COSMOLOGY

POP goes the universe

THE LATEST ASTROPHYSICAL MEASUREMENTS, COMBINED WITH THEORETICAL PROBLEMS, CAST DOUBT ON THE LONG-CHERISHED INFLATIONARY THEORY OF THE EARLY COSMOS AND SUGGEST WE NEED NEW IDEAS

By Anna Ijjas, Paul J. Steinhardt and Abraham Loeb

Photographs by The Voorhes

ON MARCH 21, 2013, the European Space Agency held an international press conference to announce new results from a satellite called Planck. The spacecraft had mapped the cosmic microwave background (CMB) radiation, light emitted more than 13 billion years ago just after the big bang, in better detail than ever before. The new map, scientists told the audience of journalists, confirms a theory that cosmologists have held dear for 35 years: that the universe began with a bang followed by a brief period of hyperaccelerated expansion known as inflation. This expansion smoothed the universe to such an extent that, billions of years later, it remains nearly uniform all over space and in every direction and "flat," as opposed to curved like a sphere, except for tiny variations in the concentration of matter that account for the finely detailed hierarchy of stars, galaxies and galaxy clusters around us.

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The principal message of the press conference was that the Planck data perfectly fit the predictions of the simplest inflationary models, reinforcing the impression that the theory is firmly established. The book on cosmology seemed to be closed, the team suggested.

Following the announcement, the three of us discussed its ramifications at the Harvard-Smithsonian Center for Astrophysics. Ijjas was then a visiting graduate student from Germany; Steinhardt, who had been one of the original architects of inflationary theory three decades ago but whose later work pointed out serious problems with its theoretical foundations, was spending his sabbatical at Harvard; and Loeb was our host as chair of the astronomy department. We all remarked on the meticulously precise observations of the Planck team. We disagreed, however, with the interpretation. If anything, the Planck data disfavored the simplest inflation models and exacerbated long-standing foundational problems with the theory, providing new reasons to consider competing ideas about the origin and evolution of the universe.

In the years since, more precise data gathered by the Planck satellite and other instruments have made the case only stronger. Yet even now the cosmology community has not taken a cold, honest look at the big bang inflationary theory or paid significant attention to critics who question whether inflation happened. Rather cosmologists appear to accept at face value the proponents' assertion that we must believe the inflationary theory because it offers the only simple explanation of the observed features of the universe. But, as we will explain, the Planck data, added to theoretical problems, have shaken the foundations of this assertion.

FOLLOWING THE ORACLE

TO DEMONSTRATE inflation's problems, we will start by following the edict of its proponents: assume inflation to be true without question. Let us imagine that a professed oracle informed us that inflation definitely occurred shortly after the big bang. If we were to accept the oracle's claim as fact, what precisely would it tell us about the evolution of the universe? If inflation truly offered a simple explanation of the universe, you would expect the oracle's declaration to tell us a lot about what to expect in the Planck satellite data.

