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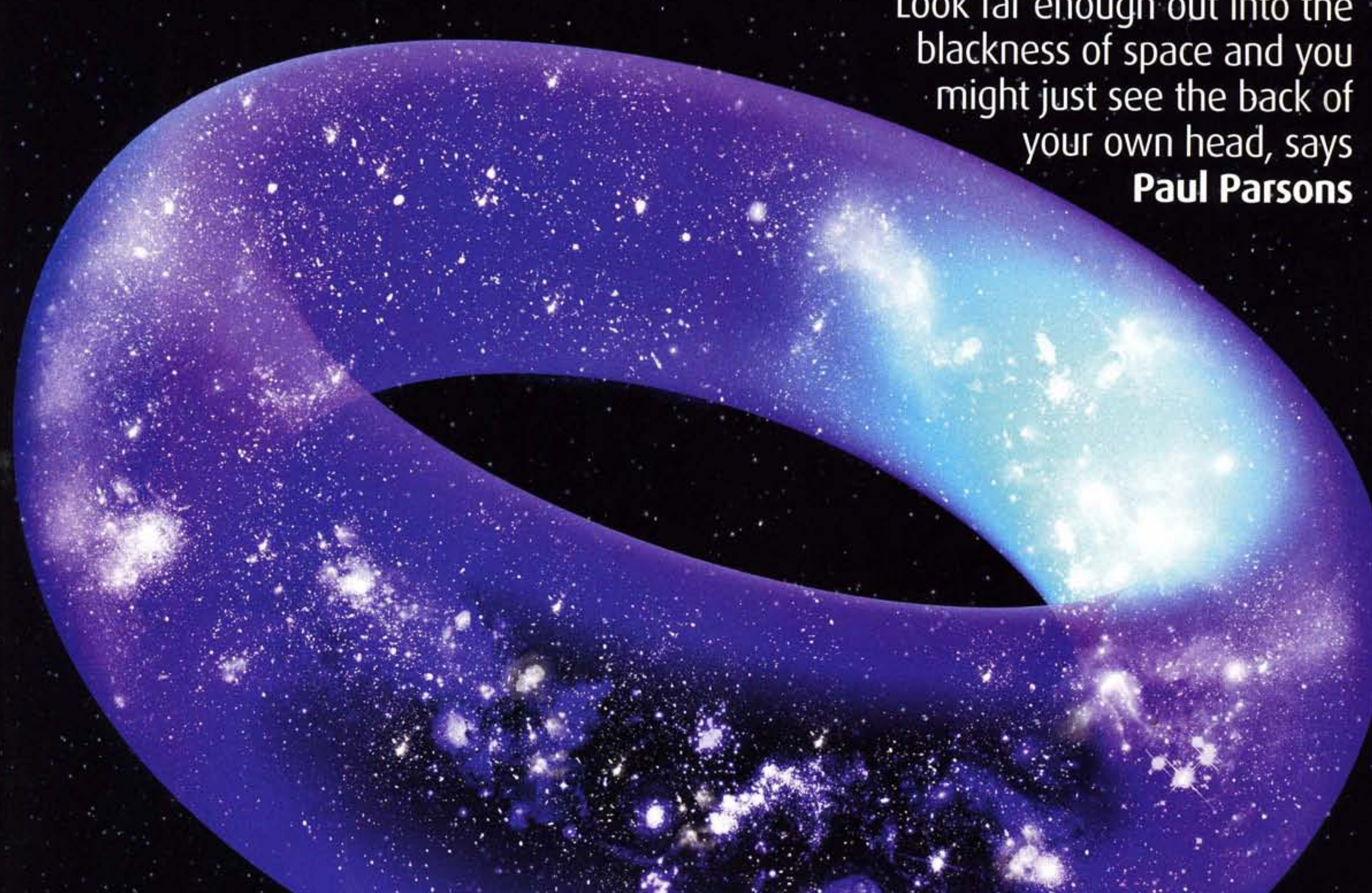
The wraparound universe

Look far enough out into the blackness of space and you might just see the back of your own head, says **Paul Parsons**



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IT'S A QUESTION MOST OF US HAVE LAIN awake puzzling over: where does space end? And if it does end, then what lies beyond? Most astronomers were convinced our Universe was infinite, literally without end. But dramatic new evidence has now thrown up a mind-boggling possibility – that space is not only finite, but wrapped around itself like a giant cosmic video game. Leave on one side and you magically reappear on the other.

