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News

What happened before the Big Bang?

Want to know more about the Universe? Take part in our second online poll!
In our online poll to find out what Plus readers would most like to know about the Universe, you told us that you'd like to find out what happened before the Big Bang. We took the question to the renowned cosmologist John D. Barrow, Professor of Mathematical Sciences at the University of Cambridge, and here is his answer. If your mind starts to bubble, don't worry, so did ours! You can also hear Professor Barrow's answer in a Podcast.

What happened before the Big Bang?

An image taken by the Hubble Space Telescope. It shows stars in the Globular Star cluster NGC 6397, which is one of the closest to us, about 8500 light years from the Earth. Image courtesy NASA.

The term *Big Bang* has several layers of meaning. What most astronomers mean when they refer to a *Big Bang theory of the Universe* is the idea that the Universe is expanding, as Edwin Hubble first discovered in the 1920s distant galaxy clusters are moving away from one another with ever increasing speed. This implies that in the past things in the Universe were closer together, the Universe was more compressed, hotter and denser, and that in the future it will become even less hot and dense. [Puzzled by the idea of an expanding Universe? See the box below for Barrow's explanation.]

But within this picture there are all sorts of options. One is that as you go back into the past, following the Universe to earlier and earlier times when it was hotter and denser, you reach some special time when, if you believe your equations, density and temperature were infinite. Einstein's theory of gravity gives you a way of calculating when this infinite state occurred: only 13.7 billion years ago. This is very striking, because you can walk around places in Scandinavia and Scotland and pick up rocks that are 3 billion years old. We believe that the whole solar system is only about 4.6 billion years old. So we're apparently very close to what seems to be the beginning of everything.

The expanding Universe

Many people think of the expansion of the Universe like an explosion, so it must have a centre and there must be an edge. If we see everything expanding around us in the Universe, doesn't this mean that we're at its centre? But there is no centre of the Universe and there is no edge of expansion. The easy case to visualise is that of an infinite Universe. Let's think of a two−dimensional Universe, a rubber sheet that goes on infinitely in each direction. If this infinite sheet was being stretched, then no matter where you stood on it, you'd see everything expanding away from you. You could draw a circle around yourself which describes the edge of your observable universe the radius of that circle would be the distance that light has been able to travel since the sheet started expanding. We call that our *horizon*. It's not that there is no sheet beyond the boundary of that circle, it's just that we can't see it yet.

But what if the Universe is finite? If you pick up a flat piece of paper, it seems obvious that there has to be a centre and an edge. But the Universe is all there is. It's not an explosion and it's not expanding into something. So a two−dimensional Universe can't be flat like a piece of paper. But it can be like the surface of a sphere. It's finite if you wanted to paint that surface you'd need only a finite amount of paint but if you were an ant walking around on it, you'd never run into an edge. So a curved surface can be finite but have no edge.

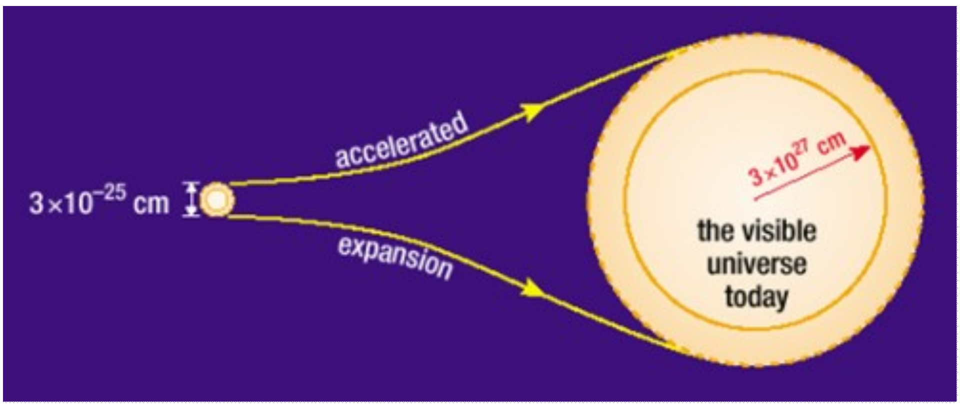
This is how we should think of a finite expanding Universe. If we inflate a balloon marked with crosses, all the crosses move away from each other as the balloon expands. If you were sitting on the balloon, you'd see all the crosses moving away from you. The centre of the expansion does not lie on the balloon.

