Is the universe a fractal?

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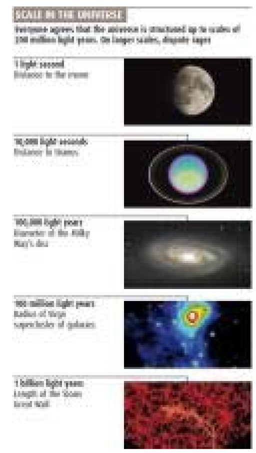
Written across the sky is a secret, a hidden blueprint detailing the original design of the universe itself. The spread of matter throughout space follows a pattern laid out at the beginning of time and scaled up to incredible proportions by nearly 14 billion years of cosmic expansion. Today that pattern is gradually being decoded by analysing maps of the distribution of the stars, and what has been uncovered could shake modern cosmology to its foundations.



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Scale in the universe

Cosmology is founded on the assumption that when you look at the universe at the vastest scales, matter is spread more or less evenly throughout space. Cosmologists call this a "smooth" structure. But a small band of researchers, led by statistical physicist Luciano Pietronero of the University of Rome and the Institute of Complex Systems, Italy, argues that this assumption is at odds with what we can see. Instead they claim that the galaxies form a structure that isn't smooth at all: some parts of it have lots of matter, others don't, but the matter always falls into the same patterns, in large and small versions, at whatever scale you look. In other words, the universe is fractal.

It is a controversial view, and one that sparked an intense debate over a decade ago. Since then, astronomers have surveyed ever-greater numbers of galaxies, taking larger and larger samples of the universe. Now the biggest galaxy survey ever and a brand new map of the universe's dark matter are adding fuel to the fire.

At stake is far more than the way galaxies cluster. A fractal universe could undermine cosmology's most basic assumptions. "All of the observations we make depend to a greater or lesser extent on the idea that the universe is homogeneous," says David Hogg of New York University, who leads a team of physicists that disputes Pietronero's view.

This idea that matter is spread more or less evenly throughout the universe is embodied in Einstein's cosmological principle. Einstein formulated it after publishing his general theory of relativity, which describes how the distribution of mass bends space-time and creates gravity. It allows cosmologists to use the equations of general relativity to describe the geometry of the whole universe. As a result it has led to a picture of a universe expanding uniformly from the big bang and in which cosmological measurements have defined meanings.

Fractals allow Pietronero to paint a very different sort of picture - one in which the irregular distribution of matter that we see around us never evens out into a smooth structure, but repeats itself at ever grander scales. Fractals are familiar enough: we see them in the branching of trees, the curves of coastlines, lungs, turbulence and clouds. No matter what scale you look at them, fractal patterns look the same. Think of broccoli: a tiny branch looks much the same as the whole vegetable. Zoom in or zoom out, the structure looks the same - exquisitely detailed, never smooth. Fractals can be beautiful to look at, but when it comes to galaxies it may be a subversive kind of beauty.

Certainly the universe does not look smooth. Some regions contain clusters of matter; others are virtually empty. Hundreds of billions of stars group together to form galaxies, and galaxies congregate in clusters. Clusters assemble into colossal structures called superclusters that can stretch out for 100 million light years and look uncannily like fractal patterns (see Diagram).

Even superclusters string together in long filaments and sheets that stretch like ghostly cobwebs across an otherwise empty sky. The Sloan Great Wall, for example, which was discovered in 2003, spans more than a billion light years. These filaments and sheets seem to encircle huge voids of empty space. The voids range from 100 to 400 million light years in diameter, making the whole assemblage appear as an immense, glowing lattice punctuated by wells of darkness.

No one disputes that the universe is far from smooth on relatively small scales - by which cosmologists mean thousands of light years. But Hogg's team is convinced that if you zoom further out, smoothness reigns. "When you're looking at the size scales of galaxies, groups of galaxies, clusters, superclusters and filaments, it looks like a fractal," says Hogg. "But once you get larger than all of that, then it starts to look homogeneous."

What has convinced him is his team's analysis of the latest data from the Sloan Digital Sky Survey, the largest 3D map of the galactic universe so far. His team insists that the map is proof of smoothness. The fractal camp, however, are sceptical. In fact, they say the Sloan observations confirm what they've been claiming all along.

