The Cosmic Puzzle

What is Dark Energy? Are we in a true vacuum or a false vacuum? Are early inflation and late inflation related?

by KATE BECKER

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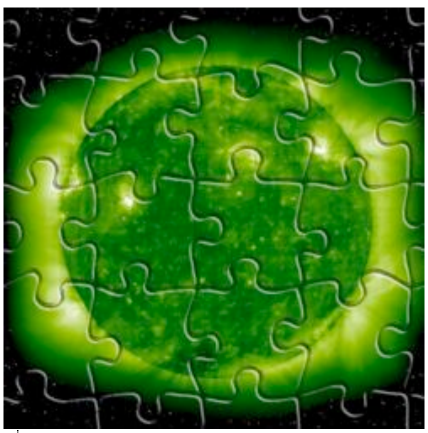
Imagine that you're almost done with a difficult a jigsaw puzzle, save for one last missing piece. You know the size and shape of the missing piece, and you think you even know what the finished picture will look like once the piece is in place. Triumph!

Now imagine that you're actually missing much more than one piece—that, in fact, all the pieces you'd fit together so carefully were just the tiniest section of a much bigger puzzle. Suddenly, you have no idea what the finished picture will look like—and you have a lot more work to do.



PUZZLE
What is Dark Energy?

That's what happened to cosmologists in the 1990s. After carefully piecing together a census of all the "ordinary" matter in the universe—that is, the mass contained in all the light-emitting stars, nebulae, and galaxies—scientists had moved on to cataloging the "dark" matter—matter we can see only through its gravitational effect on illuminated matter. Piece by piece, scientists were assembling a picture of the universe, and, it turns out, coming up short.

In 1998, astronomers made a discovery that fundamentally changed our understanding of the universe. Using distant supernovae as cosmic beacons, the astronomers clocked the rate at which our universe is expanding. They expected to find that the expansion was decelerating, or slowly coasting to a stop from the Big Bang.

But the supernovae were actually receding faster and faster from the Earth. What's more, all of the known matter in the universe—both ordinary and dark—could not provide the energy necessary to propel that acceleration. The discovery meant that, somewhere in their census of the universe, astronomers had missed something big.

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>
> *- Alexander Vilenkin*

"For most people it was very hard to believe," recalls Alexander Vilenkin, a cosmologist at Tufts University. "They hoped there was something wrong with the measurements, and that the whole thing will soon go away." So when the measurements were confirmed, adds Vilenkin, "the particle physics community was in shock."

Energy Sleuths

Despite the initial shock, according to Sean Carroll, a physicist at the California Institute of Technology, "There was an immediate recognition that, if true, it would solve a handful of problems in one fell swoop."

Cosmologists called the mystery energy driving the universe's acceleration "dark energy," cosmology jargon for "we don't know what the heck it is." Here's what we do know about dark energy.

First, it has negative pressure. That is, when a force like gravity tugs on dark energy, dark energy tugs back. This rubber-band quality of dark energy has caused some scientists to describe it as a kind of anti-gravity.

ALEXANDER VILENKIN
Tufts University

Second, unlike dark matter, dark energy doesn't "clump" together with ordinary matter. Instead, dark energy permeates every inch of empty space. And because dark energy is woven into the very fabric of space, the bigger the universe gets, the more dark energy there is to go around. Therefore, as the universe expands, dark energy is becoming a more important constituent all the time.

What in physics meets both these criteria? Physicists have one candidate: quantum vacuum energy, the energy contained in the quantum mechanical ghost particles that pop in and out of existence in accordance with Heisenberg's Uncertainty Principle. But the predicted magnitude of this energy is so outrageously off the mark that many physicists think it might actually be equal to zero.

SEAN CARROLL
California Institute of Technology

"We're stuck with two very interesting problems," says Carroll. "Why is the vacuum energy too big on paper," and why should it in fact be small?

Better Late Than Never – Or Is It?

Some cosmologists are looking back in time for clues to dark energy-caused cosmic acceleration. After all, our universe is no stranger to growth spurts: It experienced a big one immediately after the Big Bang, when it ballooned up out of nothingness in a tiny fraction of a second.

Alan Guth, a physicist at the Massachusetts Institute of Technology, dubbed that initial split-second expansion "inflation." Inflation elegantly explains many of our universe's most surprising qualities: its apparent uniformity over large distances, its "flat" geometry, and the existence of galaxies and galaxy clusters. Could the inflation of the infant universe ("early" inflation) be tied to the "late" inflation astronomers are observing today?

"If we understand how and why accelerated expansion happens in one context, then we might be able to understand how and why it happens in the other context," says University of Michigan physicist Fred Adams. "However, at the current time, we just do not know if they are related or not."

"The conventional wisdom is that the two inflations are unrelated," adds Vilenkin.

There is another potential solution to the dark energy problem, one with disturbing implications for the fate of our world. Perhaps the vacuum energy powering the accelerating expansion of the universe isn't actually the lowest energy there is. Maybe, as Carroll describes it, "The real, honest-to-goodness vacuum energy *is* zero," and we just haven't reached it yet. If that is the case, we're living in what theorists call a "false vacuum."

"The concept of a false vacuum is that empty space has nonzero energy density associated with it, so that space is not really empty, but rather has some energy density that acts like a cosmological constant," says Adams. The cosmological constant—famously proposed, then retracted, by Einstein—is a mathematical placeholder in the equations of cosmology.

The problem, says Carroll, is that "you can't tell the difference between a false vacuum that will eventually decay and one that will be stable forever."

Or rather, you wouldn't want to: "The only way to prove observationally that we live in a false vacuum is to observe its decay," explains Vilenkin. "This would require a bubble of true vacuum to nucleate, expand, and ultimately engulf our Earth, turning everything here into some alien forms of matter. The bubble will come practically without warning, as it expands close to the speed of light." Without warning is good, since the bubble wouldn't be fun.

In this scenario, the universe is like a man who falls out his window but is caught by an awning below: Our universe took its first fall at the time of the Big Bang, and though things may look stable right now, we're actually balanced on a cosmic awning, just waiting for the next fall to go splat on the ground.

FRED ADAMS
University of Michigan

Luckily, most models of inflation describe our universe as "slowly rolling" toward a true vacuum, not plummeting out a window, explains Carroll. Distinguishing between the two scenarios is "a huge project for observational cosmologists," Carroll says.

Scientists are currently working to track the expansion of the universe with ever-greater accuracy, using the same kind of supernovae that first hinted at the existence of dark energy, as well as by examining how structures like galaxy clusters form and evolve.

Whether those results will complete the jigsaw puzzle remains to be seen. But scientists like Adams, Vilenkin, and Carroll agree that there is no puzzle they would rather be solving.