"This model seems to be the natural interpretation of the data," says Boudewijn Roukema, of the Torun Centre for Astronomy, at Nicolaus Copernicus University in Poland. "Most physical objects we know of have finite masses and sizes. Why should the Universe be any different?"

Astronomers have long entertained the idea that space might not go on forever. In 1924, Russian mathematician Alexander Friedmann used Einstein's new theory of relativity to work out that if the matter in our Universe was above a certain 'critical density' (averaging at around one thousand-billion-billion-billionth of a gram per cubic centimetre), then its gravity would be sufficient to curve the whole of space into a sphere.

The surface of an ordinary sphere has only two dimensions, so in order to describe the three-dimensional space of our Universe, Friedmann extended the concept to what mathematicians call a 'hypersphere' – a sphere with a 3D surface. Astronauts could, in principle, set off in any direction in a hyperspherical universe and arrive back where they started, much like sailors circumnavigating the 2D globe of the Earth.

IN A NUTSHELL
What is cosmic topology?

It's the question even relativity can't answer: what shape is the Universe? Is it an infinite flat sheet, a closed sphere, a ring-shaped 'torus', or something altogether more bizarre? Nobody knows for sure, but tantalising new evidence suggests space may have a complex wraparound structure based on a 12-sided dodecahedron. Exit on one side of the dodecahedron and you re-enter through the opposite face. It's a controversial claim, but data from a new satellite due for launch this summer could settle the debate.

Shaping the Universe

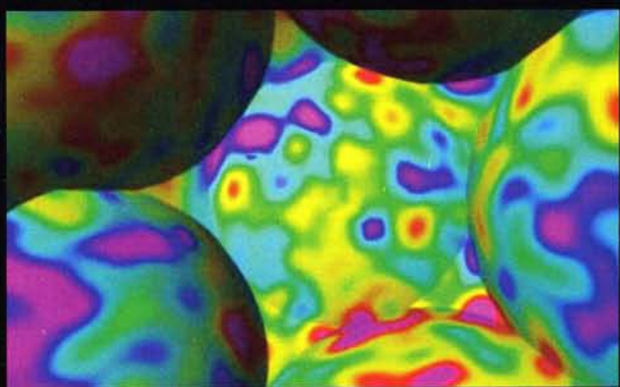
A sphere is the simplest example of a space that's finite, yet has no boundary. But it's not the only one. Think of a flat sheet of paper rolled up into a cylinder. Now imagine that the paper was flexible enough so that the cylinder itself could be curled around and the two ends glued together to make a shape a bit like a ring doughnut, known as a 'torus'. If you were living on the surface of a torus, there would be two possible routes that could bring you back to the point where you set off – either a long hike around the ring, or a short-cut through the hole in the middle.

Above: **Alexander Friedmann said the Universe could be curved**

Top: **Friedmann worked out how space can wrap round on itself to make a sphere**

Because of this, experts say the sphere and the torus have different 'topologies': the ball is said to be 'simply connected', while the doughnut is 'multiply connected'. Topology is a branch of maths that deals with classifying shapes according to how points on their surfaces join up. Any shapes that can be continuously deformed into one another – without cutting or gluing them – are said to be topologically the same thing. So to a topologist, a ring doughnut and a teacup are much the same thing, whereas a doughnut and, say, a tennis ball are very different. That's because if the ball was made of plasticine it's impossible to deform it into a doughnut without poking a hole in the middle (remember, no cutting is allowed). But if you start with a doughnut, then it's a simple matter to shrink the ring into a handle and fashion the rest of it into the concave shape of a cup.

