Selected Article

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Fabric of the final frontier

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Space is a vacuum, featureless, blank and devoid of structure. Or is it? Neil Russell thinks space-time could be wearing a pinstriped suit

PARTICLES flying through space and time blindly follow the path set by any forces that are acting on them. Apart from these forces, four dimensional space-time itself is nothing but a blank canvas, a featureless backdrop against which everything plays out. So no matter what direction or speed a particle is moving at, its behaviour is the same.

This picture underlies the whole of modern physics in the form of a principle called Lorentz symmetry. But not everyone is happy with it. Instead of being a directionless backdrop, space could just as easily be dotted with minuscule invisible arrows that exert a subtle influence on particle behaviour. Imagine space-time wearing a pinstripe suit, with the pinstripes formed by rows of these tiny arrows. Any particles flying past will be weakly influenced by the pinstripes. The spin of electrons, the polarisation of photons, or the energy levels of atoms will be changed ever so slightly, depending on their direction and speed as they travel through the pinstriped space.

Over the past 6 or 7 years, almost two-dozen experiments have searched for signs of these pinstripes, by looking for violations of Lorentz symmetry. More experiments are planned worldwide, and some are proposed for the International Space Station. The results so far indicate that the effects of different kinds of pinstriping must be extremely subtle, if they exist at all. But this has only spurred physicists on to look harder.

Implicit in the search is a challenge to conventional thinking in modern physics. Lorentz symmetry, or the idea that there are no preferred directions or speeds in space, is a cherished principle. The love affair began in 1905, when Einstein developed his theory of special relativity, key to which was Lorentz symmetry. But in 1989, Alan Kostelecký of Indiana University in Bloomington and his colleagues in the US and Europe first argued that space need not be completely blank, or Lorentz symmetric, but could be endowed with a set of complicated quantities giving it a pinstripe structure (*Physical Review D*, vol 40, p 1886). Questioning Lorentz symmetry is serious stuff, but Kostelecký is undaunted.

"This is about understanding nature and space-time at its most fundamental level." To do that, he says, cherished ideas may well have to be overthrown.

Their approach, called the Standard Model Extension (SME), can be thought of as a description of all possible ways in which Lorentz symmetry can be violated in nature. To check for different kinds of violation, physicists have carried out a series of experiments whose results will help theorists working towards a unified theory of physics. More importantly, it could change our concept of space-time forever.

The most famous experiment to look for distinguishable directions in space was carried out in 1886 by Albert Michelson and Edward Morley in a laboratory at what is now Case Western Reserve University in Cleveland, Ohio. They were trying to detect an invisible luminiferous ether that was believed to pervade space. The ether theory said that light beams consisted of disturbances in the ether. Michelson and Morley compared the speed of light beams moving perpendicular and parallel to the direction of the ether that supposedly drifted through the laboratory as the Earth moved through space. They were unable to detect any difference in the speed of the two beams - thus disproving the ether theory.

Over the past century, there have been numerous experiments to test Lorentz symmetry, most of which share some features of the classic Michelson-Morley experiment. Broadly speaking, they fall into two categories: those that look for preferred directions, and those that look for preferred speeds. None has found any evidence for either, and so Lorentz symmetry has come to acquire the status of an unassailable principle of nature.

But Kostelecký argues that these experiments were limited because they did not consider all the different ways the principle of Lorentz symmetry could be violated. For example, the pinstripes may be invisible to photons, but visible to other particles, like protons or neutrons, he says. Or perhaps the pinstripes affect some aspect of photons other than their speed, such as their polarisation. And if pinstriping does affect other particles, it could be their spin or energy that are affected, not their speed.

The SME lays out all these possible kinds of pinstriping. Its breadth and applicability is striking: it is a general, self-consistent framework indicating every feasible manner in which Lorentz symmetry can be violated. With the SME's arrival experimentalists have been suddenly presented with a startling plethora of ways in which pinstripes could show themselves.

How did this come about? There are many reasons for thinking space might be pinstriped in some way. Theoretical physicists have tried for decades to find a way to unify the microscopic world of quantum theory and the curved space-time of general relativity. A consistent theory, a so-called quantum gravity theory, would encompass all the forces of nature and tell us how the universe behaved at the very earliest moments after the big bang.

Perhaps the most popular approach to uniting gravity, electromagnetism, and the strong and weak nuclear forces is string theory, in which point objects are replaced by microscopic strings. String theory may be able to bring together all the particles and symmetries of nature into a single elegant framework. In some versions of string theory there is a background field that enables violations of Lorentz symmetry to take place at low energies. This idea is called spontaneous symmetry breaking and Kostelecký prefers it to a symmetry that is universally respected. "Nature's beauty is more subtle than perfect symmetry," he says.

There is a simple way to understand the idea of spontaneous symmetry breaking. Imagine applying an inwards force to both ends of a flexible upright rod. As the force is increased, a point is reached where the middle of the rod spontaneously pops outwards in an unpredictable direction. The rod thus gains a sideways orientation even though the original state and the applied force did not have one.

A similar effect is exploited in particle physics. Physicists believe that space is pervaded by a field, called the Higgs field, which can create the Higgs particle at extremely high energies. The Higgs field is thought to have spontaneously frozen at a particular magnitude as the universe cooled just moments after the big bang. Symmetry breaking occurred because there were many equivalent constant values that the Higgs field could have frozen at, but it only froze at one. And this value in turn determined other values, such as the mass of electrons and some other particles. The freezing of the Higgs field is just like the spontaneous directional choice for the rod bending. The more complicated SME fields that we propose are frozen in fixed directions in space.

