Inflation handily explains how the universe expanded after the big bang. Is it all a bit too convenient? Maggie McKee investigates

Pop-up universe

IT WAS still dark and bitterly cold when Paul Steinhardt met Anna Ijjas at her office in Harvard on 21 March. They had risen before dawn to watch researchers in Paris announce the first major results from the European Space Agency’s Planck satellite, which has been mapping light from the universe’s infancy since 2009.

Other missions have studied this light, aka the cosmic microwave background. But cosmologists the world over were itching to find out what Planck had seen because its detectors are at least three times as sharp as those on any previous satellite. It therefore provides the best-ever portrait of the universe not long after the big bang.

Would Planck lend weight to our leading theory of a well-mannered universe that underwent a precocious growth spurt known as inflation? Or would it force us back to the drawing board to understand our cosmic past?

“The overall conclusion is that it is an extremely good match to the Planck data,” announced George Efstathiou at the Paris meeting. “If I were an inflationary theorist I’d be very happy.”

But after reading the Planck team’s paper, which went online shortly after the briefings, Ijjas reached the opposite conclusion. And soon she convinced Steinhardt and Avi Loeb, the head of Harvard University’s astronomy department, that the results were troubling.

“Planck has created some problems for inflation that weren’t there before,” says Steinhardt, a cosmologist at Princeton University in New Jersey.

Others disagree with that conclusion. But if Ijjas, Loeb and Steinhardt are right and inflation really is in difficulties, it would spell disaster for our entire understanding of the cosmos. Either way, Planck is driving us to take a harder look at the theory.

Smooth operator

Inflation proposes that our corner of space expanded by a factor or $10^{25}$ or more in a tiny fraction of a second soon after the big bang. To get a sense of how incredible this expansion is, imagine the full stop at the end of this sentence growing to 1 million light years across in the blink of an eye. Yet this remarkable theory has become part of our standard picture of cosmology because it seems to elegantly account for a number of astronomical puzzles.

One is the astonishing evenness of the universe. Observations show that the microwave background radiation filling the cosmos is the same temperature everywhere to within 0.0003 °C. That’s surprising because it is also true for parts of the sky that appear too far away for light to have had time to travel between them. So there is no way heat radiation could have evened out the roiling temperatures present at the universe’s birth.

Inflation provides an explanation – these parts of space had been in contact before inflation began, and had simply been pushed to great distances when the universe suddenly swelled up.

And yet, if the universe was identical everywhere then there would be no structures like galaxies, stars and planets. Inflation has an answer for this too. Quantum fluctuations in energy continually produced small dents in space-time. When inflation began soon after the big bang, it stretched these dents out to cosmic proportions, and they acted as nests for matter to fall into and eventually grow into the structures we see today. These nests appear as spots that are slightly warmer and cooler than the average temperature of the cosmic microwave background (CMB). They were first measured by the COBE satellite in 1992 and now by Planck in unprecedented detail. “Planck confirmed the quantum
"Once inflation starts, it is impossible to turn off completely, leading to an infinite number of universes"

The energy that an electric field stores is proportional to the square of its strength, a relationship that in a graph looks like a U-shaped parabola. It means that where the field is twice as strong, it harbours four times the energy. Yet the inflaton’s behaviour is up for grabs. If it exists, the value of its potential energy dictated how fast space expanded due to inflation. So it must have been positive when inflation started and then dropped to zero when it ended. But how high did the energy reach, and how did it vary from inflation’s start to its end? Hundreds of models have suggested different answers to these questions. “You’re allowed to invent any energy curve you want,” says Steinhardt.

Previous, lower-resolution maps of the CMB weren’t detailed enough to give a clear picture of how the process might have played out. If you imagine the speed of inflation changing in the same way as a ball rolling down a hill, it wasn’t clear whether the hill was like the inside of a bowl – amounting to inflation that is fast to begin with and slows down at the end – or the outside of an upturned one. Also unclear was whether it was a shallow soup bowl or a tall vase.

Planck’s improved view of the distribution of CMB temperatures points to a slide down the outside of a shallow bowl. That makes things difficult, says Ijjas, because such “plateau models” are complicated. They need to be finely tuned to provide sufficient inflation and to avoid a scenario in which the universe collapses into a black hole. Some plateau models therefore call for the universe to have started out a billion times smoother than do simpler models with a steeper energy curve. “That’s a very big problem, because inflation was introduced to explain the smoothness of the universe,” says Ijjas. Loeb agrees: “If you require the universe to be homogeneous to start with, you’re not solving that problem.”

This adds up to what Ijjas, Loeb and Steinhardt call an “initial conditions problem” for plateau models of inflation. They also suffer from being unlikely, the trio say, in the sense that models that produce more inflation and produce it more easily are more likely to have occurred. Plateau models fail on that account too. “The models which are now favoured by the data are theoretically exponentially less likely,” Ijjas says.