Now these ideas are filtering down into cosmology – the study of the



A wraparound universe makes multiple copies of itself

CIRCULAR REASONING

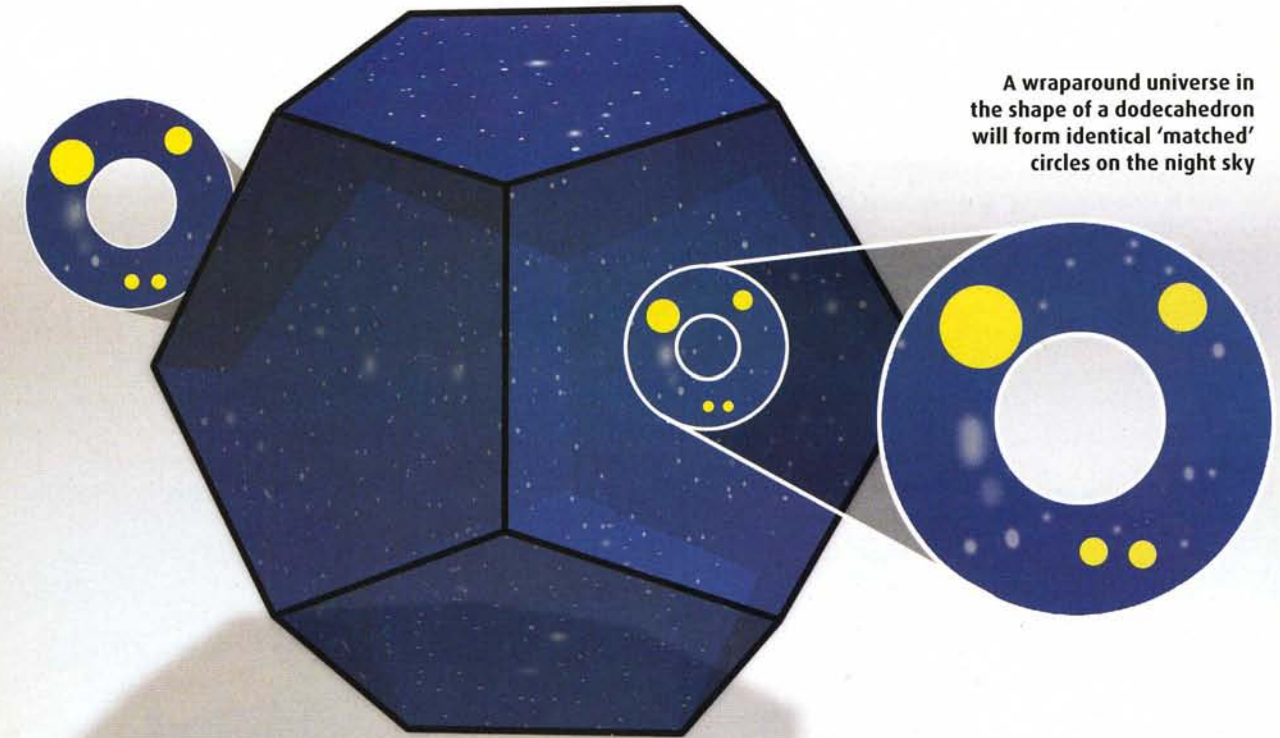
How pairs of circles on the night sky could reveal whether we live in a wraparound universe

Space is pervaded by the electromagnetic echo of the Big Bang. Astronomers call this echo the 'cosmic microwave background' (CMB) radiation, and imprinted on it are the tiny density ripples from which galaxies and the Universe as we know it later grew.

The CMB is a bit like a giant sphere surrounding the Earth. But if we live in a wraparound universe, then this sphere will be wrapped around with it, and could overlap with itself. Where the CMB sphere meets itself it forms a circle – like the circle formed by two soap bubbles stuck together. Only here, the two are actually the same bubble – one that's reached all the way around the Universe. That means that an astronomer on Earth, at the centre of the bubble, can see two copies of the circle (albeit mirror images) in opposite directions on the night sky.

Astronomers have therefore been searching the sky for pairs of these 'matched circles', that have the same pattern of CMB ripples around their edges. Detecting the circles would be a clear sign that our Universe has a wraparound structure.

Earlier this year, a team of astronomers led by Boudewijn Roukema, of Poland's Torun Centre for Astronomy, scoured the CMB for circles. The team arranged 12 annuli – 'thickened' circles – one on each face of a dodecahedron, and ran it through a computer to scan for matches with the CMB. They found one orientation of the dodecahedron in particular that gave an exceptionally strong fit to the data. Their claim remains controversial, though it could be confirmed or refuted by new experimental data in 2009.



A wraparound universe in the shape of a dodecahedron will form identical 'matched' circles on the night sky

Universe at large. "In traditional *cosmology*, the space of the Universe is always assumed to have simply connected topology," says Jean-Pierre Luminet, at the Paris Meudon Observatory, France. "People are now considering multiply connected models of space."

