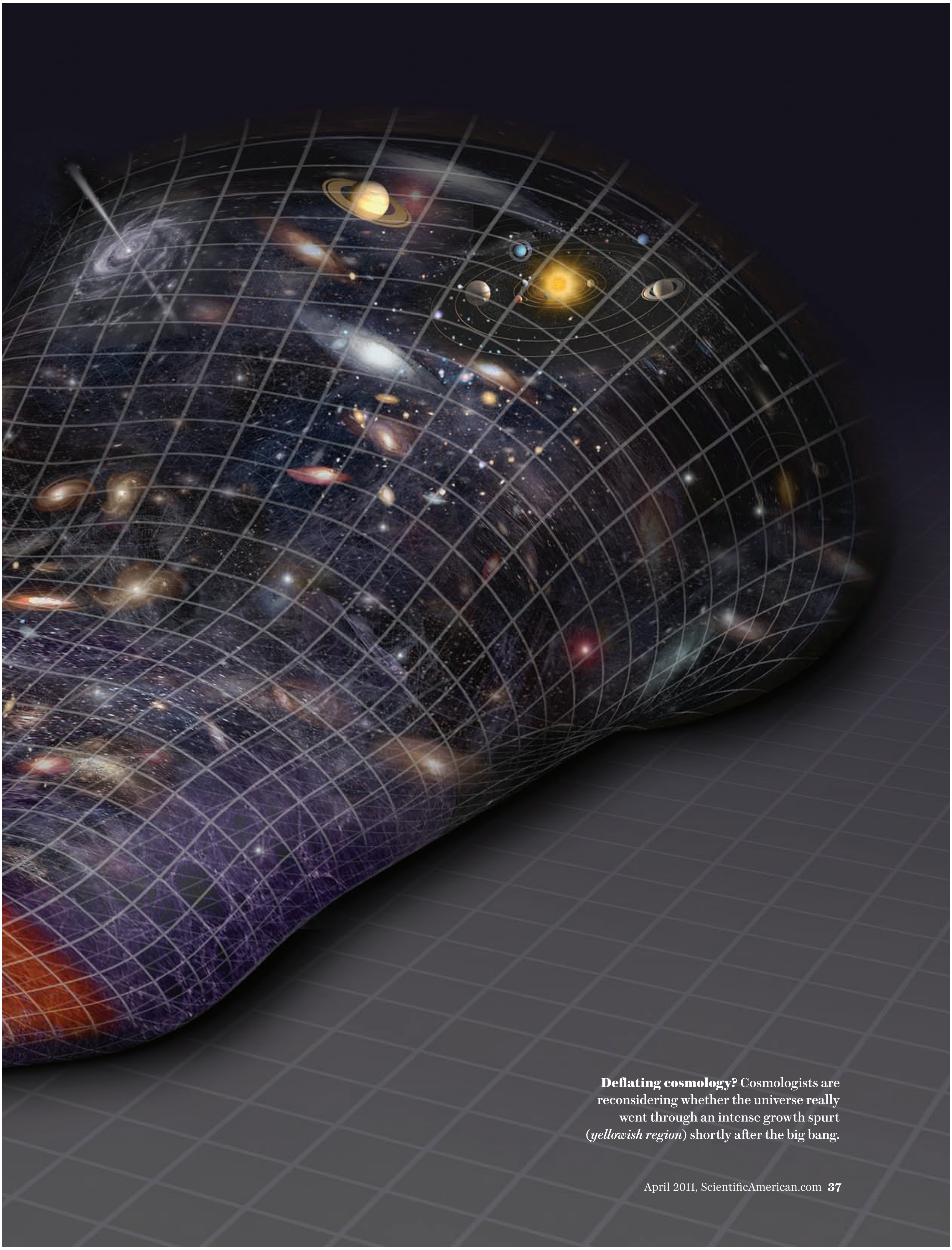
The Inflation Debate

Is the theory at the heart of modern cosmology deeply flawed?

By Paul J. Steinhardt



Illustrations by Malcolm Godwin



Deflating cosmology? Cosmologists are reconsidering whether the universe really went through an intense growth spurt (*yellowish region*) shortly after the big bang.

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THIRTY YEARS AGO ALAN H. GUTH, THEN A STRUGGLING PHYSICS postdoc at the Stanford Linear Accelerator Center, gave a series of seminars in which he introduced "inflation" into the lexicon of cosmology. The term refers to a brief burst of hyperaccelerated expansion that, he argued, may have occurred during the first instants after the big bang. One of these seminars took place at Harvard University, where I myself was a postdoc. I was immediately captivated by the idea, and I have been thinking about it almost every day since. Many of my colleagues working in astrophysics, gravitational physics and particle physics have been similarly engrossed. To this day the development and testing of the inflationary theory of the universe is one of the most active and successful areas of scientific investigation.