Martin Bucher of the University of Paris Diderot, who was one of the leaders of the Planck team that focused on inflation, agrees that “not every potential is plausible”. But he says the measurements do not rule out all of the models with steeper curves. That’s because inflation is thought to have pushed most of the universe so far away from us that light from those distant regions has not had time to reach us in the 14 billion years or so since the big bang. The hot and cold spots produced in the very early phases of inflation would be larger than our observable universe, giving us a view of only part of it. “There’s tons and tons of inflation that you don’t see,” says Bucher.

An infinity of universes

The energy curve derived from our observable universe seems to look like an upturned shallow soup bowl. But it could have a steep part too, starting off steeply and then flattening off before falling again – looking for all the world like a Hershey’s Kiss chocolate.

Andrei Linde of Stanford University discussed a model with such an energy curve at a physics conference in Santa Barbara, California, in April. Because the potential energy starts out high, there is no need to assume the newborn universe was the same on very large scales. “You have no problems with initial conditions,” he pointed out.

According to Linde, who is one of the architects of inflation theory, creating the “shoulder” between the steep and flat part of the curve means tuning the potential by about 1 per cent to fit the Planck measurements. Yet Ijjas and her colleagues say such tweaks are undesirable. “You can always go back and find a potential that will give you what you need, but if you’re just reverse-engineering the initial conditions, that’s not a good approach to doing basic science,” says Loeb. “It doesn’t lead you to believe that the model is predictive.”

Their third criticism of inflation concerns what Planck doesn’t see. Once inflation starts, it is thought to be impossible to turn off completely, leading to an infinite number of universes. But the Planck data shows no obvious sign of them. A giant cold spot has been seen, and some researchers claim it might be a sign of an interaction with another universe. However, its presence may be nothing more than a statistical fluke. Since inflation is supposed to make universes
it is affected by the Higgs field, is not in its lowest possible energy state. Instead, it appears to be metastable, meaning that at some point it could decay into its lowest energy state. If that happens, it would cause the universe to collapse into a point of infinite density.

**Cosmic phoenix**

The diagnosis of metastability for the Higgs vacuum is itself on shaky ground, but if it is metastable that presents two problems for inflation. Add the Higgs and inflaton fields, for example, and you wouldn’t necessarily have the energy needed to inflate in the first place, says Steinhardt. And if inflation did take place and was extremely energetic, it could have caused the Higgs vacuum to decay and so wiped out the universe.

So what to do? Although Steinhardt was one of the founders of inflationary theory, he has an alternative idea that avoids these problems. He and Neil Turok of the Perimeter Institute for Theoretical Physics in Waterloo, Ontario, Canada, have worked on a theory in which the universe alternates between periods of expansion and contraction. In this cyclic model, the big bang is not a birth but a rebirth, a cosmic phoenix rising from the ashes.

The reincarnated universe accomplishes the same things over the course of its past life that inflation does in a fraction of a second. Its long, slow contraction, for example, brings together far-flung regions of space explaining why they appear eerily clone-like today. “There’s so much more time for physical processes to occur,” says Steinhardt.

In the latest version of the theory, developed with Itzhak Bars at the University of Southern California in Los Angeles, the contraction happens so slowly and gently that the Higgs vacuum can remain in its metastable state from one cycle to the next.

Other theorists point out that the cyclic model has a number of shortcomings, which Steinhardt and his colleagues are working to address. “I am not wedded to inflation; in fact, I think we are in need of a grander idea,” says Michael Turner of the University of Chicago. “I am not convinced the cyclic model is that grander idea.”

Certainly for some physicists, inflation is at an impasse. The bad news is that further experimental tests may not be definitive. Inflation should have shaken space-time itself, triggering gravitational waves that spread throughout the universe. But just how violent this shaking was, and therefore how likely we are to be able to detect the waves today, varies according to each model. Planck and other missions are looking for the subtle imprint these waves left on the CMB and results are expected within a year.

Such waves are not compatible with the cyclic model, since the contraction should have been too gentle to rattle space-time significantly. “If they detect gravitational waves, the cyclic model is ruled out,” says Ijjas.

But even if no signal is found, inflation still has a fighting chance. It might just mean that inflation was less energetic than generally thought, says Sabino Matarrese, a Planck team leader at the University of Padua in Italy.

The fact that inflation contains a multitude of predictions works against it, because that makes it difficult to falsify. “If you find something that has in it the potential to explain everything, then that is problematic,” says Benjamin Wandelt at Sorbonne University in Paris and a Planck team leader. “Unsinkable theories are highly suspect in science.”

The problem, he and others say, is that there is no well-agreed guiding principle from particle physics illuminating what the inflaton should be. “The truth is, we don’t have a compelling model for inflation or even a class of compelling models,” says Turner.

Matarrese thinks some progress could be made if physicists pin down why the universe is made up of more matter than antimatter, since the energy in the inflaton field should have been converted into particles of both when inflation ended. If gravitational waves are not seen at the expected energy scale after a careful search, “inflation would be in trouble”, says Matarrese.

The uncertainty over inflation is “just the tension that we live with at the moment”, says Wandelt. Passions can run high in the debate over its existence because missions like Planck are providing a window into the universe’s first moments and researchers are anxious to get a better view. “It is a very, very special time in the history of human ideas,” he says.

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