The most basic multiply connected topology that could describe our Universe is a hypertorus – an extension of the 2D torus to three-dimensional space. While an ordinary torus is made by joining opposite edges of a flat sheet, the hypertorus is what you get by 'rolling up' a cube of space and gluing together its opposite faces. The result is that if you exit the cube through one face you'll re-enter it through the face opposite.

» JARGON BUSTER

Topology
How points in space join up with one another

Simply connected
The topology of flat, infinite space

Multiply connected
More complex topology, where space wraps around on itself

Twelve faces

According to Boudewijn Roukema's team at Torun Centre for Astronomy in Poland, our Universe might have just this sort of structure. Rather than bending and gluing a simple cube, they've found evidence that the topology of space amounts to connecting up opposite faces of a dodecahedron – a polyhedron with 12 sides, each a regular pentagon. It's the shape, oddly enough, that the ancient Greeks used to represent the Universe.

The idea was first put forward by a team of theoretical cosmologists led by Luminet, and published in science journal *Nature* in 2003. Luminet's team had noticed something odd in observations of the cosmic microwave background (CMB) radiation – a kind of electromagnetic echo from the Big Bang. Imprinted on the CMB are ripples and splodges, tiny irregularities in microwave temperature. These correspond to irregularities in the density of matter in the early Universe.

In 2001, a NASA spacecraft called the Wilkinson Microwave Anisotropy Probe (WMAP) returned the most

ASK THE EXPERT

Jean-Pierre Luminet
Paris Meudon Observatory, France

What determines the overall shape of the Universe?
Most of the behaviour of the Universe is determined by the general theory of relativity, but general relativity is only a local theory and cannot specify the global condition of spacetime. So, in order to make cosmological models, assuming that space could have a multiply-connected shape, it is necessary to add some purely topological assumption, independent from general relativity. This will come from a fundamental theory larger than general relativity – for instance, a consistent quantum theory of gravity.

Can the topology of the Universe change?
In the framework of general relativity, a mathematical theorem, proved in the 1970s, showed that space topology cannot change during the Universe's evolution. Change of topology can be imagined only in quantum gravity theories.

So could measurements of cosmic topology hint at the correct quantum theory of gravity?
In the ideal situation, yes: if we could detect special topology for space now, the only explanation would be in the quantum era, shortly after the Big Bang, which was governed by a fundamental theory – like maybe a superstring theory or loop quantum gravity. So, in principle, detecting a given topology now should give a constraint on that theory. But quantum gravity theories are not yet developed enough to include this kind of constraint.

If the Universe is multiply connected, could we see images of our own galaxy?
In principle, yes. But, in fact, in our model, the radius of space is about 90 per cent of the distance light could have travelled since the Big Bang. And in that case it is not possible to have ghost images of our Milky Way. The closest ghost image of the Milky Way would correspond to emission of the image at a time when our galaxy did not exist yet.

What will be the next big thing in cosmic topology?
If the angular resolution of the Planck spacecraft really is better than WMAP, maybe we could detect a topological signal. The main step would be to include more topological considerations into the quantum gravity theories. But this kind of work is still in its infancy.

Multiple copies of the Earth in a dodecahedral universe

accurate maps of the CMB ever compiled. Analysis of the maps revealed the size and distribution of the ripples and splodges, and showed them to be in excellent agreement with the standard view of the Universe as simply connected and infinite.

