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Title
Letters

Permalink
https://escholarship.org/uc/item/03w4z3nm

Journal
Scientific American, 317(1)

ISSN
0036-8733

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Publication Date
2017-06-20

DOI
10.1038/scientificamerican0717-5

Peer reviewed

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February 2017

A COSMIC CONTROVERSY

The origins of space and time are among the most mysterious and contentious topics in science. Our February 2017 article "Pop Goes the Universe" argues against the dominant idea that the early cosmos underwent an extremely rapid expansion called inflation. Its authors instead advocate for another scenario—that our universe began not with a bang but with a bounce from a previously contracting cosmos. In the letter below, a group of 33 physicists who study inflationary cosmology respond to that article. It is followed by a reply from the authors.

In "Pop Goes the Universe," by Anna Ijjas, Paul J. Steinhardt and Abraham Loeb, the authors (hereafter "IS&L") make the case for a bouncing cosmology, as was proposed by Steinhardt and others in 2001. They close by making the extraordinary claim that inflationary cosmology "cannot be evaluated using the scientific method" and go on to assert that some scientists who accept inflation have proposed "discarding one of [science's] defining properties: empirical testability," thereby "promoting the idea of some kind of nonempirical science." We have no idea what scientists they are referring to. We disagree with a number of statements in their article, but in this letter, we will focus on our categorical disagreement with these statements about the testability of inflation.

There is no disputing the fact that inflation has become the dominant paradigm in cosmology. Many scientists from around the world have been hard at work for years investigating models of cosmic inflation and comparing these predictions with empirical observations. According to the high-energy physics database INSPIRE, there are now more than 14,000 papers in the scientific literature, written by over 9,000 distinct scientists, that use the word "inflation" or "inflationary" in their titles or abstracts. By claiming that inflationary cosmology lies outside the scientific method, IS&L are dismissing the research of not only all the authors of this letter but also that of a substantial contingent of the scientific community. Moreover, as the work of several major international collaborations has made clear, inflation is not only testable, but it has been subjected to a significant number of tests and so far has passed every one.

Inflation is not a unique theory but rather a class of models based on similar principles. Of course, nobody believes that all these models are correct, so the relevant question is whether there exists at least one model of inflation that seems well motivated, in terms of the underlying particle physics assumptions, and that correctly describes the measurable properties of our universe. This is very similar to the early steps in the development of the Standard Model of particle physics, when a variety of quantum field theory models were explored in search of one that fit all the experiments.

Although there is in principle a wide space of inflationary models to examine, there is a very simple class of inflationary models (technically, "single-field slow-roll" models) that all give very similar predictions for most observable quantities—predictions that were clearly enunciated decades ago. These "standard" inflationary models form a well-defined class that has been studied extensively. (IS&L have expressed strong opinions about what they consider to be the simplest models within this class, but simplicity is subjective, and we see no reason to restrict attention to such a narrow subclass.) Some of the standard inflationary models have now been ruled out by precise empirical data, and this is part of the desirable process of using observation to thin out the set of viable models. But many models in this class continue to be very successful empirically.

The standard inflationary models predict that the universe should have a critical mass density (that is, it should be geometrically flat), and they also predict the statistical properties of the faint ripples that we detect in the cosmic microwave background (CMB). First, the ripples should be nearly "scale-invariant," meaning that they have nearly the same intensity at all angular scales. Second, the ripples should be "adiabatic," meaning that the perturbations are the same in all components: the ordinary matter, radiation and dark matter all fluctuate together. Third, they should be "Gaussian," which is a statement about the statistical patterns of relatively bright and dark regions. Fourth and finally, the models also make predictions for the patterns of polarization in the CMB, which can be divided into two classes, called E-modes and B-modes. The predictions for the E-modes are very similar for all standard inflationary models, whereas the levels of B-modes, which are a measure of gravitational radiation in the early universe, vary significantly within the class of standard models.

The remarkable fact is that, starting with the results of the Cosmic Background Explorer (COBE) satellite in 1992, numerous experiments have confirmed that these predictions (along with several others too technical to discuss here) accurately describe our universe. The average mass density of the universe has now been measured

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to an accuracy of about half of a percent, and it agrees perfectly with the prediction of inflation. (When inflation was first proposed, the average mass density was uncertain by at least a factor of three, so this is an impressive success.) The ripples of the CMB have been measured carefully by two more satellite experiments, the Wilkinson Microwave Anisotropy Probe (WMAP) and the Planck satellite, as well as many ground- and balloon-based experiments—all confirming that the primordial fluctuations are indeed nearly scale-invariant and very accurately adiabatic and Gaussian, precisely as predicted (ahead of time) by standard models of inflation. The B-modes of polarization have not yet been seen, which is consistent with many, though not all, of the standard models, and the E-modes are found to agree with the predictions. In 2016 the Planck satellite team (a collaboration of about 260 authors) summarized its conclusions by saying that "the *Planck* results offer powerful evidence in favour of simple inflationary models." So if inflation is untestable, as IS&L would have us believe, why have there been so many tests of it and with such remarkable success?

While the successes of inflationary models are unmistakable, IS&L nonetheless make the claim that inflation is untestable. (We are bewildered by IS&L's assertion that the dramatic observational successes of inflation should be discounted while they accuse the advocates of inflation of abandoning empirical science!) They contend, for example, that inflation is untestable because its predictions can be changed by varying the shape of the inflationary energy density curve or the initial conditions. But the testability of a theory in no way requires that all its predictions be independent of the choice of parameters. If such parameter independence were required, then we would also have to question the status of the Standard Model, with its empirically determined particle content and 19 or more empirically determined parameters.