Its raison d'être is to fill a gap in the original big bang theory. The basic idea of the big bang is that the universe has been slowly expanding and cooling ever since it began some 13.7 billion years ago. This process of expansion and cooling explains many of the detailed features of the universe seen today, but with a catch: the universe had to start off with certain properties. For instance, it had to be extremely uniform, with only extremely tiny variations in the distribution of matter and energy. Also, the universe had to be geometrically flat, meaning that curves and warps in the fabric of space did not bend the paths of light rays and moving objects.

But why should the primordial universe have been so uniform and flat? A priori, these starting conditions seemed unlikely. That is where Guth's idea came in. He argued that even if the universe had started off in total disarray—with a highly nonuniform distribution of energy and a gnarled shape—a spectacular growth spurt would have spread out energy until it was evenly dispersed and straightened out any curves and warps in space. When this period of inflation ended, the universe would have continued to expand at the more mellow pace of the original big bang theory but now with just the right conditions for stars and galaxies to evolve to the state where we see them today.

The idea is so compelling that cosmologists, including me, routinely describe it to students, journalists and the public as an established fact. Yet something peculiar has happened to inflationary theory in the 30 years since Guth introduced it. As the case for inflation has grown stronger, so has the case against. The two cases are not equally well known: the evidence favoring inflation is familiar to a broad range of physicists, astrophysicists and science aficionados. Surprisingly few seem to follow the case against inflation except for a small group of us who have been quietly striving to address the challenges. Most astrophysicists have gone about their business testing the predictions of textbook inflationary theory without worrying about these deeper issues, hoping they would eventually be resolved. Unfortunately, the problems have resisted our best efforts to date.

As someone who has contributed both to inflationary theory [see "The Inflationary Universe," by Alan H. Guth and Paul J. Steinhardt; SCIENTIFIC AMERICAN, May 1984] and to competing theories, I feel torn, and I sense that many of my colleagues are not sure what to make of the case against, either. To dramatize our strange predicament, I will place inflationary cosmology on trial, presenting the two extreme points of view. First, I will act as fervent advocate "for," presenting the strongest advantages of the theory, and then, with equal fervor, as advocate "against," presenting the most serious unresolved problems.

THE CASE FOR INFLATION

INFLATION is so well known that the case for it can be brief. A few more details are necessary to appreciate its advantages fully. Inflation relies on a special ingredient known as inflationary energy, which, combined with gravity, can drive the universe to expand by an astonishing amount over a brief instant. The inflationary energy must be hugely dense, and its density must remain nearly constant during the inflationary epoch. Its most unusual property of all is that its gravity must repel rather than attract. The repulsion is what causes space to swell so rapidly.

What gave Guth's idea its appeal was that theorists had already identified many possible sources of such energy. The leading example is a hypothesized relative of the magnetic field known as a scalar field, which, in the particular case of inflation,

IN BRIEF

Cosmic inflation is so widely accepted that it is often taken as established fact. The idea is that the geometry and uniformity of the cosmos were established during an intense early growth spurt.

But some of the theory's creators, including the author, are having second thoughts. As the original theory has developed, cracks have appeared in its logical foundations.

Highly improbable conditions are required to start inflation. Worse, inflation goes on eternally, producing infinitely many outcomes, so the theory makes no firm observational predictions.

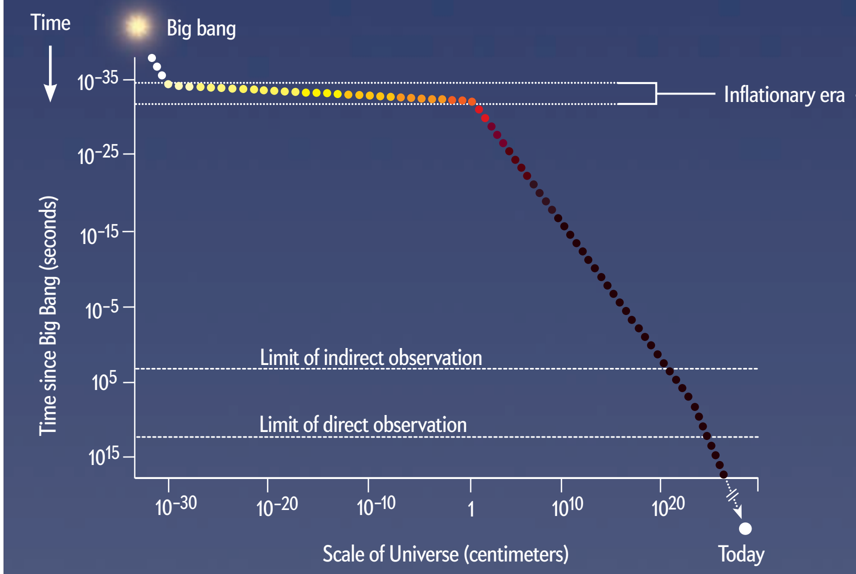
Scientists debate among (and within) themselves whether these troubles are teething pains or signs of a deeper rot. Various proposals are circulating for ways to fix inflation or replace it.