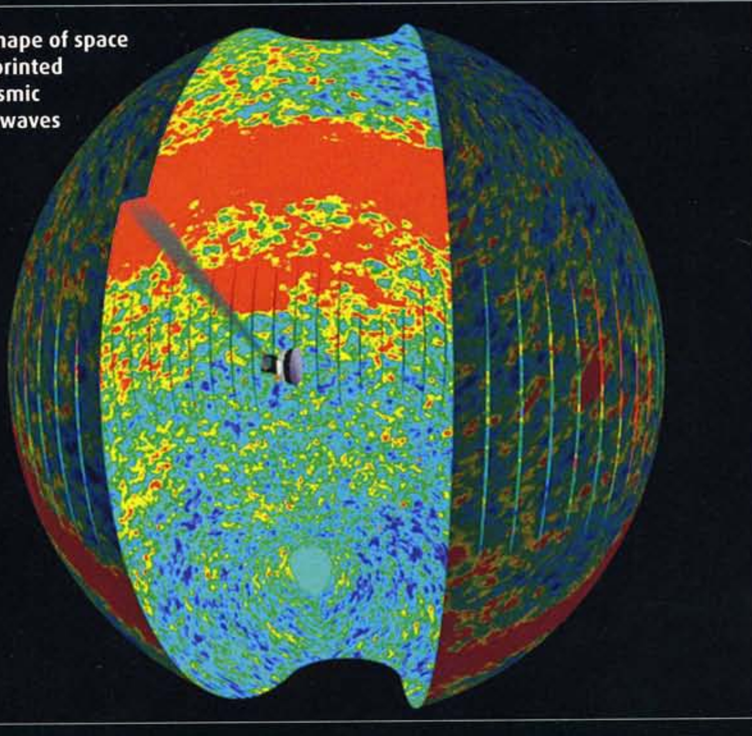
There was just one problem: at large scales, the ripples and splodges abruptly vanished. Imagine taking a picture of the CMB and gradually cranking up the pixel size, making the image coarser and coarser – there came a point where the picture suddenly went blank. And this was totally at odds with the standard view.

To Luminet, it was a clear sign that the Universe is finite. "Space cannot contain vibrations larger than space itself," he says. "This leads to a cut-off of power in the CMB observations, which is what WMAP saw."

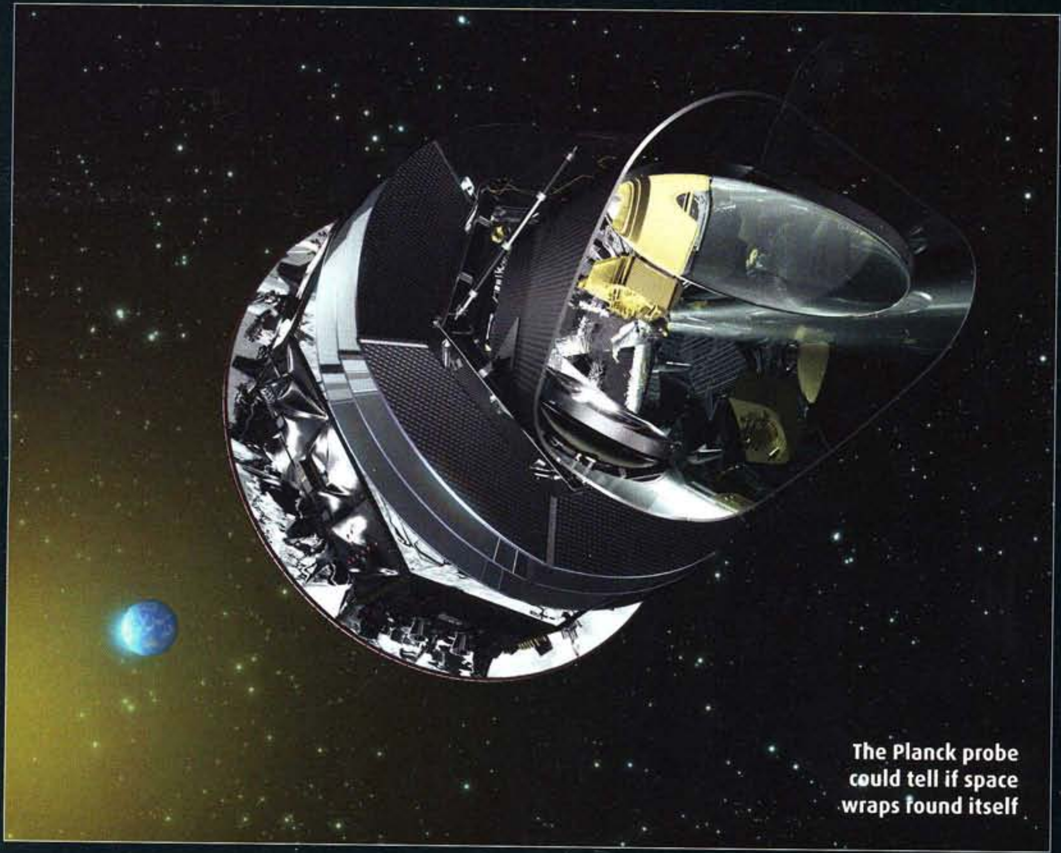
To an astronomer on the inside, a dodecahedral universe would resemble a cosmic hall of mirrors – multiple images of the universe stacking up behind one another as the observer's line of sight circled repeatedly around the multiply connected space. At least, in principle. The scale of the WMAP cut-off suggests that if our Universe really is a dodecahedron, then it's quite a big one – roughly 90 billion lightyears in diameter. And in that case, light simply hasn't had time to complete very many circuits around it since the Big Bang.

