Fractured Universe

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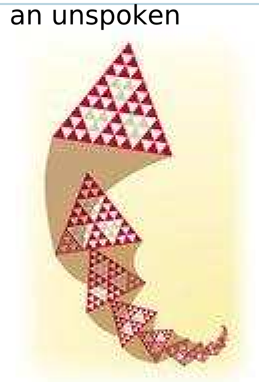
WHEN cosmologists speculate on the nature of the Universe, they make an unspoken assumption-that matter is spread uniformly throughout space. Yet when astronomers peer out across the Universe they see something very different. Galaxies are gathered together in great chains and walls which snake around vast regions of empty space called voids. The Universe appears anything but uniform.



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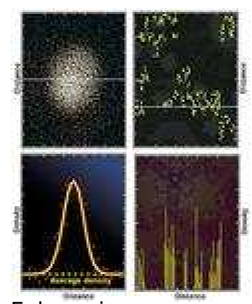
Fractals example

"Yes, there does appear to be a contradiction," admits Ofer Lahav of the Hebrew University in Jerusalem and the Institute of Astronomy in Cambridge. But Lahav contends that the Universe, though undeniably clumpy on the small scale, becomes smooth on the largest scales. "I like to think of it as an ocean, which looks choppy on the scale of individual waves but from far above, on scale of tens of kilometres, is perfectly smooth," he says.

Lahav's is very much the conventional view. "I would say that more than 95 per cent of astronomers believe the Universe is uniform on the very large scale," says Peter Coles, professor of astrophysics at the University of Nottingham. But an opposing opinion is now causing a stir. A maverick group based in Europe has suggested that the Universe never becomes smoothed out, even on the largest scales. "My contention is that it is clumpy on all the scales so far explored," says Francesco Sylos Labini, an astronomer at the University of Geneva. "In fact, studies we have done show that the distribution of matter is fractal, just like a tree or a cloud."



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Galaxy cluster density

If this dissenting view is correct and the Universe doesn't become smoothed out on the very largest scales, the consequences for cosmology are profound. "We're lost," says Coles. "The foundations of the big bang models would crumble away. We'd be left with no explanation for the big bang, or galaxy formation, or the distribution of galaxies in the Universe."

The standard models for describing the big bang and the evolution of the Universe are called Friedmann-Robertson-Walker (FRW) models. Their starting point was general relativity, the theory of gravity published by Einstein in 1915. In 1922, following Einstein's lead, the Russian physicist Aleksandr Friedmann applied general relativity to the whole Universe. (His equations were later recast by the American cosmologist Howard Robertson and Briton Arthur Walker). It was Einstein and Friedmann who first made the assumption that the Universe is both homogeneous-the same in all places-and isotropic-the same in all directions. This is known as the Cosmological Principle.

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Galaxy clusters

There were two reasons for making such an assumption. The first was purely practical: Einstein's complex equations are extremely difficult to solve for a Universe that is not smooth. The second reflected a scarcity of observations of the Universe. "Nobody knew anything about the large-scale structure of the Universe-galaxies weren't even generally accepted as the building blocks of the cosmos," says Lahav. "The simplest thing in the circumstances was to apply Ockham's razor and assume a homogeneous and isotropic Universe."

For most of this century, this assumption has been impossible to prove observationally. But now astronomers have begun to observe a big enough chunk of the Universe to at last put it to the test. In the 1980s, two of the most important galaxy surveys were the CfA red shift survey, carried out by Margaret Geller and John Huchra of Harvard-Smithsonian Center for Astrophysics, and the IRAS red shift survey carried out using NASA's Infrared Astronomical Satellite. Both probed out to about 300 million light years-or, to put it another way, they looked back to a time when the Universe was about 95 per cent of its present age.

There is no doubt that on this relatively small scale, the Universe is far from homogeneous. Most astronomers talk of "hierarchical clustering"-galaxies clumping together into clusters and clusters into superclusters. One commonly used measure of homogeneity is the "two-point correlation function". This is the probability of observing a galaxy at a certain distance from a chosen galaxy compared with the probability of finding one at the same distance if galaxies are spread uniformly throughout space. It turns out that you are twice as likely to find a galaxy at 15 million light years from a given galaxy in the real Universe as in a uniform Universe.

However, according to Lahav and his Cambridge colleagues Kelvin Wu and Martin Rees, this measure gradually declines towards 1 as scale increases. They estimate that the Universe becomes nearly homogeneous on scales larger than about 900 million light years-looking back to when the Universe was about 85 per cent of its present age. "On the largest scales we have probed, the Universe appears to become perfectly smooth," says Lahav.