And this is where scientists start to worry. A prediction of something infinite is often a sign that the theory you are using to make that prediction has reached the limits of its applicability. For example, imagine you are an aerodynamicist wanting to predict the speed of an air flow. If your model is very simple, for example if it ignores the friction of the air, then it might predict that something changes infinitely quickly in a finite time. But no aerodynamicist would believe that this is what really happens. They would take that prediction as an indication that you have to go back to square one and make your model a little bit better, for example by introducing the friction of air. When you then solve the equations you will find that things change very, very quickly, but not infinitely quickly.

So what cosmologists are working very keenly on today is a possible extension of Einstein's theory of gravity, one which includes quantum theory, which can give a more accurate description of the apparent beginning of the Universe. Nobody agrees on exactly how to do this: it's right on the edge of current research. Some theories predict that the Universe doesn't have a beginning at all, but that if you follow it backward in time, it eventually bounces, almost like a ball, into a previous state in which it was contracting. The Universe may behave cyclically contracting, expanding and contracting again or it may be that it bounced into expansion only once and will keep on expanding forever. Another possibility is that the Universe began in some rather uninteresting stationary state, and then started to expand due to the effect of quantum fluctuations. In that scenario, the expansion has a beginning, but the Universe itself doesn't necessarily have one.

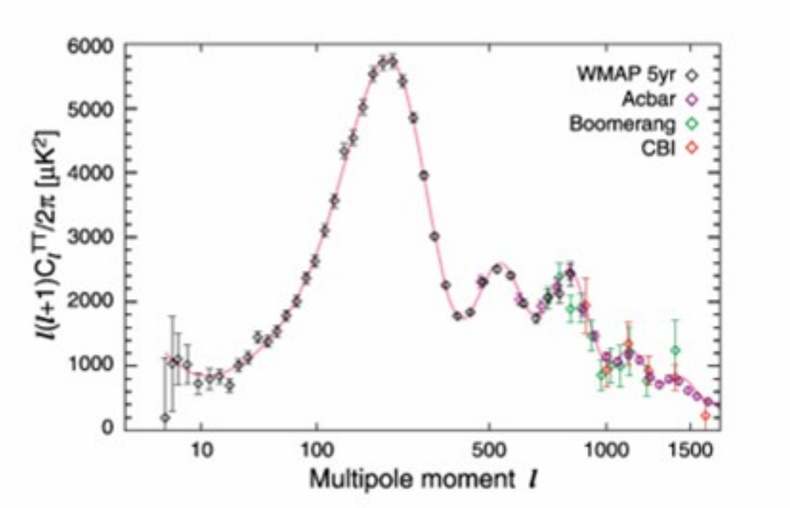
The inflationary universe

There are also much more exotic possibilities which have come to light in the last ten years, and they are usually associated with the idea of a multiverse. Our Universe might be one of many possible universes. Or, more specifically, our part of the Universe might be behaving differently to other parts of the Universe. Imagine a Universe which is expanding in different ways in different places. In some places it's rather cool, like the part that we live in, but elsewhere it may be much hotter. In some parts it may be collapsing, rather than expanding. If the Universe is infinite, there is no end to the amount of variation possible.



Inflation predicts that the whole part of the Universe that is visible to us today (about 3×10^{27} cm in radius) has expanded from a region that was once small enough for light signals to travel across it (3×10^{-25} cm at a time of 10^{35} seconds). If inflation did not occur, then the rate of expansion is too slow for this to happen. The visible part of the Universe would then have expanded from a region that is too large for light signals to create similar properties in different parts of the visible Universe today, as observed.

This type of scenario has emerged from a theory called the *inflationary universe*, which explains rather well many of the properties that we observe our visible part of the Universe to have. The theory requires that in the past, the very, very distant past, there was a short period of time when the expansion of the Universe accelerated. This results in a rate of expansion very close to the one we see today, and it also makes rather definite predictions about the little fluctuations and differences in density and temperature we should observe today, some of which turned into galaxies and stars. We can test this theory using satellite observations and it has survived all the tests that we have set it so far: there is very good agreement between observation and theory.