CLASSICAL VIEW OF INFLATION

The Ultimate Growth Spurt

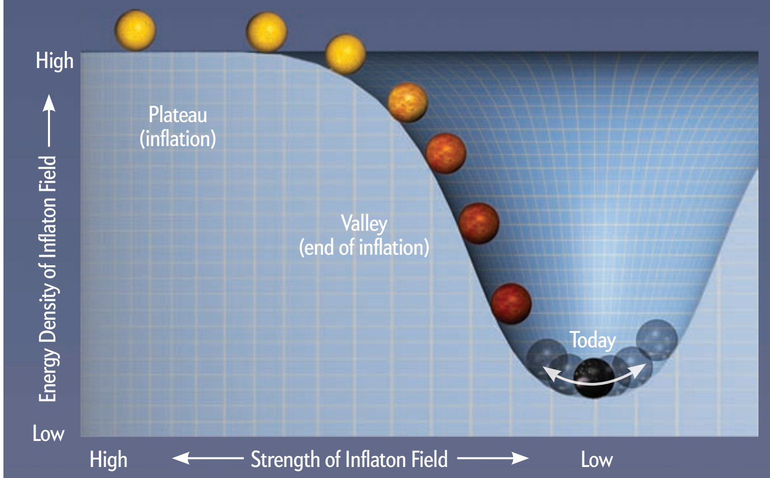
Astronomers observe that the universe is expanding and has been doing so for 13.7 billion years. But what happened at the very earliest times, too early to see directly? The leading idea is known as cosmic inflation. It supposes that the embryonic universe abruptly ballooned in size. Such a growth spurt would have ironed out any curves and warps in space, thus explaining the geometry of the universe today, and left behind slight nonuniformities that seeded galaxies.

WHAT INFLATION DID

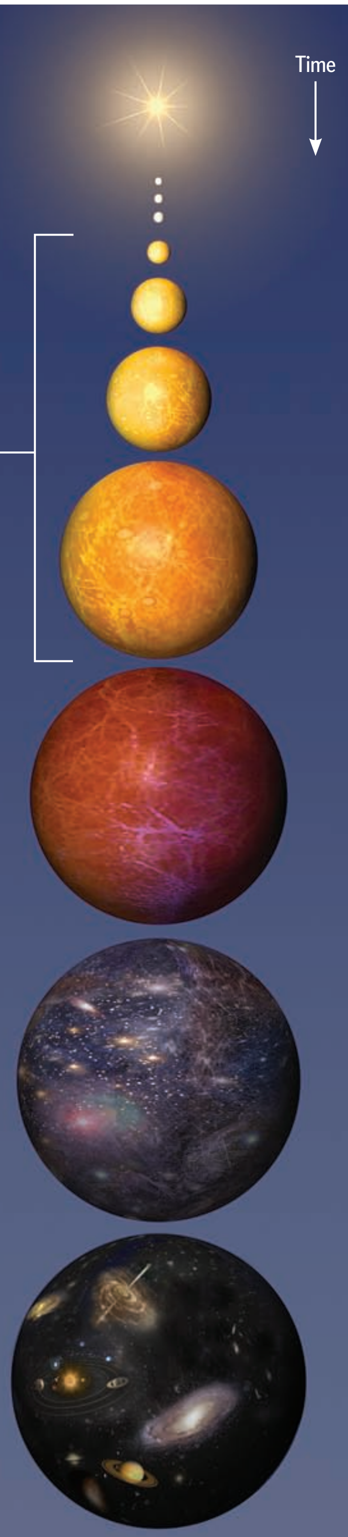


The amount of growth was impressive even by astronomers' standards. Within 10^{-30} second, the universe enlarged by a factor of at least 10^{25} in every direction. It expanded at an accelerated rate, pulling regions of space apart faster than the speed of light.

WHAT CAUSED INFLATION



A relative of the magnetic field, the "inflaton" generated a repulsive gravitational force that drove space to swell rapidly momentarily. For that to occur, the field's energy density had to vary with strength such that it had a high-energy plateau and a low-energy valley. The field evolved like a ball rolling downhill. On the plateau, it exerted the repulsive force. When it hit the valley, inflation ended.