Fractal dimension

But the mavericks, led by Lucian Pietronero of the University of Rome, dispute this. Having analysed the same galaxy surveys as everyone else, they claim that hierarchical clustering continues through to the very largest scales. This property, of similar patterns recurring at every scale, is a defining characteristic of fractals (see Diagram). "Our tests show that the Universe never becomes homogeneous in the available galaxy samples," says Sylos Labini, who began his work while in Pietronero's team. "It remains hierarchically clustered. It remains fractal."

The team maintains that orthodox cosmologists are mistaken. "What they are seeing is an artefact of the way they analyse galaxy surveys," says Sylos Labini. In conventional calculations of how close to homogeneity the Universe is-the two-point correlation function, for example-astronomers look for departures from the average density of the Universe. This necessarily assumes that there is such a thing as average density (see Diagrams) (here). "If the Universe is fractal, however, it has no characteristic scale," says Sylos Labini. "Everything, including the average density, changes with scale so the concept is meaningless. It's not surprising that people find the Universe is homogeneous when homogeneity is one of their basic assumptions."

To avoid this, Pietronero and his team calculate the extent of galaxy clustering by using statistical methods that take account of the properties of fractals. The simplest technique is to measure the number of neighbours around a chosen galaxy within a radius R. In fractal maths, this number is proportional to RD, where D, the fractal dimension, can have any value between 0 and 3. When D is 3, galaxies are distributed evenly within a sphere-the conventional view. But when D is not a whole number-fractal, that is-the galaxies cease to be distributed evenly.

From their measurements, Pietronero and his colleagues estimate that D is about 2.1, implying that the Universe is fractal on scales up to 300 million light years. There is a proviso, however. "We should not forget the invisible `dark' matter, which is thought to account for at least 90 per cent of the mass in the Universe," says Sylos Labini.

If the voids we see, apparently empty of galaxies, are in fact full of dark matter, then the Universe may still be homogeneous and FRW models will apply. "However, it seems very unlikely that the clustering of ordinary light-emitting matter and dark matter would be completely different," says Sylos Labini. If, on the other hand, the voids are empty of dark matter and the distribution of dark matter is roughly the same as that of ordinary matter, then the Universe is even more inhomogeneous than the luminous matter indicates.

Of crucial importance, then, are observations that are sensitive to the distribution of all matter rather than merely the distribution of luminous matter, which is what the galaxy surveys provide. One such probe is provided by the "streaming motions" of galaxies. As well as taking part in the continuing expansion of the Universe, some galaxies are also attracted by the gravity of unseen concentrations of mass, and move towards them. From this streaming motion, astronomers can deduce the total amount of matter pulling them through space.

Invisible mass

Another mass probe is provided by galaxies whose light is distorted, or "gravitationally lensed", by the gravity of matter close to the path it takes on its journey to Earth. "The indications so far are that the visible mass in the Universe roughly traces out the invisible mass," says Lahav. So dark matter does not bolster Sylos Labini's contention that the Universe is fractal (or, for that matter, Lahav's that the Universe is fractal on small scales and homogeneous on larger ones.)

But just suppose the Universe were fractal. Would it be the catastrophe that theorists claim? Would it mean abandoning the existing cosmological models? "Yes," says Sylos Labini. "The usual FRW models all assume a Universe with a constant matter density."

One way we could obtain solutions to Einstein's equations for a nonuniform Universe would be to assume that the inhomogeneity is simply a small "perturbation" on a homogeneous

Universe. But this won't work for a fractal Universe, because it is more than a mere perturbation-it is radically different. The problem with a fractal is that it cannot even be described at each point in space by the formulas that conventional theory uses. "It is impossible to solve Einstein's equations exactly for a fractal distribution of matter," says Sylos Labini.

Despite this formidable theoretical challenges, Sylos Labini believes a fractal Universe is more exciting than a homogeneous one. "We are facing a new and challenging problem which we are a long way from solving," he says. "For some questions, the fractal structure leads to a radically new perspective and this is hard to accept. But it is based on the best data and analyses available. It is neither a conjecture nor a model-it is a fact."

Few would go anything like as far as this, though Coles admits that galaxy surveys as yet provide only weak evidence that matter is distributed smoothly throughout the Universe. "Existing galaxy surveys sample too small a volume to show the scale of homogeneity," he says.