An important point is that standard inflationary models *could have failed any of the empirical tests described above, but they did not.* IS&L write about how "a failing theory gets increasingly immunized against experiment by attempts to patch it," insinuating that this has something to do with inflation. But despite IS&L's rhetoric, it is standard practice in empirical science to modify a theory as new data come to light, as, for example, the Standard Model has been modified to account for newly discovered quarks and leptons. For inflationary cosmology, meanwhile, there has so far been no need to go beyond the class of standard inflationary models.

IS&L also assert that inflation is untestable because it leads to eternal inflation and a multiverse. Yet although the possibility of a multiverse is an active area of study, this possibility in no way interferes with the empirical testability of inflation. If the multiverse picture is valid, then the Standard Model would be properly understood as a description of the physics in our visible universe, and similarly the models of inflation that are being refined by current observations would describe the ways inflation can happen in our particular part of the universe. Both theories would remain squarely within the domain of empirical science. Scientists would still be able to compare newly obtained data—from astrophysical observations and particle physics experiments—with precise, quantitative predictions of specific inflationary and particle physics models. Note that this issue is separate from the loftier goal of developing a theoretical framework that can predict, without the use of observational data, the specific models of particle physics and inflation that should be expected to describe our visible universe.

Like any scientific theory, inflation need not address *all* conceivable questions. Inflationary models, like all scientific theories, rest on a set of assumptions, and to understand those assumptions we might need to appeal to some deeper theory. This, however, does not undermine the success of inflationary models. The situation is similar to the standard hot big bang cosmology: the fact that it left several questions unresolved, such as the near-critical mass density and the origin of structure (which are solved elegantly by inflation), does not undermine its many successful predictions, including its prediction of the relative abundances of light chemical elements. The fact that our knowledge of the universe is still incomplete is absolutely no reason to ignore the impressive *empirical* success of the standard inflationary models.

During the more than 35 years of its existence, inflationary theory has gradually become the main cosmological paradigm describing the early stages of the evolution of the universe and the formation of its large-scale structure. No one claims that inflation has become certain; scientific theories don't get proved the way mathematical theorems do, but as time passes, the successful ones become better and better established by improved experimental tests and theoretical advances. This has happened with inflation. Progress continues, supported by the enthusiastic efforts of many scientists who have chosen to participate in this vibrant branch of cosmology.

Empirical science is alive and well!

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THE AUTHORS REPLY: We have great respect for the scientists who signed the rebuttal to our article, but we are disappointed by their response, which misses our key point: the differences between the inflationary theory once thought to be possible and the theory as understood today. The claim that inflation has been confirmed refers to the outdated theory before we understood its fundamental problems. We firmly believe that in a healthy scientific community, respectful disagreement is possible and hence reject the suggestion that by pointing out problems, we are discarding the work of all of those who developed the theory of inflation and enabled precise measurements of the universe.

Historically, the thinking about inflation was based on a series of misunderstandings. It was not understood that the outcome of inflation is highly sensitive to initial conditions. And it was not understood that inflation generically leads to eternal inflation and, consequently, a multiverse—an infinite diversity of outcomes. Papers claiming that inflation predicts this or that ignore these problems.

Our point is that we should be talking about the contemporary version of inflation, warts and all, not some defunct relic. Logically, if the outcome of inflation is highly sensitive to initial conditions that are not yet understood, as the respondents concede, the outcome cannot be determined. And if inflation produces a multiverse in which, to quote a previous statement from one of the responding authors (Guth), "anything that can happen will happen"—it makes no sense whatsoever to talk about predictions. Unlike the Standard Model, even after fixing all the parameters, any inflationary model gives an infinite diversity of outcomes with none preferred over any other. This makes inflation immune from any observational test. For more details, see our 2014 paper "Inflationary Schism" (preprint available at https://arxiv.org/abs/1402.6980).

We are three independent thinkers representing different generations of scientists. Our article was not intended to revisit old debates but to discuss the implications of recent observations and to point out unresolved issues that present opportunities for a new generation of young cosmologists to make a lasting impact. We hope readers will go back and review our article's concluding paragraphs. We advocated against invoking authority and for open recognition of the shortcomings of current concepts, a reinvigorated effort to resolve these problems and an open-minded exploration of diverse ideas that avoid them altogether. We stand by these principles.

March 2017

GENE JOB

"Should Babies Be Sequenced?" by Bonnie Rochman, discusses how we can now sequence newborns' genomes to screen for genetic risks not included in standard tests and the potential issues with doing so.

Widespread DNA sequencing is incompatible with the U.S.'s largely employer-provided health care system. If a hiring manager compares two otherwise equal candidates, one of whom has a genetic predisposition that doubles the chance of developing a rare disease, that candidate probably won't get the job.

John Schmitt *via e-mail*

TURING PLANS

In discussing the flaws of the Turing test, in which a machine tries to convince an interrogator it is human, in "Am I Human?" Gary Marcus notes that "one can 'win' simply by being deceptive or feigning ignorance." By applying that insight to the Washington Beltway, we may well find that the U.S. is governed by robots. And we humans may indeed get "tired of winning."

John Leydon *Aldie, Va.*

I applaud the effort to devise more rigorous tests of human-level artificial intelligence, as described by Marcus and by John Pavlus in "The New Turing Tests." But what if someone creates a machine that truly passes the old Turing test, not through trickery but genuine intelligence? Will we say to it, "Sorry, because you cannot summarize a video (as in the I-Athlon test) or build a house out of blocks (as in the Physically Embodied Turing Test), we cannot recognize your intelligence?" Could Helen Keller summarize a video? Can Stephen Hawking build a house out of blocks?

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