The volume of space we observe today was a quadrillionth the size of an atom when inflation began. During inflation it grew to the size of a dime. In the billions of years since then, space has continued to expand but at a mellower pace, allowing structures such as galaxies to form. (This figure is conceptual and not to scale.)

Graphic by Jen Christiansen (top left)

is known as the "inflaton" field. The famous Higgs particle now being sought at CERN's Large Hadron Collider near Geneva derives from another scalar field.

Like all fields, the inflaton has a certain strength at every point in space, which determines the force it exerts on itself and on other fields. During the inflationary phase, its strength is nearly constant everywhere. Depending on how strong a field is, it has a certain amount of energy in it—what physicists call potential energy. The relation between the strength and the energy can be represented by a curve on a graph. For the inflaton, cosmologists hypothesize that the curve looks like the cross section through a valley and a gently sloped plateau [*see box on preceding page*]. If the field begins with a strength corresponding to some point on the plateau, it will gradually lose both strength and energy, as if sliding down the slope. In fact, the equations are similar to those of a ball rolling down a hill of the same shape as the potential energy curve.

The inflaton's potential energy can cause the universe to expand at an accelerated rate. In the process, it can smooth and flatten the universe, provided the field remains on the plateau long enough (about 10^{-30} second) to stretch the universe by a factor of 10^{25} or more along each direction. Inflation ends when the field reaches the end of the plateau and rushes downhill to the energy valley below. At this point, the potential energy converts into more familiar forms of energy—namely, the dark matter, hot ordinary matter and radiation that fill the universe today. The universe enters a period of modest, decelerating expansion during which the material coalesces into cosmic structures.

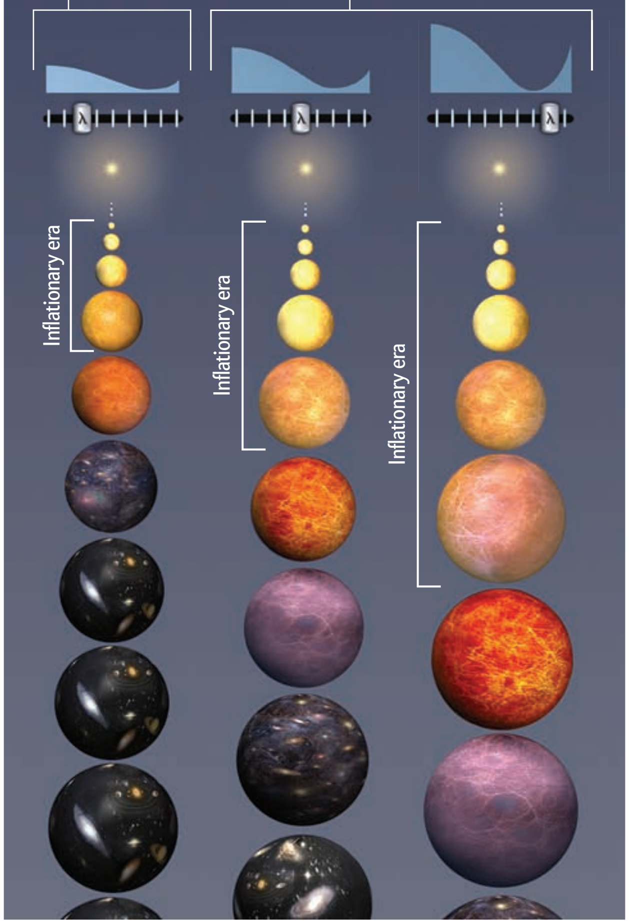
PROBLEM #1: "BAD" INFLATION

Unlikely to Be Good

Inflation was supposed to create a huge volume of space matching the observed large-scale features of our universe naturally. But unless the inflaton energy curve had a very specific shape (obtained by finely tuning one or more parameters, abbreviated λ here), the outcome would be "bad"—a huge volume with too high a density and the wrong distribution of galaxies. Given the range of possible λ values, bad inflation seems more likely.

"Good" inflation: Only for a narrow range of λ does inflation yield the observed galaxy density.

"Bad" inflation: A typical value of λ produces a higher galaxy density and possibly more space.



Inflation smoothes the universe just as stretching a rubber sheet smoothes its wrinkles, but it does not do so perfectly. Small irregularities remain because of quantum effects. The laws of quantum physics dictate that a field such as the inflaton not have exactly the same strength everywhere in space but that it undergo random fluctuations. These fluctuations cause inflation to end at slightly different times in different regions of space, heating them to slightly different temperatures. These spatial variations are the seeds that will eventually grow into stars and galaxies. A prediction of inflationary theory is that the variations are nearly scale-invariant. That is, they do not depend on the size of the region; they occur with equal magnitude on all scales.