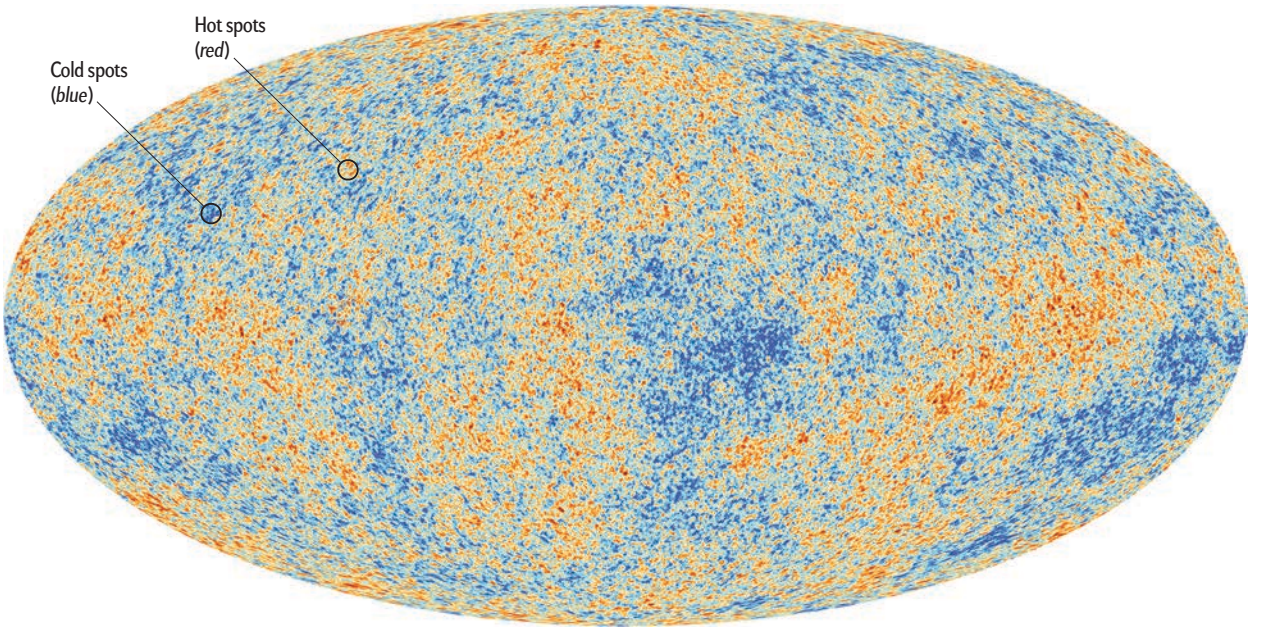
One thing it would tell us is that at some time shortly after the big bang there had to have been a tiny patch of space filled with an exotic form of energy that triggered a period of rapidly accelerated expansion ("inflation") of the patch. Most familiar forms of energy, such as that contained in matter and radiation, resist and slow the expansion of the universe because of gravitational self-attraction. Inflation requires that the universe be filled with a high density of energy that gravitationally self-repels, thereby enhancing the expansion and causing it to speed up. It is important to note, however, that this critical ingredient,

IN BRIEF

The latest measurements of the cosmic microwave background (CMB), the universe's oldest light, raise concerns about the inflationary theory of the cosmos—the idea that space expanded exponentially in the first moments of time. **Inflation typically produces** a different pattern of temperature variation in the CMB (although it can be made to predict almost any outcome). It would also generate primordial gravitational waves, which have not been found. **The data suggest** cosmologists should reassess this favored paradigm and consider new ideas about how the universe began.

Snapshot of the Infant Universe

This map from the Planck satellite launched by the European Space Agency shows the cosmic microwave background (CMB)—the oldest observable light in the universe—which offers the best picture yet of the infant cosmos. Blue areas of the sky represent spots where the temperature of the CMB, and thus, the early universe, was cooler, and red regions reflect warmer locales. Proponents of inflation, a theory suggesting the cosmos expanded rapidly in its first moments, claim that the pattern of hot and cold spots here is consistent with this notion. Yet the theory can actually produce any pattern and typically generates a larger variation in temperature than this map shows. Furthermore, if inflation took place the CMB should contain evidence of cosmic gravitational waves—ripples in spacetime caused by the early stretching—yet it does not. Instead, the Planck data reveal that the real story of our universe's history is still wide open.



COURTESY OF ESA AND THE PLANCK COLLABORATION

referred to as inflationary energy, is purely hypothetical; we have no direct evidence that it exists. Furthermore, there are literally hundreds of proposals from the past 35 years for what the inflationary energy may be, each generating very different rates of inflation and very different overall amounts of stretching. Thus, it is clear that inflation is not a precise theory but a highly flexible framework that encompasses many possibilities.

But what could the oracle's assertion tell us that is true for all the models, independent of the specific type of inflationary energy? For one thing, we could be sure from our basic knowledge of quantum physics that the temperature and density of matter throughout the universe after inflation ends must vary somewhat from place to place. Random quantum fluctuations in the concentration of inflationary energy on subatomic scales would be stretched during inflation into cosmic-sized regions with differing amounts of inflationary energy. According to the theory, the accelerated expansion ends when the inflationary energy decays into ordinary matter and radiation. In places where the inflationary energy density (the amount of inflationary energy in a cubic meter of space) is slightly greater, the accelerated expansion would last slightly longer, and the density and temperature of the universe would be slightly higher when the inflationary energy finally decays. The quantum-induced variations in inflationary energy would thereby be transcribed into a pattern of slightly hotter and colder spots in the cosmic microwave background light, which preserves a record of those times. Over the ensuing 13.7 billion years, the tiny density and temperature variations in the cosmos would condense under the influence of gravity to form a pattern of galaxies and large-scale structures.