The beauty of this is that even if the underlying theory of quantum gravity is Lorentz symmetric, there could still be broken Lorentz symmetry, or pinstripes, around us. And our chances of detecting nature violating Lorentz symmetry are better than ever before. Not only does the SME give researchers specific information about what to look for, but advances in technology continue to increase the ability of experiments to resolve minuscule effects.

To see directional effects, an experiment must be able to "point" in different directions. Michelson and Morley pointed their apparatus by setting up paths for light to travel in perpendicular directions. But there are many other ways an experimental apparatus can have a direction.

For example, microwave cavities, which force microwaves to bounce back and forth at fixed frequencies, have recently been used to perform pinstripe tests in the US and Germany. The cavities are cylindrical, giving the experiments the ability to point in a direction. As the apparatus turns and moves with the rotation of the Earth, pinstripes could affect the oscillation modes of the microwaves within them. This could be observed by a rise or fall in the frequency of the microwaves.

Earlier this year, John Lipa and colleagues at Stanford University in California compared the frequency of microwaves in two cavities pointing in different directions and showed that pinstripes were not visible to photons within the limits of their experiment. In July, Achim Peter's group at the Humboldt University in Berlin pushed these limits down to around 100 times the sensitivity, but again failed to find any evidence for pinstripes.

Masers, microwave versions of lasers in which the spinning of nuclei and electrons generates microwaves, are also excellent systems for seeking out pinstripes. Ron Walsworth and colleagues at the Harvard-Smithsonian Center for Astrophysics in Cambridge, Massachusetts, built a maser containing helium and xenon gas in a bulb with an east-west magnetic field running through it. They monitored the energy of the microwave radiation from the helium maser using the xenon as a reference. Any small variations would be evidence of the pinstripes affecting the helium and xenon differently. This would occur because the angle between the magnetic field and the pinstripes change as the Earth rotates.

Instead, the experiment found a variation of less than 10^{-31} gigaelectronvolts in the microwave energy. The results show that the coefficients describing Lorentz violation associated with the neutron spin are extremely small. They rule out the visibility of pinstripes to regular matter at scales approaching the Planck scale - the tiny scale at which the weak effect of gravity becomes as big as those of other forces. "Masers can be used as atomic clocks - mankind's most sensitive tools for measuring changes in energy," says Walsworth.

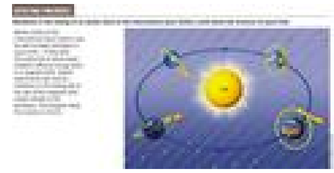
Bounds on symmetry breaking by more exotic particles have also been obtained. In 2001, Vernon Hughes of Yale University in New Haven, Connecticut, and colleagues found that muons don't appear to be sensitive to background pinstripes either, within the limits of their experiment. The group looked at the energies of the radiation emitted from the muonium atom - a hydrogen atom with the proton replaced by a positive muon - when it was placed in a magnetic field that defined a direction. There was no sign of any pinstripes of any magnitude down to the Planck scale.

With no sign of pinstripes showing in experiments, some researchers took a different approach and tried to see if pinstripes would have an effect on the polarisation of photons, which is the direction in which their electric field oscillates. Kostelecký and colleague Matt Mewes at Indiana University in Bloomington compared the polarisation of light of different colours that had travelled from distant cosmological sources. Even after light has travelled for several billion years, no measurable polarisation difference was discerned. The results rule out Lorentz violation relating to the polarisation of light at a level that surpasses laboratory tests by about 17 orders of magnitude, a truly far-reaching result.

Atomic clocks are also good pinstripe detectors, even though one does not think of a clock as having a direction. An atomic clock is a container of atoms with a magnetic field running through it. The clock ticks take the form of the oscillations of the radiation emitted when the atoms pass between two energy levels. If either the matter in the atoms or photons of radiation are sensitive to the presence of pinstripes, there should be slight perturbations in the energy levels of the clock atoms, and changes in the frequency of the emitted radiation as the clock changes direction.

Both the European Space Agency and NASA have plans to put atomic clocks onto the International Space Station (ISS). Lipa's group at Stanford is building a less noise-prone superconducting microwave oscillator (SUMO), which will be put into flight under NASA's guidance. One advantage of the ISS for these experiments is that it rotates every 90 minutes, making it easier to detect changes in the pinstripe directions (see Graphic).

So far, not a single experiment has found clear evidence for pinstripes, but many physicists are enthusiastic about future tests. We now know that it is possible to search for the pinstripes of space-time in a huge variety of ways. If we succeed in our quest, and discover that Lorentz symmetry can be broken, it would radically change our perspective on fundamental particles and help us towards a theory of quantum gravity. And who knows, if we do find pinstripes, future spacecraft may fly with a "pinstripe compass" that can identify directions in space-time. Provided we can find out which particles are able to see pinstripes in space-time, this craft will know exactly which way it is going.



Neil Russell
Neil Russell is a professor of physics at Northern Michigan University in Marquette, Michigan. He investigates the application of Lorentz symmetry theory to experiments

DETECTING PINSTRIPES

Variations in the ticking of an atomic clock on the International Space Station could reveal the structure of space-time

Atomic clocks on the International Space Station may be able to detect pinstripes in space-time – if they exist. The clocks tick as atoms move between different energy levels in a magnetic field. Several experiments will look for variations in the ticking rate as the axis of the magnetic field rotates relative to the pinstripes. This happens every 90 minutes on the ISS