The case for inflation can be summarized by three dictums. First, inflation is inevitable. Developments in theoretical physics since Guth's proposal have only strengthened the hypothesis that the early universe contained fields that could conceivably drive inflation. Hundreds of them appear in unified theories of physics, such as string theory. In the chaotic primeval universe, there was sure to be some patch of space where one of these fields met the conditions for inflation.

Second, inflation explains why the universe is so uniform and flat today. No one knows how uniform or flat the universe was when it emerged from the big bang, but with inflation there is no need to know because the period of accelerated expansion stretched it into the right shape.

Third, and probably the most compelling, inflationary theory is powerfully predictive. For example, numerous observations of the cosmic microwave background radiation and the distribution of galaxies have confirmed that the spatial variations in energy in the early universe were nearly scale-invariant.

THE CASE AGAINST INFLATION

THE FIRST SIGNS that a theory is failing are usually small discrepancies between observations and predictions. That is not the situation here: the data are in exquisite accord with the inflationary predictions set down in the early 1980s. Instead the case against inflation challenges the logical foundations of the theory. Does the theory really work as advertised? Are the predictions made in the early 1980s still the predictions of the inflationary model as we understand it today? There is an argument to be made that the answer to both questions is no.

The first dictum holds that inflation is inevitable. But if it is, there is an awkward corollary: bad inflation is more likely than good inflation. "Bad inflation" means a period of accelerated expansion whose outcome conflicts with what we observe. For example, the temperature variations might be too large. The difference between good and bad hinges on the precise shape of the potential energy curve, which is controlled by a numerical parameter that could, in principle, take on any value whatsoever. Only an extremely narrow range of values could produce the observed temperature variation. In a typical inflationary model, the value must be near 10^{-15}—that is, zero to 15 decimal places. A less fine-tuned choice, such as zero to only 12 or 10 or eight decimal places, would produce bad inflation: the same degree of accelerated expansion (or more) but with a large temperature variation that is inconsistent with observations.

We could ignore bad inflation if it were incompatible with life. In that case, even if such large temperature variations could arise in principle, we could never observe them. Reasoning of this kind is known as the anthropic principle. Yet it does not apply here. Larger temperature variations would result in more stars and galaxies—the universe would, if anything, be more habitable than it is now.

Not only is bad inflation more likely than good inflation, but no inflation is more likely than either. University of Oxford physicist Roger Penrose first made this point in the 1980s. He applied thermodynamic principles, similar to those used to describe configurations of atoms and molecules in a gas, to count the possible starting configurations of the inflaton and gravitational fields. Some of these configurations lead to inflation and thence to a nearly uniform, flat distribution of matter and a geometrically flat shape. Other configurations lead to a uniform, flat universe directly—without inflation. Both sets of configurations are rare, so obtaining a flat universe is unlikely overall. Penrose's shocking conclusion, though, was that obtaining a flat universe without inflation is much more likely than with inflation—by a factor of 10 to the googol (10^{100}) power!