That is a good start, though somewhat vague. Could we predict the numbers and arrangements of galaxies throughout space? The degree to which space is curved and warped? The amount of matter, or other forms of energy, that makes up the current universe? The answer is no. Inflation is such a flexible idea that any outcome is possible. Does inflation tell us why the big bang happened or how the initial patch of space was created that eventually evolved into the universe observed today? The answer, again, is no.

If we knew inflation to be true, we would also not be able to predict much about the hotspots and cold spots observed by the Planck satellite. The Planck map and earlier studies of the CMB indicate that the pattern of hot and cold spots is nearly the same no matter how close in you zoom, a property that scientists call "scale invariance." The latest Planck data show that the deviation from perfect scale invariance is tiny, only a few percent, and that the average temperature variation across all spots is rough-

ly 0.01 percent. Proponents of inflation often emphasize that it is possible to produce a pattern with these properties. Yet such statements leave out a key point: *inflation allows many other patterns of hot and cold spots that are not nearly scale-invariant and that typically have a temperature variation much greater than the observed value.* In other words, scale invariance is possible, but so is a large deviation from scale invariance and everything in between, depending on the details of the inflationary energy density one assumes. Thus, the arrangement Planck saw cannot be taken as confirmation of inflation.

Notably, if we knew inflation had occurred, there is one feature we could be fairly certain of finding in the Planck CMB observations because it is common to all the simplest forms of inflationary energy, including those presented in standard textbooks. At the same time that quantum fluctuations produce random variations in inflationary energy, they also produce random warps in space that propagate as waves of spatial distortion across the universe once inflation ends. These disturbances, known as gravitational waves, are another source of hotspots and cold spots in the cosmic microwave background radiation, albeit ones that have a distinctive polarizing effect (that is, the gravitational waves cause light to have a certain preferred orientation for its electric field depending on whether the light comes from a hot or cold spot, or some place in between).

Unfortunately, the search for inflationary gravitational waves has not panned out. Although cosmologists first observed hotspots and cold spots with the COBE (COsmic Background Explorer) satellite in 1992 and with many subsequent experiments, including even more recent Planck satellite results from 2015, they have not found any signs of the cosmic gravitational waves expected from inflation, as of this writing, despite painstaking searches for them. (On March 17, 2014, scientists at the BICEP2 experiment at the South Pole announced the detection of cosmic gravitational waves but later retracted their claim when they realized they had actually observed a polarization effect caused by dust grains within the Milky Way.) Note that these expected cosmic gravitational waves have nothing to do with the gravitational waves created by merging black holes in the modern universe found by the Laser Interferometer Gravitational wave Observatory (LIGO) in 2015.

The Planck satellite results—a combination of an unexpectedly small (few percent) deviation from perfect scale invariance in the pattern of hot and colds spots in the CMB and the failure to detect cosmic gravitational waves—are stunning. For the first time in more than 30 years, the simplest inflationary models, including those described in standard textbooks, are strongly disfavored by observations. Of course, theorists rapidly rushed to patch the inflationary picture but at the cost of making arcane models of inflationary energy and revealing yet further problems.

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A SKIER ON A HILL

TO FULLY APPRECIATE the impact of the Planck measurements, it helps to take a close look at the inflationary models that proponents of inflation are putting forward, warts and all.

Inflationary energy is thought to arise from a hypothetical field, called the inflaton, analogous to an electric field, that permeates space and has a strength (or value) at every point in space. Since the inflaton is hypothetical, theorists are free to imagine that the inflaton is gravitationally self-repulsive to cause the expansion of the universe to accelerate. The strength of the inflaton field at a given point in space determines the inflationary energy density there. The relation between the strength of the field and the energy density can be represented by a curve on a graph that looks like a hill [*see box on page 00*]. Each of the hundreds of inflationary energy models that have been proposed has a precise shape for this hill that determines the properties of the universe after inflation is over—for instance, whether or not the universe is flat and smooth and has nearly scale-invariant temperature and density variations.