But Lahav and his colleagues do not rely solely on galaxy surveys to support their case that the Universe is ultimately homogeneous. They bolster it with other evidence, such as the cosmic background radiation, the microwave "afterglow" of the big bang which still fills the Universe 15 billion years after the event. Since this radiation comes from an era within a mere 300 000 years of the birth of the Universe, it gives a look-back time close to 0 per cent the age of the Universe.

In 1991, NASA's Cosmic Background Explorer satellite (COBE) discovered that the temperature of the background radiation varies by less than 1 part in 100 000 from one direction in the sky to another. Since the radiation was in intimate contact with matter at the time, this allows astronomers to estimate the smoothness of matter at the beginning of the Universe. "We're talking about no variations bigger than 1 part in 100 000," says Lahav. "So, on the biggest scales possible, the Universe is almost completely smooth."

Not unexpectedly, Sylos Labini sees things differently. He questions the wisdom of jumping straight from the distribution of radiation seen by COBE to that of matter. "Inferring the distribution of matter from the distribution of radiation requires a complex theory with many assumptions," he says. "We should be very cautious."

On the other hand, Lahav points out that Sylos Labini and his colleagues have trouble explaining why there should be a fractal distribution of matter in the Universe. "There is no dynamical theory to explain how such a fractal Universe could have arisen from the pretty smooth initial state we know existed in the big bang," says Lahav.

"Yes, that's true," admits Sylos Labini. "It's a very difficult problem: how does gravity turn an initially smooth distribution of matter to a fractal one?" But just because something is hard to explain has nothing to do with whether it is true or not. "Facing a hard problem is far more interesting than hiding it under the rug by an inconsistent procedure," he says.

By contrast, Lahav says his picture is easier to explain. "The transition from hierarchical clustering to homogeneity is completely compatible with the accepted ideas of galaxy formation," he says. In the conventional picture, the Universe starts off with tiny density fluctuations-ripples in an otherwise smooth distribution of matter. Nobody knows for sure how these came about but a fair bet is that they were impressed on the Universe by quantum processes in the first split second of its existence. These are then amplified by gravity: denser regions of the Universe have stronger gravity, so they pull in more matter, making them more dense, and so on. "It's like capitalism," says Lahav. "The rich get richer and the poor poorer."

However, this process must also take account of the fact that the Universe is expanding and this expansion tries to pull apart material that is trying to clump. On the small scale gravity wins and material clumps into galaxies and clusters-and even superclusters. But the expansion gets bigger as the scale increases. This is the famous Hubble law, which says that the velocity of recession of two galaxies increases in step with their separation. Inevitably, then, there is a scale at which the expansion overwhelms gravity and no more structures can form. "This is where we see the transition to homogeneity," says Lahav.

There is clearly a huge gap between a look-back time of 95 per cent for the galaxy surveys and a look-back time of close to 0 per cent for the big bang radiation. Lahav goes as far as calling the region in between an "observational desert". Until cosmologists find oases in this desert, the debate over whether the Universe is homogeneous will not be resolved.

At least one such oasis does exist, and Lahav and his colleagues have recently visited it. This is the cosmic X-ray background, a universal glow of X-rays that was discovered in 1962 and is thought to be the total of all emissions from "active galaxies" such as distant quasars. Lahav believes their average distance is as much as 1800 million light years, which corresponds to a look-back time of about 12 per cent of the age of the Universe. "The evidence from the X-ray background is that the Universe is smooth on such large scales," says Lahav. Coles agrees. "I'm 99 per cent sure the Universe is homogeneous," he says.

Of course, Sylos Labini has a different interpretation. "I make the same argument as for the cosmic background radiation," he says. "A fractal distribution of active galaxies will appear isotropic on average-but this does not imply homogeneity."

Galaxy surveys that see farther out across the Universe are crucial for filling the gap, and two are already under way. The American-Japanese Sloan Digital Sky Survey, which uses a purpose-built telescope in New Mexico, should observe a total of 1 million galaxies over a quarter of the sky. And the Anglo-Australian Two-Degree Field, or 2dF, survey has already measured the red shift of more than 40 000 galaxies, and aims to measure 250 000. Both surveys will probe to a look-back time of 85 per cent of the age of the Universe.

Astronomers are also trying to observe variations in the temperature of the cosmic microwave background radiation between parts of the sky that are 1 degree apart or less. These correspond to regions of the Universe smaller than were probed by COBE but still much larger than the biggest galaxy surveys. So while the galaxy surveys push into the desert from one direction, the cosmic background experiments are coming in from the other. "When they meet in the middle, the argument will be over," says Lahav.

From issue 2200 of New Scientist magazine, 21 August 1999, page 22

Close this window