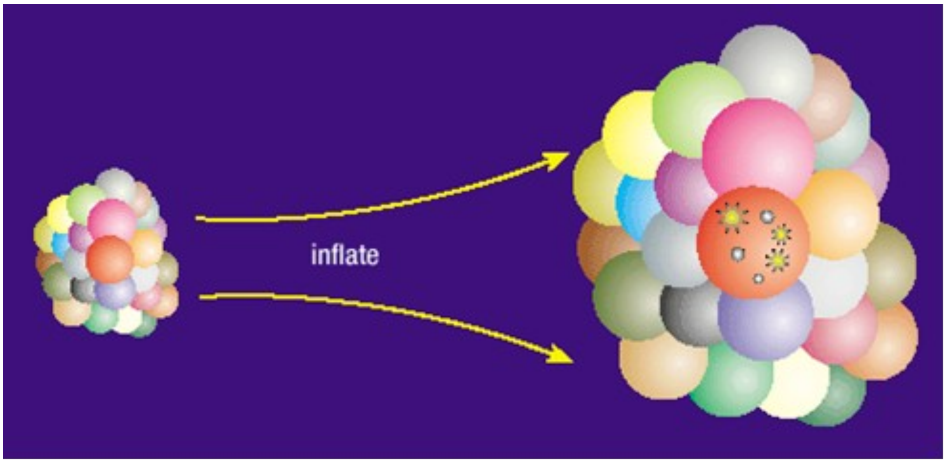


This graph shows the good agreement of predictions of the inflation theory and observations. The magnitude of temperature variations in the background radiation from the early Universe is plotted vertically against the *multipole moment* (related to the angular separation in the sky we go from large separations to small ones as we go from left to right along the axis. The highest peak is near one degree). The solid line represents the prediction of the simplest inflationary model and the data points are from satellites and ground−based experiments.

Feeling dizzy? Why not listen to this interview in our podcast?
But there is an extension to the inflation theory that is much more controversial. It says that the early burst of accelerated expansion should have affected different parts of the Universe in different ways. If we could see far enough into the Universe, we would eventually see regions of different density, with different structure to what we see in our own neighbourhood (and our neighbourhood is around 14 billion light years in size), that resulted from the accelerated expansion of our part of the early Universe.

The bubble multiverse

The next aspect of the inflation theory, which was discovered by cosmologists, is that the early surge of expansion can become self−perpetuating in each piece of the Universe. So a region will surge, and within it there will be another little piece that suddenly surges again. It is like a foam of bubbles where each bubble creates more bubbles that expand too. You should think of each bubble in the foam as being rather like the whole of our visible part of our Universe today. If we could see outside of our bubble, we would see into another bubble in the foam where conditions are different.

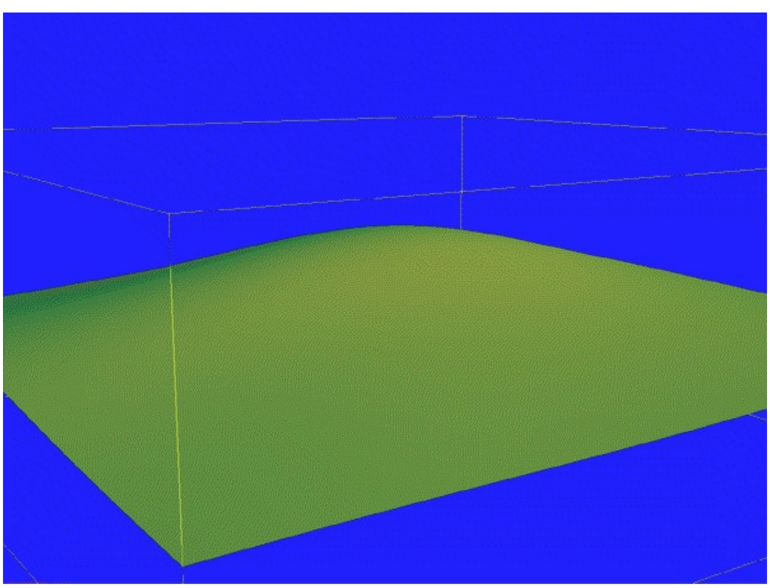


An inflating bubble multiverse.

One rather shocking thing about this bubble making is that the whole process need not have a beginning or an end. In fact, the equations that describe it predict that it doesn't have an end, and almost certainly doesn't have a beginning. But each individual bubble, like the one we're in, does have a beginning, and it may also have an end. Suddenly the question of whether the Universe has a beginning has a slightly more complicated answer. It is a bit like the life time of the human race: each individual has a particular finite life time, but the age of the race as a whole is much greater. So the new possibility that has emerged is that the Universe may become very different if we look at it on a large enough scale, and that its history is very complicated. Before the apparent beginning of our part of the Universe, there would have been a quantum "foam" which was missing our bubble, but had many others that may have been very different in structure.

