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SPECIAL ISSUE

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The long arms of the law


SHONAGH RAE

Did Newton and Einstein get gravity all wrong? **David Shiga** investigates the dark force embracing the cosmos

A GOOD bit of our universe – 23 per cent of it, to be exact – seems to be made up of stuff we can't even see. Except, what if it isn't?

The leading cosmological theory says that invisible "dark matter" lurks in the hearts of galaxies, its extra gravity keeping the outermost stars from flying off into the void and generally making clusters of galaxies look the way they do. Nobody knows what this mysterious matter is, but it must be there, because all the visible stars, planets and other bodies do not have enough mass to account for the celestial motions we observe, according to Newtonian gravity.

But what if Newton was wrong? It's a long-standing question whether his law of gravity, supposed to explain everything from falling apples to spinning galaxies, might actually be flawed. That is the claim of a growing number of physicists who support a controversial alternative theory called modified Newtonian dynamics, or MOND. The theory has recently overcome some serious problems that had plagued it since its inception – such as how it fits with general relativity – and it is now able to make surprising predictions about the evolution of the universe.

Suddenly, people who used to scoff at the renegade theory are giving it a second look, sparking one of the hottest debates in astrophysics. If MOND is correct, it will pull the rug out from under the established view of gravity and dark matter, which together underpin almost everything we know about astronomy. "From being really out in the cold from a theoretical point of view, MOND is now being taken very seriously," says University of Oxford physicist James Binney.

What has made people sit up and take notice is a 2004 paper by Jacob Bekenstein of the Hebrew University of Jerusalem in Israel (*New Scientist*, 22 January 2005, p 10). His paper, the culmination of a 20-year quest to reconcile MOND with relativity, seems to have stood the test of time and has convinced several other groups to work on the theory and test its predictions. Their results suggest Bekenstein is on to something deeper: a theory of gravity that preserves the best aspects of relativity, but with modifications that could make dark matter obsolete – even as efforts to find it are heating up.

The story goes back to 1933, when Swiss astronomer Fritz Zwicky noticed that galaxies in certain clusters were moving so fast that the clusters shouldn't be able to hold onto them – yet they did. To explain this, Zwicky suggested that extra, unseen matter in the clusters provided the gravitational glue. He called this stuff dark matter. By the 1970s, astronomers realised there was a similar problem for individual galaxies: they are spinning so quickly that they should tear themselves apart. Here too, dark matter was invoked.

In 1981, physicist Mordehai Milgrom hit upon the alternative theory of MOND. He was at Princeton University at the time but soon moved to the Weizmann Institute near Tel Aviv, Israel, where he remains today. He went to visit Bekenstein, then at Ben-Gurion University in Beersheba in the south of the country. "He said he had something very interesting to show me," recalls Bekenstein, who was best known for his work on the thermodynamics of black holes. Milgrom set out his idea that galaxies and galaxy clusters might remain intact not because of unseen matter but because gravity itself does not weaken with distance as quickly as Newton's law says it should. Intrigued, Bekenstein began working with Milgrom on the theory.

The name MOND contrasts the theory with Newtonian gravity, even though this was essentially replaced by Einstein's general relativity in the early 20th century; the name makes sense because astronomers still use Newton's equations for most situations. However, Milgrom and Bekenstein were effectively challenging relativity too. That's because MOND would have to be different enough from relativity to make gravity noticeably stronger in the outskirts of galaxies, yet not so different that it contradicted aspects of relativity verified in observations stretching back to 1919.

Rethinking relativity

That was a problem. Milgrom published his theory in 1983, but no one could see how to reconcile it with Einstein's well-tested model. Also, it seemed too ad hoc in that it simply modified gravity below a certain strength, thereby altering its behaviour typically at large distances. So in 1984, Milgrom and Bekenstein published a version that attempted to explain MOND as a modified version of general relativity. They took relativity and added a second gravitational field to provide the extra pull needed to keep spinning galaxies stable.

There was a snag, however: disturbances in this extra field would travel faster than the speed of light, creating a breakdown of cause and effect. Neither Milgrom nor Bekenstein knew how to fix this, so they both gave up the quest for a while. "When you see a big mountain in front of you, the first feeling you have is that it's the end. I mean, you're not going to get over this," Bekenstein says.

Ten years on and things had grown worse, with the discovery of new evidence for dark matter. Astronomers had been examining the way gravity bends light as it passes by galaxies, a phenomenon called gravitational ▶

DARK MATTER vs MOND

A cosmological battle has raged for decades between supporters of dark matter and modified Newtonian dynamics (MOND)

1933	Fritz Zwicky coins term "dark matter" to describe unseen mass in galaxy clusters
1978	Astronomers show that many galaxies are spinning too quickly to hold themselves together unless they are full of dark matter
1983	Mordehai Milgrom publishes a modified gravity theory called MOND. It explains why galaxies don't fly apart without invoking dark matter, but remains at odds with Einstein's relativity
1990s	Studies of galaxies and galaxy clusters show that their gravity bends light more strongly than is expected without dark matter. MOND researchers start devising improved theories to explain extra light bending without dark matter
1994	Jacob Bekenstein and Robert Sanders prove that any theory that resolves the light-bending issue and meshes MOND with relativity must involve at least three mathematical fields
2000	New data on the cosmic microwave background reinforces the standard, dark-matter picture of the universe
2004	Jacob Bekenstein devises a version of MOND that is consistent with relativity
2005	Constantinos Skordis and others show that relativistic MOND provides a good fit to the microwave background data
2008	LISA Pathfinder spacecraft could detect gravitational anomalies due to MOND

A good MOND is hard to find

Where do you go to look for modified Newtonian dynamics (MOND)? Try our own solar system. Since the early 1980s, NASA's Pioneer 10 and 11 space probes have been coasting away from the sun in the outer solar system. Puzzlingly, they have been decelerating more quickly than Newton's law of gravity would predict. The cause of this "Pioneer effect" is hotly debated, but the rate of deceleration is about what you would expect if Jacob Bekenstein's theory were correct. Still, most physicists won't accept the modified gravity explanation unless a dedicated mission confirms the Pioneer effect is real.