It might appear to be deadlock, but at least with the Sloan survey the two sides can agree what they're disagreeing about. For years Pietronero and his team argued that the statistical methods mainstream cosmologists were using to establish homogeneity were flawed because they start off by assuming that matter is evenly spread. The team was mostly ignored until 2004, when Hogg and astrophysicist Daniel Eisenstein of the University of Arizona in Tucson spent a summer in Paris with Pietronero's colleagues, cosmologists Francesco Sylos Labini of the Enrico Fermi Centre and the Institute for Complex Systems, Rome, and Michael Joyce of the Pierre and Marie Curie University, Paris.

"We argued every day about fractals," Hogg says. "Those battles raged over lunch and coffee and finally convinced us by the end of our visit that we should be doing the analysis as they say."

When they returned to the US, Hogg and Eisenstein applied the fractal team's methods to a sample of 55,000 luminous red galaxies mapped by Sloan. They found that the galaxies do form a fractal pattern, but as they looked at bigger and bigger scales, the pattern appeared to disintegrate and smooth out at just over 200 million light years - a scale far larger than most cosmologists had expected.

But Pietronero and Sylos Labini are not convinced. Instead, they believe that if astronomers could continue to zoom out and look at even larger scales, they would find more clustering. They suspect that the apparent smoothness at 200 million light years is not real, but rather an illusion created by statistical effects due to the limited range of the Sloan survey.

Hogg's team, though, insist that their evidence of homogeneity is statistically significant. "I think the result really is secure," says Hogg. "I would stake my scientific reputation on that."

Even if the result is real, mainstream cosmologists still have a huge problem on their hands. The fact that the fractal patterning extends to far bigger scales than anyone had expected means that there must be far bigger structures than anyone expected - structures that are even bigger than superclusters. The fractal team argues that the standard model cannot explain the existence of these galactic giants. "If you look at the galaxy data, you can see enormous objects hundreds of millions of light years across, stuff that's really huge," says Pietronero. "This is a huge problem. You're going to have to change the story very radically."

The usual story runs something like this. In the tiny fluctuations of the nascent universe, matter began to collect in denser regions, setting off a chain reaction of gravitational collapse that has given us the large-scale structure we see today. Gravity has worked from the bottom up, building galaxies first, then collecting galaxies into clusters, then clusters into superclusters and so forth. But while the matter has been clumping together, the universe has been expanding, and thus a battle has ensued: gravity versus expansion.

According to Pietronero, there simply hasn't been enough time since the universe came into being 14 billion years ago for gravity to sculpt structures larger than about 30 million light years across: expansion would have prevented anything larger from forming. "The existence of structures much larger than this implies a crisis of the present view of structure formation," he says.

This present view is the "cold dark matter model", in which the glowing masses of stars and galaxies are only the tip of the cosmic iceberg. Luminous matter makes up roughly 15 per cent of all the matter in the universe - the other 85 per cent is mysterious dark matter.

Hogg's team says that the new observations do not undermine the standard view as Pietronero claims. Instead, they maintain that the cold dark matter model explains the Sloan data quite accurately. For that to be true, however, Hogg's team have to put a number called a bias parameter into their equations. It reflects the difference between the distribution of matter in computer simulations of the cold dark matter model and the observed distribution of luminous matter.

Collisions between particles of ordinary matter help it clump together, but dark matter is thought not to behave in the same way. That suggests it could be spread out in space more evenly than ordinary matter, so cosmologists assume that the distribution of the matter we can see - galaxies, say - is not a true reflection of the distribution of all the matter that is out there. They believe the structure of the universe is really much "smoother" than it appears to be, because dark matter dominates. In the case of the Sloan survey, the bias is 2: the visible galaxies are clumped twice as densely as the predicted total distribution of matter in the universe.

Sylos Labini, however, sees the bias as a fudge that allows cosmologists to discount the observed clustering of galaxies and to assume that the gigantic clusters of superclusters are only half the problem they appear to be. "The bias is a way to hide the size of structures behind some ad hoc parameter," he says.