After the release of the Planck data, cosmologists find themselves in a situation much like the following scenario: Imagine you live in an isolated town set in a valley bounded by hills. The only people that you have ever seen in the town are residents, until one day a stranger appears. Everyone wants to know how the stranger got to your town. You consult the town gossip (aka the local oracle), who claims to know that the stranger got here by skiing. Believing the gossip, you consider that there are only two hills that lead to your valley. Anyone reading the guidebook would know the first hill, which can be easily accessed using a ski lift. All pistes there have a steady decrease; the visibility and snow conditions are generally good. The second hill is completely different. It is not included in any standard skiing guidebook. No wonder! Its top is known for avalanches. The one path down to your town is challenging because it begins on a flat ridge that suddenly ends at a steep cliff. Furthermore, there is no ski lift. The only conceivable way of starting to ski down this hill is first to jump from a plane and, using a parachute, land at a particular place on the ridge (with inches of precision) and hit with just the right velocity; the slightest mistake would lead the skier off-track toward a distant valley or trap the skier on top of the hill; in the worst case, an avalanche might begin before the skier reaches

the ridge so that the person would not survive. If the town gossip is right that the stranger arrived by skiing, it is only reasonable to conclude that she came down the first hill.

It would be crazy to imagine anyone taking the second path because the chances of successfully reaching the town are infinitesimal compared with the path down the other hill. But then you notice something about the stranger. She has no ticket for the ski lift attached to her jacket. Based on this observation and the town gossip's continued insistence that the stranger arrived on skis, you are forced to the weird conclusion that the stranger must have taken the second mountain. Or perhaps she did not ski in at all, and you need to question the reliability of the town gossip.

Analogously, if a professed oracle informed us that the universe evolved to its present condition via inflation, we would expect an inflationary energy density curve like the hill described in the guidebooks because it has a simple shape from top to bottom, the fewest adjustable parameters and the least delicate conditions necessary for starting inflation. Indeed, up until now, the textbooks on inflationary cosmology have almost all presented energy curves of this simple, uniform shape. In particular, the energy density along these simple curves steadily increases as the field strength changes so that it is possible to have an initial value of the inflaton field for which the inflationary energy density is equal to a number called the Planck density (10^{120} times greater than the density today), the total energy density available when the universe first emerged from the big bang. With this advantageous starting condition in which the only form of energy is inflationary, accelerated expansion would begin immediately. During inflation, the strength of the inflaton field would naturally evolve so that the energy density slowly and smoothly decreases following the curve down to the valley where the curve bottoms out, corresponding to the universe we inhabit today. (We can think of this progression as the inflaton field "skiing" down the curve.) This is the classic story of inflation presented in textbooks.

But the Planck observations tell us this story cannot be right. The simple inflationary curves produce hot and cold spots with a larger deviation from scale invariance than observed and gravitational waves strong enough to have been detected. If we continue to insist that inflation happened, the Planck results require that the inflaton field "skied" down a more complicated energy density curve shaped like the second hill, the one with high avalanche risk and a low, flat ridge ending with a steep cliff down to a valley. Instead of a simple, ever rising shape, such an energy curve would rise sharply (forming a cliff) away from its minimum until it suddenly flattens out along a plateau (forming a ridge) at an energy density that is a trillion times less than the Planck density available immediately after the big bang. In that case, the inflationary energy density would comprise an infinitesimal fraction of the total energy density after the big bang, far too small to cause the universe to inflate right away.

TWO VERSIONS OF A THEORY

Inflation as a Ski Slope

If inflation took place, it must have been triggered by a hypothetical "inflationary energy," caused by a field called "the inflaton" that would have permeated space. Different versions of inflation theory propose different relationships between the strength of the inflaton field and the density of inflationary energy. Two of those relationships are plotted here. One (*blue at left*) is akin to the traditional textbook models of inflation; the other (*pink at right*) requires very special starting conditions and thus seems implausible. Analogy with two ski hills offers an idea of why the second class of models—the kind of inflation that has not been ruled out by recent data—is hard to swallow.