I believe that the inflationary universe is a theory that contains a large part of the truth, because its predictions fit our observations extremely well. So we have some confidence that our bit of the Universe underwent this surge in expansion.

Our bubble



This computer simulation illustrates the self−perpetuating nature of inflation. The formation of a hill in the beginning of the simulation illustrates the onset of inflation. After a while, individual peaks form on top of the first hill, and later themselves grow further peaks, and so on, illustrating how inflating bubbles form inside inflating bubbles. Simulation courtesy Andrei Linde.

The theory of the bubble Universe predicts that inflated bubbles may be very different from each other, and there are only some bubbles that we could possibly exist in. For example, those that only last for a second are no good: we can only be in a rather long−lived bubble, which lasts for at least ten billion years and so gets really big. This is because there needs to be time for stars to form, and for stars to provide elements like carbon, nitrogen and oxygen in order to enable such a complex thing as life to evolve. We have to be in a big, rather old, and cold bubble.

There is an interesting unsolved problem, which is to try and work out the probability that you get bubbles with particular characteristics. What's the likelihood that you get a big, old bubble of the sort you need for life? Is it fantastically improbable, is it really fairly probable, or just in between? This is one of these problems that we hope will soon be solved. It's really a mathematical problem to formulate probability in this cosmological situation.

As a cosmologist, what would Barrow himself like to know about the Universe?

A few years ago we found out that today the expansion of the Universe is accelerating. This is how it would have behaved during the early surge of inflation. It's almost as if the Universe is inflating again. The current surge of acceleration began around 4.5 billion years ago, coincidentally at a similar time to when the solar system formed. It was lucky it didn't begin to accelerate much earlier, or there wouldn't be any stars or galaxies because they cannot condense out of the expanding Universe once it starts to accelerate: matter is separating too fast for gravity to pull it back into lumps.

So the big mysteries are why the Universe's expansion began to accelerate at that time, and what is the form of energy, known as *dark energy*, which is responsible for the acceleration. It's a form of energy that has a repulsive gravitational effect. This is clearly happening in the Universe today, but we have no idea of the exact identity of this dark energy, and why it's come into play late in the history of the Universe. If it is always going to be around, then the Universe's expansion will keep accelerating forever. The Universe will never collapse back to a *big crunch*. The Universe will just keep getting cooler, and more and more boring, and everything will eventually die out. So identifying this dark energy is a rather crucial point in our understanding of the future of the Universe. It's a huge gap in our understanding because 72% of the energy in the Universe is dark energy. Of the rest, 4% is ordinary matter, the stuff that we are made of, and that shining stars are made of. The remaining 24% is what's called *dark matter*: this consists of stars that don't shine in the dark, and possibly elementary particles like neutrinos. Dark matter is a puzzle, but not a mystery like dark energy. We hope that the Large Hadron Collider at CERN will help us identify the particles that make up the dark matter, but we have no good ideas about the dark energy.

Other bubbles

Another interesting question is how we could ever test whether all the other bubbles exist. We can't see them because they're beyond the visible horizon of the Universe 14 billion light years away. This is a philosophical question, almost like a science−fiction scenario. Since we can't see the other bubbles, should we allow them to be part of our picture of the Universe at all? In the 1930s there was a great debate about whether the philosophy of science should be based upon *verification*: you make a prediction and then you test by experiment if you can verify it and the theory. This approach soon went out of favour: if your theory predicts that all apples are green, and you only find green apples, then this doesn't prove that your theory is correct.

There may be some other explanation, rather different from your theory, for why apples all seem to be green, or you may not have run into red apples yet. Philosophers like Karl Popper instead focused on *falsification*. You falsify your theory, if you find a red apple; then you can definitely rule it out, and maybe you can rule out lots of other theories too.

We can't verify the existence of other bubbles, but it may still be possible to falsify the theory. If there are other bubbles, then there might be a particular observable feature, which is the same in each. Then, if you didn't observe this feature in our bubble, the theory would be falsified. So although we can't see the other bubbles, it's still conceivable that we could test our theory, because it might say things about all bubbles. That may be the best that we can hope for.

Post a comment on this article, see other people's comments and discuss.

About the author

John D. Barrow is a cosmologist working on the early history and large scale structure of the Universe at the University of Cambridge. He has also written a large number of popular science books and is Director of the Millennium Mathematics Project of which *Plus* is a part.

Plus is part of the family of activities in the Millennium Mathematics Project, which also includes the NRICH and MOTIVATE sites.