Mainstream cosmologists, however, feel the bias is justified, assuming that galaxies cluster in regions of space that are replete with excess dark matter. According to the standard model, dark matter is everywhere, but galaxies only shine in the rare regions where dark matter is densest. Dark matter also lingers in the voids where no light shines but here it is thinly spread out. In other words, while the luminous galaxies look very clustered, the underlying blanket of dark matter is far smoother, supporting the claim of homogeneity. "If the cold dark matter model is correct, then there should be dark matter in the voids," Hogg says.

The million-dollar question is: what is the real distribution of dark matter? Is dark matter smooth or fractal? Is it clustered like the galaxies, or does it spread out, unseen, into the great voids? If the voids are full of dark matter, then the apparent fractal distribution of luminous matter becomes rather insignificant. But if the voids are truly empty, the fractal claim requires a closer look.

Astronomers are now providing our first glimpse into the voids and our first look at the pattern of invisible matter. Richard Massey of the California Institute of Technology in Pasadena and others in the Cosmic Evolution Survey project have just created the first 3D map of dark matter in the universe (*New Scientist*, 13 January, p 5). They were able to find the dark matter by observing its gravitational effect on any light streaming past it. Combining data from the Hubble Space Telescope, the Subaru telescope in Hawaii and the Very Large Telescope in Chile, they mapped the distribution of dark matter at scales ranging from 23 million to 200 million light years across.

Massey's team found that the dark matter distribution is nearly identical to the luminous matter distribution. "The first thing that strikes me is the voids," Massey says. "Vast expanses of space are completely empty. The dark matter makes up a criss-crossing network of strings and sheets around these voids. And all the luminous matter lies within the densest regions of dark matter."

Although this distribution of dark matter seems to favour the idea that the universe is fractal, Hogg isn't convinced. "It is interesting," he says, "but measurements of dark matter are much less precise than measurements of galaxy distributions."

"The result is very new," Massey agrees. "It demonstrates a very exciting new way of looking directly at dark matter and will be vital in future work, but hasn't yet been subject to all the analysis that has been applied to galaxy surveys." When asked if the dark matter exhibits an explicitly fractal structure, Massey replies, "We don't know yet."

"The universe is not a fractal," Hogg insists, "and if it were a fractal it would create many more problems that we currently have." A universe patterned by fractals would throw all of cosmology out the window. Einstein's cosmic equations would be tossed first, with the big bang and the expansion of the universe following closely behind.

Hogg's team feel that until there's a theory to explain why the galaxy clustering is fractal, there's no point in taking it seriously. "My view is that there's no reason to even contemplate a fractal structure for the universe until there is a physical fractal model," says Hogg. "Until there's an inhomogeneous fractal model to test, it's like tilting at windmills."

Pietronero is equally insistent. "This is fact," he says. "It's not a theory." He says he is interested only in what he sees in the data and argues that the galaxies are fractal regardless of whether someone can explain why.

As it turns out, there is one model that may be able to explain a fractal universe. The work of a little-known French astrophysicist named Laurent Nottale, the theory is called "scale relativity" (see "Fractured space-time"). According to Nottale, the distribution of matter in the universe is fractal because space-time itself is fractal. It is a theory on the fringe, but if the universe does turn out to be fractal, more people might sit up and take notice.

A resolution to the fractal debate will only come with more data. Sloan is currently charting more galaxies and will release a new map in the middle of 2008. According to Sylos Labini, this will cover over 650 million light years and should tell us if the apparent transition to homogeneity extends beyond 200 million light years. For now, the pattern of the world, imprinted at the origin of the universe, remains a secret glimpsed only in the knowing shimmer of the stars.

Fractured space-time

French astrophysicist Laurent Nottale has developed a theory that takes fractals to a whole new level. A researcher at the Meudon Observatory in Paris, Nottale set out to extend Einstein's principle of relativity - in which the laws of physics remain the same regardless of the motion of an observer - to a theory in which the laws of physics would remain the same regardless of the scale at which the universe is being observed. He found that the underlying space-time of such a theory would have to be fractal.

In Nottale's theory, called scale relativity, the underlying fractality of space-time is most noticeable in the quantum world. Quantum behaviour, he claims, can be understood geometrically - particles move along fractal trajectories. On large scales, his model could explain a fractal pattern of the galaxies.

The most profound question in physics today is how to unify the really small with the really big - and when it comes to matters of scale, fractals may turn out to be a key ingredient.

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