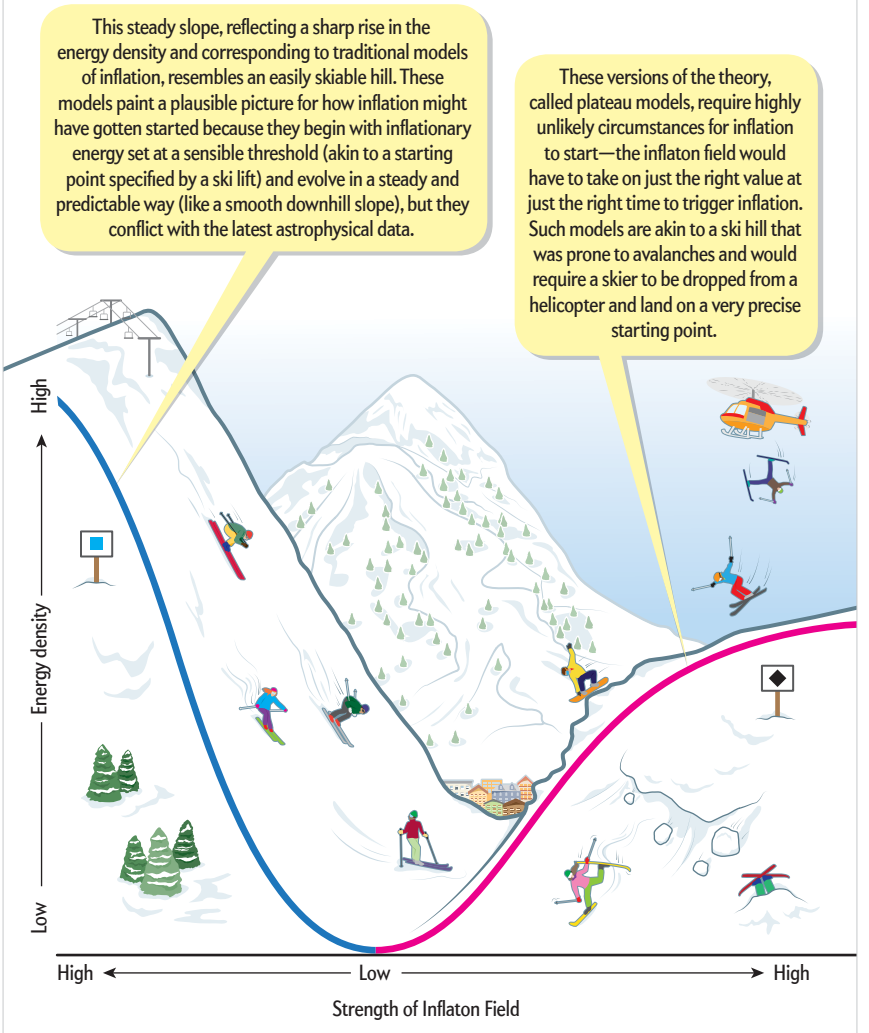

Illustration by Brown Bird Design

Because the universe is not inflating, the inflaton field is free to begin with any initial value and change at breakneck speed, like the skier jumping from the helicopter. Yet inflation can only start if the inflaton field eventually reaches a value corresponding to a point along the plateau and if the inflaton field changes very slowly. Just as it is treacherous for the skier dropped from high altitudes to land on the flat ridge at the right velocity to ski smoothly down, so it is nearly impossible for the inflaton field to reduce its speed at just the right rate and at the right value of the field to begin inflation. To make matters worse, because the universe is not inflating during this period after the big bang when the inflaton speed is slowing, any initial warps or unevenness in the distribution of energy throughout the universe would increase; when they grow large, they prevent inflation from starting no matter how the inflaton evolves, just as an avalanche can block the skier from a smooth downhill ski no matter how perfect the trajectory from the helicopter to the ridge.

In other words, by accepting the oracle's word and insisting that inflation occurred, you would be forced by the Planck data to the weird conclusion that inflation started with a plateaulike energy density curve despite all its problems. Or maybe at this point you would question the oracle's credibility.

