

Nonempirical Science!??

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 claim 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 work 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 of 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 (i.e., 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, while the level of B-modes, which are a measure of gravitational radiation in the early universe, varies 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 to an accuracy of about half of a percent, and 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, WMAP (Wilkinson Microwave Anisotropy Probe) and the *Planck* satellite, as well as many ground-based 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 2015 the *Planck* satellite team (a collaboration of 259 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 at the same time 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 of Particle Physics, 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 didn’t*. 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. However, despite IS&L’s rhetoric, it is standard practice in empirical science to modify a theory as new data comes to light, as for example the Standard Model of Particle Physics 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. However, while 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 of Particle Physics 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 which 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 that for 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!

MORE TO EXPLORE

Inflationary Paradigm after Planck 2013. A. H. Guth, D. I. Kaiser and Y. Nomura, in *Physics Letters B*, Vol. 733, pages 112–119; June 2, 2014; <https://arxiv.org/abs/1312.7619>.

Inflationary Cosmology after Planck 2013. A. Linde, in *Proceedings, 100th Les Houches Summer School: Post-Planck Cosmology*, Les Houches, France, July 8 - August 2, 2013, Oxford University Press (2015), pages 231–316; <https://arxiv.org/abs/1402.0526>.

Signed by:

Alan H. Guth*

Victor F. Weisskopf Professor of Physics, Massachusetts Institute of Technology
http://web.mit.edu/physics/people/faculty/guth_alan.html

David I. Kaiser*

Germeshausen Professor of the History of Science and Professor of Physics,
Massachusetts Institute of Technology
http://web.mit.edu/physics/people/faculty/kaiser_david.html

Andrei D. Linde*

Harald Trap Friis Professor of Physics, Stanford University
<https://physics.stanford.edu/people/faculty/andrei-linde>

Yasunori Nomura*

Professor of Physics and Director, Berkeley Center for Theoretical Physics,
University of California, Berkeley
<http://physics.berkeley.edu/people/faculty/yasunori-nomura>

Charles L. Bennett

Bloomberg Distinguished Professor and Alumni Centennial Professor of Physics
and Astronomy, Johns Hopkins University
Principal Investigator, Wilkinson Microwave Anisotropy Probe (WMAP) mission
Deputy Principal Investigator and Science Working Group member, Cosmic
Background Explorer (COBE) mission
<http://physics-astronomy.jhu.edu/directory/charles-l-bennett/>

J. Richard Bond

University Professor, University of Toronto and Director, Canadian Institute for
Advanced Research Cosmology and Gravity Program, Canadian Institute for
Theoretical Astrophysics
Member of the Planck collaboration
<http://www.cita.utoronto.ca/~bond/>

François Bouchet

Director of Research, Institut d'Astrophysique de Paris, CNRS and Sorbonne
Universities
Deputy Principal Investigator, Planck satellite HFI (High Frequency Instrument)
Consortium and Member, Planck Science Team
<http://savoirs.ens.fr/conferencier.php?id=145>

Sean Carroll

Research Professor of Physics, California Institute of Technology
http://www.astro.caltech.edu/people/faculty/Sean_Carroll.html

George Efstathiou

Professor of Astrophysics and Director of the Kavli Institute for Cosmology,
University of Cambridge
Member, Planck Science Team
<http://www.ast.cam.ac.uk/~gpe/>

Stephen Hawking

Lucasian Professor of Mathematics (Emeritus) and Dennis Stanton Avery and Sally Tsui Wong-Avery Director of Research, Department of Applied Mathematics and Theoretical Physics, University of Cambridge
<http://www.damtp.cam.ac.uk/people/s.w.hawking/>

Renata Kallosh

Professor of Physics, Stanford University
<https://physics.stanford.edu/people/faculty/renata-kallosh>

Eiichiro Komatsu

Director of the Department of Physical Cosmology, Max-Planck-Institute für Astrophysik, Garching
Member, Wilkinson Microwave Anisotropy Probe (WMAP) collaboration
<http://wwwmpa.mpa-garching.mpg.de/~komatsu/>

Lawrence Krauss

Foundation Professor and Director, The Origins Project at Arizona State University
<http://krauss.faculty.asu.edu>