THE PERILS OF AN ETERNAL INFLATION

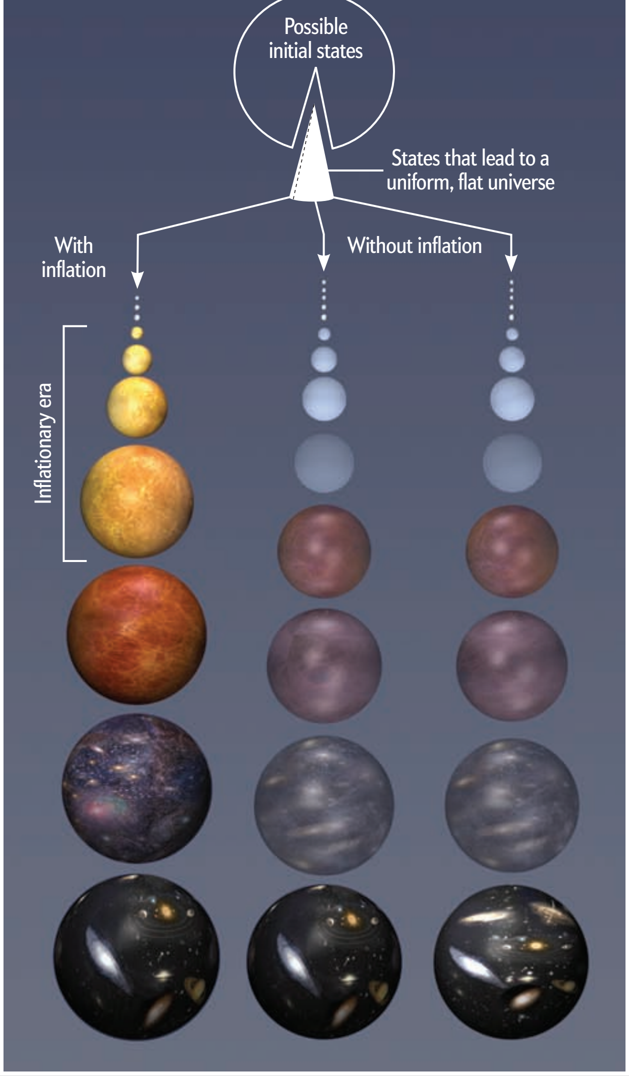
ANOTHER APPROACH reaching a similar conclusion extrapolates the history of the universe from its current conditions backward in time using the established physical laws. The extrapolation is not unique: given the average flat and smooth conditions today, many different sequences of events could have come before. In 2008 Gary W. Gibbons of the University of Cambridge and Neil G. Turok of the Perimeter Institute for Theoretical Physics in Ontario showed that an overwhelming number of extrapolations have insignificant amounts of inflation. This conclusion is consistent with Penrose's. Both seem counterintuitive because a flat and smooth universe is unlikely, and inflation is a powerful mechanism for obtaining the needed smoothing and flattening. Yet this advantage appears to be completely offset by the fact that the conditions for starting inflation are so improbable. When all factors are taken into account, the universe is more likely to have achieved its current conditions without inflation than with it.

Many physicists and astrophysicists find these theoretical arguments unconvincing compared with a more compelling one favoring inflation: namely, the agreement between the predictions formulated in the early 1980s and the magnificent cosmological observations available today. Matching experiments trumps any theoretical argument. But the strange twist to this story is that the predictions of the early 1980s were based on a naive understanding of how inflation actually works—a picture that has turned out to be dead wrong.

PROBLEM #2: STARTING CONDITIONS

It Had to Be Just So

Inflation was supposed to occur no matter what the initial conditions of the universe were. Further analysis suggests otherwise. Of all the ways the universe could have begun, only a tiny fraction would lead to the uniform, flat state observed today. An overwhelming fraction of these would reach this state without significant inflation; only an infinitesimal fraction would do so by going through a long period of inflation.



The change in view began with the realization that inflation is eternal: once begun, it never ends [see "The Self-Reproducing Inflationary Universe," by Andrei Linde; Scientific American, November 1994]. The self-perpetuating nature of inflation is the direct result of quantum physics combined with accelerated expansion. Recall that quantum fluctuations can slightly delay when inflation ends. Where these fluctuations are small, so are their effects. Yet the fluctuations are uncontrollably random. In some regions of space, they will be large, leading to substantial delays.

Such procrastinating rogue regions are extremely rare, so you might think it safe to ignore them. You cannot, because they are inflating. They continue to grow and, in a matter of instants, dwarf the well-behaved region that ended inflation on time. The result is a sea of inflating space surrounding a little island filled with hot matter and radiation. What is more, rogue regions spawn new rogue regions, as well as new islands of matter—each a self-contained universe. The process continues ad infinitum, creating an unbounded number of islands surrounded by ever more inflating space. If you are not disturbed by this picture, don't worry—you should not be. The disturbing news comes next.

The islands are not all the same. The inherently random nature of quantum physics ensures that some are highly nonuniform or strongly warped. Their nonuniformity sounds like the problem of bad inflation described earlier, but the cause is different. Bad inflation occurs because the parameters controlling the shape of the potential energy curve are likely to be too large. Here nonuniformity can result from eternal inflation and random quantum fluctuations no matter what values the parameters have.

To be quantitatively precise, the word "some" above should be replaced with "an infinite number of." In an eternally inflating universe, an infinite number of islands will have properties like the ones we observe, but an infinite number will not. The true outcome of inflation was best summarized by Guth: "In an eternally inflating universe, anything that can happen will happen; in fact, it will happen an infinite number of times."

So is our universe the exception or the rule? In an infinite collection of islands, it is hard to tell. As an analogy, suppose you have a sack containing a known finite number of quarters and pennies. If you reach in and pick a coin randomly, you can make a firm prediction about which coin you are most likely to choose. If the sack contains an infinite number of quarter and pennies, though, you cannot. To try to assess the probabilities, you sort the coins into piles. You start by putting one quarter into the pile, then one penny, then a second quarter, then a second penny, and so on. This procedure gives you the impression that there is an equal number of each denomination. But then you try a different system, first piling 10 quarters, then one penny, then 10 quarters, then another penny, and so on. Now you have the impression that there are 10 quarters for every penny.