THE "MULTIMESS"

THERE IS, OF COURSE, NO ORACLE. We should not just accept the assumption that inflation happened, especially because it does not offer a simple explanation of the observed features of the universe. Cosmologists should evaluate the theory by adopting the standard scientific procedure of estimating the odds that inflation occurred given what we observe about the universe. In this respect, it is undoubtedly bad news that current data rule out the simplest inflationary models and favor more contrived ones. But truth be told, the latest observations are not the first problem encountered by inflation theory; rather these results have sharpened and added a new twist to established issues.

For example, we should consider whether it is reasonable for the universe to have had the initial conditions necessary for *any* kind of inflationary energy whatsoever. Two improbable criteria have to be satisfied for inflation to start. First, shortly after the big bang, there has to be a patch of space where the quantum fluctuations of spacetime have died down and the space is well described by Einstein's classical equations of general relativity; second, the patch of space must be flat enough and have a smooth enough distribution of energy that the inflationary energy can grow to dominate all other forms of energy. Several theoretical estimates of the probability of finding a patch with these characteristics just after the big bang suggest that it is more difficult than finding a snowy mountain equipped with a ski lift and well-maintained ski slopes in the middle of a desert.

More important, if it were easy to find a patch emerging from the big bang that is flat and smooth enough to start inflation, then inflation would not be needed in the first place. Recall that the entire motivation for introducing it was to explain how the visible universe came to have these properties; if starting inflation requires those same properties, with the only difference being that a smaller patch of space is needed, that is hardly progress.

Such issues are just the beginning of our problems, however. Not only does inflation require starting conditions that are difficult to obtain, it also impossible to stop inflation once it gets going. This snag traces back to the quantum fluctuations in spacetime. They cause the strength of the inflaton field to vary from place to place, resulting in some spots in space ending inflation earlier than others. We tend to think of quantum fluctuations as tiny, but as early as 1983, theorists, including Steinhardt, came to realize that large quantum jumps in the inflaton field, though rare, could totally change the inflationary story. Large jumps can increase the strength of the inflaton field to values much higher than average, causing inflation to last much longer. Although large jumps are rare, the regions that undergo them expand enormously in volume compared with regions that do not undergo them and quickly dominate space. Within instants, an area that stops inflating becomes surrounded and

dwarfed by regions still inflating. The process then repeats. In most of the swelled region, the inflaton field strength will change in a way that causes the energy density to decrease and inflation to end, but rare large quantum jumps will keep inflation going in some places and create even more inflating volume. And so the process continues, ad infinitum.

In this way, inflation continues eternally, generating an infinite number of patches where inflation has ended, each creating a universe unto itself. Only in these patches where inflation has stopped is the expansion rate of space slow enough to form galaxies, stars, planets and life. The worrisome implication is that the cosmological properties of each patch differ because of the inherent randomizing effect of quantum fluctuations. In general, most universes will not turn out warp-free or flat; the distribution of matter will not be nearly smooth; and the pattern of hot and cold spots in the CMB light there will not be nearly scale-invariant. The patches span an infinite number of different possible outcomes, with no kind of patch, including

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one like our visible universe, being more probable than another. The result is what cosmologists call the multiverse. Because every patch can have any physically conceivable properties, the multiverse does not explain why our universe has the very special conditions that we observe—they are purely accidental features of our particular patch.

And perhaps even this picture is too rosy. Some scientists dispute whether any patches of space evolve into regions like our observable universe. Instead eternal inflation may devolve into a purely quantum world of uncertain and random fluctuations everywhere, even where inflation ends. We would like to suggest "multimess" as a more apt term to describe the unresolved outcome of eternal inflation, whether it consists of an infinite multitude of patches with randomly distributed properties or a quantum mess. From our perspective, it makes no difference which description is correct. Either way, the multimess does not predict the properties of our observable universe to be the likely outcome. A good scientific theory is supposed to explain why what we observe happens instead of something else. The multimess fails this fundamental test.