David H. Lyth

Professor of Physics (Emeritus), Lancaster University
<http://www.lancaster.ac.uk/physics/about-us/people/david-lyth>

Juan Maldacena

Carl P. Feinberg Professor of Physics, Institute for Advanced Study
<https://www.sns.ias.edu/malda>

John C. Mather

Senior Astrophysicist and Goddard Fellow, NASA Goddard Space Flight Center and recipient of the Nobel Prize in Physics (2006)
Principal Investigator, Cosmic Background Explorer (COBE) mission
<https://science.gsfc.nasa.gov/sed/bio/john.c.mather>

Hiranya Peiris

Professor of Astrophysics, University College London and Director, Oskar Klein Centre for Cosmoparticle Physics, Stockholm
Member, Wilkinson Microwave Anisotropy Probe (WMAP) collaboration and Planck collaboration
<http://zuserver2.star.ucl.ac.uk/~hiranya/>

Malcolm Perry

Professor of Theoretical Physics, University of Cambridge
<http://www.damtp.cam.ac.uk/people/m.j.perry/>

Lisa Randall

Frank B. Baird, Jr., Professor of Science, Department of Physics, Harvard University
<https://www.physics.harvard.edu/people/facpages/randall>

Martin Rees

Astronomer Royal of Great Britain, former President of the Royal Society of London, and Professor (Emeritus) of Cosmology and Astrophysics, University of Cambridge

<http://www.ast.cam.ac.uk/~mjr/>

Misao Sasaki

Director, Yukawa Institute for Theoretical Physics, Kyoto University

<http://www2.yukawa.kyoto-u.ac.jp/~misao.sasaki/>

Leonardo Senatore

Associate Professor of Physics, Stanford University

<https://physics.stanford.edu/people/faculty/leonardo-senatore>

Eva Silverstein

Professor of Physics, Stanford University

<https://physics.stanford.edu/people/faculty/eva-silverstein>

George F. Smoot III

Professor of Physics (Emeritus), Founding Director, Berkeley Center for Cosmological Physics, and recipient of the Nobel Prize in Physics (2006)
Principal Investigator, Cosmic Background Explorer (COBE) mission

<http://physics.berkeley.edu/people/faculty/george-smoot-iii>

Alexei Starobinsky

Principal Researcher, Landau Institute for Theoretical Physics, Moscow

<http://www.itp.ac.ru/en/persons/starobinsky-aleksei-aleksandrovich/>

Leonard Susskind

Felix Bloch Professor of Physics and Wells Family Director, Stanford Institute for Theoretical Physics, Stanford University

<https://physics.stanford.edu/people/faculty/leonard-susskind>

Michael S. Turner

Bruce V. Rauner Distinguished Service Professor, Department of Astronomy and Astrophysics and Department of Physics, University of Chicago

<https://astro.uchicago.edu/people/michael-s-turner.php>

Alexander Vilenkin

L. and J. Bernstein Professor of Evolutionary Science and Director, Institute of Cosmology, Tufts University

<http://cosmos2.phy.tufts.edu/vilenkin.html>

Steven Weinberg

Jack S. Josey-Welch Foundation Chair and Regental Professor and Director, Theory Research Group, Department of Physics, University of Texas at Austin, and recipient of the Nobel Prize in Physics (1979)

<https://web2.ph.utexas.edu/~weintech/weinberg.html>

Rainer Weiss

Professor of Physics (Emeritus), Massachusetts Institute of Technology
Chair, Science Working Group, Cosmic Background Explorer (COBE) mission
Co-Founder, Laser Interferometric Gravitational-wave Observatory (LIGO)

http://web.mit.edu/physics/people/faculty/weiss_rainer.html

Frank Wilczek

Herman Feshbach Professor of Physics, Massachusetts Institute of Technology,
and recipient of the Nobel Prize in Physics (2004)

http://web.mit.edu/physics/people/faculty/wilczek_frank.html

Edward Witten

Charles Simonyi Professor of Physics, Institute for Advanced Study and recipient
of the Fields Medal (1990)

<https://www.sns.ias.edu/witten>

Matias Zaldarriaga

Professor of Astrophysics, Institute for Advanced Study

<https://www.sns.ias.edu/matiasz>

* corresponding authors