Which method of counting out the coins is right? The answer is neither. For an infinite collection of coins, there are an infinite number of ways of sorting that produce an infinite range of probabilities. So there is no legitimate way to judge which coin is more likely. By the same reasoning, there is no way to judge which kind of island is more likely in an eternally inflating universe.

Now you should be disturbed. What does it mean to say that inflation makes certain predictions—that, for example, the universe is uniform or has scale-invariant fluctuations—if anything that can happen will happen an infinite number of times? And if the theory does not make testable predictions, how can cosmologists claim that the theory agrees with observations, as they routinely do?

THE MEASURE OF OUR FAILURE

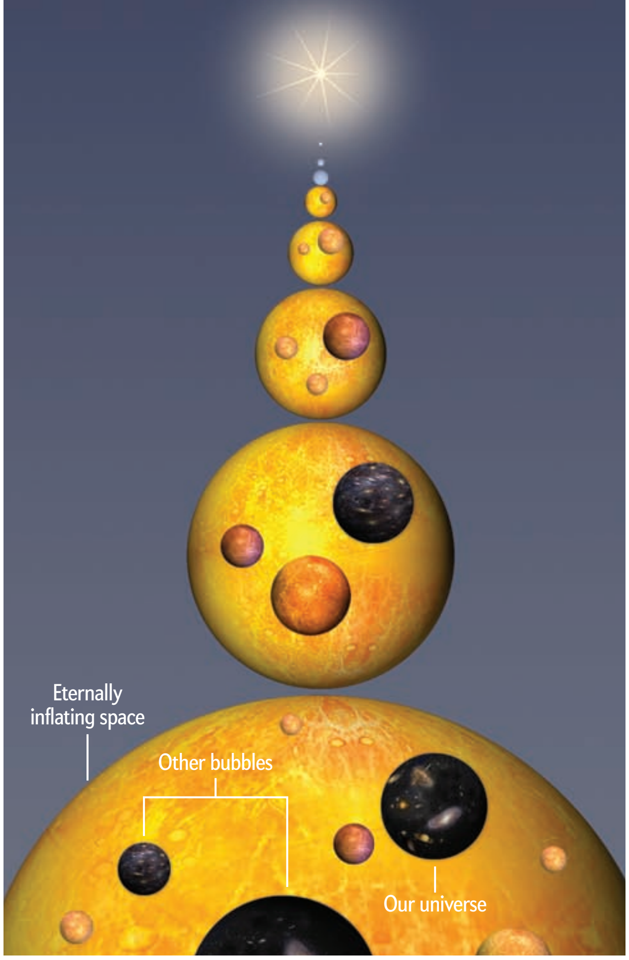
THEORISTS ARE NOT UNAWARE of the problem, but they have faith that they can resolve it and restore the naive inflationary picture of the early 1980s that attracted them to the theory in the first place. Many remain hopeful even though they have been wrestling with this issue for the past 25 years and have yet to come up with a plausible solution.

Some suggest trying to construct theories of inflation that are not eternal, to nip the infinity of universes in the bud. But eternality is a natural consequence of inflation plus quantum physics. To avoid it, the universe would have to start off in a very special initial state and with a special form of inflationary energy, so that inflation ended everywhere in space before quantum fluctuations had a chance to reignite it. In this scenario, though, the observed outcome depends sensitively on what the initial state is. That defeats the entire purpose of inflation: to explain the outcome no matter what conditions existed beforehand.

PROBLEM #3: ETERNAL INFLATION

The Abyss of Infinity

Inflation is known for making precise predictions that have been confirmed by observations. But does it really? Once inflation starts, quantum jittering keeps it going in the bulk of space. Where it does end, a bubble nucleates and grows. We live in such a bubble, but it is atypical; most are younger. In fact, an infinite number of bubbles form with an infinite variety of properties. Everything that can happen does happen in some bubble. A theory that predicts everything predicts nothing.



An alternative strategy supposes that islands like our observable universe are the most likely outcome of inflation. Proponents of this approach impose a so-called measure, a specific rule for weighting which kinds of islands are most likely—analogous to declaring that we must take three quarters for every five pennies when drawing coins from our sack. The notion of a measure, an ad hoc addition, is an open admission that inflationary theory on its own does not explain or predict anything.