PARADIGM SHIFT

GIVEN ALL THESE PROBLEMS, the prospect that inflation did not occur deserves serious consideration. If we step back, there seem to be two logical possibilities. Either the universe had a beginning, which we commonly dub the "big bang," or there was no beginning and what has been called the big bang was actually a "big bounce," a transition from some preceding cosmological phase to the present expanding phase. Although most cosmologists assume a bang, there is currently no evidence—zero—to say whether the event that occurred 13.7 billion years ago was a bang or a bounce. Yet a bounce, as opposed to a bang, does not require a subsequent period of inflation to create a universe like the one we find, so bounce theories represent a dramatic shift away from the inflation paradigm.

A bounce can achieve the same end as a bang plus inflation because before the bounce, a span of slow contraction extending for billions of years can smooth and flatten the universe. It may seem counterintuitive that slow contraction has the same effect as rapid expansion, but there is a simple argument that shows it must be so. Recall that without inflation, a slowly expanding universe would become increasingly curved, warped and nonuniform with time from the effects of gravity on space and matter. Imagine watching a film of this process run backward: a large, highly curved, warped and nonuniform universe gradually contracts and becomes flat and uniform. That is, gravity works in reverse as a smoothing agent in a slowly contracting universe.

As in the case of inflation, quantum physics amends the simple smoothing story in bounce theories as well. Quantum fluctuations change the rate of contraction from place to place so that some regions bounce and begin to expand and cool before others. Scientists can construct models in which the rate of contraction gives rise to temperature variations after the bounce that are consistent with the pattern of hot and cold spots observed by the Planck satellite. In other words, contraction before a bounce can do what inflation was supposed to do when it was first invented.

At the same time, bouncing theories have an important advantage compared with inflation: they do not produce a multimess. When the contracting phase begins, the universe is already large and classical (that is, described by Einstein's general theory of relativity), and it bounces before it shrinks to a size where quantum effects become important. As a result, there is never a stage, like the big bang, when the entire universe is dominated by quantum physics, and there is no need to invent a quantum-to-classical transition. And because there is no inflation during the smoothing to cause regions that undergo rare, large quantum fluctuations to blow up in volume, smoothing via contraction does not produce multiple universes. Recent work has produced the first detailed proposals for describing how the universe could have transitioned from contraction to expansion, enabling the construction of complete bouncing cosmologies.

NONEMPIRICAL SCIENCE?

GIVEN THE ISSUES with inflation and the possibilities of bouncing cosmologies, one would expect a lively debate among scientists today focused on how to distinguish between these theories through observations. Still, there is a hitch: inflationary cosmology, as we currently understand it, cannot be evaluated using the scientific method. As we have discussed, the expected outcome of inflation can easily change if we vary the initial conditions, change the shape of the inflationary energy density curve, or simply note that it leads to eternal inflation and a multimess. Individually and collectively, these features make inflation so flexible that no experiment can ever disprove it.

Some scientists accept that inflation is untestable but refuse to abandon it. They have proposed that, instead, science must change by discarding one of its defining properties: empirical testability. This notion has triggered a roller coaster of discussions about the nature of science and its possible redefinition, promoting the idea of some kind of nonempirical science.

A common misconception is that experiments can be used to *falsify* a theory. In practice, a failing theory gets increasingly immunized against experiment by attempts to patch it. The theory becomes more highly tuned and arcane to fit new observations until it reaches a state where its explanatory power diminishes to the point that it is no longer pursued. The explanatory power of a theory is measured by the set of possibilities it excludes. More immunization means less exclusion and less power. A theory like the multimess does not exclude anything and, hence, has zero power. Declaring an empty theory as the unquestioned standard view requires some sort of assurance outside of science. Short of a professed oracle, the only alternative is to invoke authorities. History teaches us that this is the wrong road to take.

Today we are fortunate to have sharp, fundamental questions imposed on us by observations. The fact that our leading ideas have not worked out is a historic opportunity for a theoretical breakthrough. Instead of closing the book on the early universe, we should recognize that cosmology is wide open. SA

MORE TO EXPLORE

Inflationary Paradigm in Trouble after Planck 2013. Anna Ijjas et al. in *Physics Letters B*, Vol. 723, Nos. 4–5, pages 261–266; June 25, 2013.

FROM OUR ARCHIVES

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