That's forced astronomers to adopt a different approach. They are investigating the topology of space using a method called 'matched circles'. It involves looking for circles in the CMB in different directions on the sky that have the same pattern of temperature fluctuations around their edges (see 'Circular reasoning' on p37). "If the Universe is multiply connected we could expect this kind of topological signal to be present in the WMAP data," says Luminet.

The technique was pioneered by astrophysicist David Spergel, at Princeton University, and colleagues. In 2004, they put it to use. "This was



The shape of space is imprinted on cosmic microwaves



The Planck probe could tell if space wraps found itself

one of the first things that I looked for in the WMAP data," says Spergel. "Luminet's group sent us simulated data based on their models and we were able to find all the circles in a blind test. But the same code did not find statistically significant circles in the real data from WMAP. The current data is consistent with the Universe being large and not multi-connected."

The circle thickens

It seemed that Luminet's theory was ruled out. But earlier this year, Roukema's team decided to look more closely. They suspected that data could have been blurred by random noise in WMAP's instruments and degradation of the CMB as it crossed the Universe, making the topological signal weaker. So they tweaked the matched circles method to make it more sensitive, by analysing more data. "In some sense, you could say our new method uses 'thickened' matched circles," says Roukema. "This allows us to use a larger number of data points in the maps than for a 'pure' circles method."

His team took 12 of these thickened circles, arranged to correspond with the 12 faces of a dodecahedron, and ran a computer search to try and fit them to the CMB. When they did this, they struck gold. "A clear best solution was found, in which pairs of apparently distant points are strongly correlated to one another for one particular orientation of the dodecahedron," says Roukema.

And there was another twist – quite literally. Since the opposite faces of a perfect dodecahedron are rotated from one another by 36°, matched circles should be twisted by the same amount. "We found a twist angle of 39°, plus or minus 2.5°, which is surprisingly close to what is required for the dodecahedral space model."

But Spergel doesn't buy it. "This is certainly not a detection," he says. "It's most likely a random noise fluctuation." Indeed, Roukema's team states there's a nine per cent chance the finding could just be a fluke. Yet even if it is, that still doesn't explain the cut-off seen in the WMAP data. Spergel's team put this down to chance as well, but Luminet disagrees. "The topic is controversial," he says. "In some papers, Spergel's team themselves have claimed that a statistical fluke for the WMAP cut-off was excluded at a 95 per cent confidence level."

It seems only one thing will resolve the dispute: better data. And that may get a step closer later this year, when the European Space Agency plans to launch its Planck space probe.

Planck will study the CMB in even greater detail than WMAP. Crucially, it'll survey the microwave background's polarisation – mapping the direction in which the electromagnetic fields making up the radiation are aligned. "Polarisation is definitely the key," says Andrew Jaffe, an astrophysicist at Imperial College London. "Multiply connected universe models predict a very specific relationship between polarisation and temperature. Planck should be able to make a definitive statement."

The mission is due to launch in July, but full science operations won't begin for another year. Until then, where space ends is likely to remain one of the most hotly debated questions in cosmology. And keep a few more people awake at night.

» FIND OUT MORE

http://arxiv.org/abs/0801.0006
Boudewijn Roukema's team find new evidence that the fundamental shape of the Universe is a dodecahedron

The Wraparound Universe
By Jean-Pierre Luminet (AK Peters, 2008)

tinyurl.com/2h39ss
Further explanation of the Poincaré Dodecahedral Space model investigated by Roukema *et al*

How the Universe got its Spots
By Janna Levin (W&N, 2002)

WIN

For your chance to win one of 10 copies of Jean-Pierre Luminet's *The Wraparound Universe*, just tell us the name of the new European Space Agency satellite that will study CMB radiation. Answers to the address on page 101.