Worse, theorists have come up with many equally reasonable measures that lead to different conclusions. An example is the volume measure, which says that islands should be weighted by their size. At first glance, this choice makes common sense. The intuitive idea underlying inflation is that it explains the uniformity and flatness we observe by creating large volumes of space with those properties. Unfortunately, the volume measure fails. The reason is that it favors procrastination. Consider two kinds of regions: islands like ours and others that formed later, after more inflation. By the power of exponential growth, the latter regions will occupy vastly more total volume. Hence, regions younger than ours are vastly more common. By this measure, it is unlikely we would even exist.

Measure enthusiasts take a trial-and-error approach in which they invent and test measures until, they hope, one produces the desired answer: that our universe is highly probable. Suppose they succeed someday. Then they will need another principle to justify using that measure instead of the others, yet another principle to choose that principle, and so on.

Still another alternative approach is to invoke the anthropic principle. Whereas the measure concept holds that we live in a typical island, the anthropic principle assumes we live in a very atypical island with just the minimal conditions needed to support life. The claim is that the conditions in more typical islands are incompatible with galaxies or stars or some other prerequisite for life as we know it. Even though the typical islands occupy more space than ones like ours, they can be ignored because we are interested only in regions that humans could potentially inhabit.

MORE ON
COSMIC INFLATION
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Unfortunately for this idea, the conditions in our universe are not minimal—the universe is flatter, smoother and more precisely scale-invariant than it had to be to support life. More typical islands, such as those younger than ours, are almost equally habitable yet much more numerous.

MAKING PROCRASTINATORS PAY

In light of these arguments, the oft-cited claim that cosmological data have verified the central predictions of inflationary theory is misleading, at best. What one can say is that data have confirmed predictions of the naive inflationary theory as we understood it before 1983, but this theory is not inflationary cosmology as understood today. The naive theory supposes that inflation leads to a predictable outcome governed by the laws of classical physics. The truth is that quantum physics rules inflation, and anything that can happen will happen. And if inflationary theory makes no firm predictions, what is its point?

The underlying problem is that procrastination carries no penalty—to the contrary, it is positively rewarded. Rogue regions that delay ending inflation continue to grow at an accelerating pace, so they invariably take over. In an ideal situation, any rogue regions would expand more slowly—or, better still, shrink. The overwhelming bulk of the universe would consist of well-behaved regions that end the smoothing phase on time, and our observed universe would be comfortably normal.

An alternative to inflationary cosmology that my colleagues and I have proposed, known as the cyclic theory, has just this property. According to this picture, the big bang is not the beginning of space and time [see "The Myth of the Beginning of Time," by Gabriele Veneziano; Scientific American, May 2004] but rather a "bounce" from a preceding phase of contraction to a new phase of expansion, accompanied by the creation of matter and radiation. The theory is cyclic because, after a trillion years, the expansion devolves into contraction and a new bounce to expansion again. The key point is that the smoothing of the universe occurs before the bang, during the period of contraction. Any procrastinating rogue regions continue to contract while well-behaved regions bounce on time and begin expanding, so the rogue regions remain comparatively small and negligible.

Smoothing during contraction has an observable consequence. During any smoothing phase, whether in inflationary theory or in the cyclic theory, quantum fluctuations generate small, propagating random distortions in spacetime, known as gravitational waves, that leave a distinctive imprint on the microwave background radiation. The amplitude of the waves is proportional to the energy density. Inflation would occur when the universe was extremely dense, whereas the equivalent process in the cyclic model would occur when the universe was practically empty, so the predicted imprints would be dramatically different. Of course, the cyclic theory is relatively new and may have its own problems, but it illustrates that there are conceivable alternatives that may not suffer the uncontrollable runaway of eternal inflation. Our preliminary work suggests the cyclic model avoids the other problems described earlier, too.

To be sure, I have presented the cases for and against inflation as two extremes without the opportunity for cross-examination or nuance. In a meeting held in January at the Princeton Center for Theoretical Science to discuss these issues, many leading theorists argued that the problems with inflation are mere teething pains and should not shake our confidence in the basic idea. Others (including me) contended that the problems cut to the core of the theory, and it needs a major fix or must be replaced.

In the end, the case will be decided by data. The forthcoming observations of the microwave background radiation will be telling. Experiments to search for a gravitational-wave imprint are already being conducted on mountaintops, in high-altitude balloons and onboard satellites, and results should emerge within the next two to three years. Detecting a gravitational-wave imprint would support inflation; failure to detect it would be a major setback. For inflation to make sense despite a null result, cosmologists would need to suppose that the inflaton field had a very peculiar potential with just the right shape to suppress gravitational waves, which seems contrived. Many researchers would gravitate to alternatives, like the cyclic universe theory, that naturally predict an unobservably small gravitational-wave signal. The outcome will be a critical moment in our quest to determine how the universe came to be the way it is and what will happen to it in the future.

MORE TO EXPLORE

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