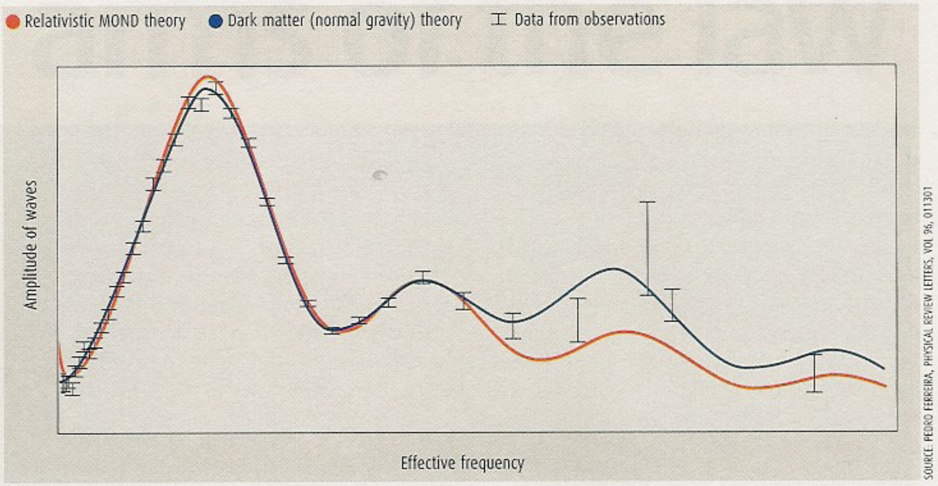
MOND might be more definitively tested through NASA and ESA's Laser Interferometer Space Antenna (LISA) project, designed to look for gravitational waves – ripples in space-time created by cataclysmic events like the collision of neutron stars. In 2008, a test mission called LISA Pathfinder will wind its way outward in larger and larger orbits around the Earth, carrying devices that sense very small accelerations.

Scientists are considering sending Pathfinder through the point in space where the gravity of the Earth and sun balance out precisely. Under Newton and Einstein, the gravitational force at that point should be zero. Under Bekenstein, however, there should still be a slight force. It is not clear whether Pathfinder will be sensitive enough to detect this force, but if it does, it will be a victory for MOND.

The main LISA mission in 2015 might also shed light on MOND if it succeeds in measuring gravitational waves. Unlike such waves in general relativity, gravitational waves in Bekenstein's theory move more slowly than light because one of the extra fields slows them down. If LISA were to find that the waves do indeed move more slowly than light, it would be strong evidence that MOND is on the right track.

CATCHING COSMIC WAVES

Relativistic MOND is able to explain a well-known pattern in the cosmic microwave background, caused by acoustic waves from the big bang. This pattern was previously understood only by assuming dark matter exists



lensing. The lensing they saw was much stronger than what the galaxies' ordinary matter should have caused, but consistent with what general relativity predicted from galaxies filled with dark matter. Either galaxies really had hidden mass, or MOND would have to provide extra light-bending too.

Bekenstein didn't give up. In 1994, he and Robert Sanders of the University of Groningen in the Netherlands proved that you could never satisfy all the demands facing MOND if you restricted yourself to adding just one field on top of the standard gravitational field in relativity. Instead, a workable relativistic version of MOND would have to contain at least three fields.

Frozen field

In 1997, Sanders published a three-field version of MOND. The third field provided extra gravitational lensing and also got rid of faster-than-light waves, but again there was a catch. The field was a type called a vector field, which at each point in space has a magnitude and a direction. To get the right lensing results, Sanders froze the vector field so that it would always point in a particular direction: the direction of time. In relativity's four-dimensional universe, time is just another direction, like up, down, left or right. The frozen field violated the symmetry principle that space-time should have no preferred direction. "That's in a sense throwing the baby out with the bath water," Bekenstein says.

And so things stood until 2003, when Bekenstein finally found a way forward. Stuck at home with an illness, he realised he could unfreeze the vector field in Sanders's theory but still get it to point in the right direction. It isn't against the rules of relativity for the field to wind up pointing in a particular direction, as long as this behaviour is not locked in beforehand. The vector field in Bekenstein's version is free to point in any direction, but it tends to align itself in the time direction through its interactions with the other fields, the way a compass needle homes in on north.

Here at last was a version of MOND in harmony with well-established parts of relativity, yet different in a way that made dark matter unnecessary. Bekenstein named it "Tensor Vector Scalar" theory, or TeVeS, after the three kinds of fields it employs (*Physical Review D*, vol 70, 083509). The tensor field, from general relativity, describes the usual gravity arising from the curvature of space-time. The scalar field gives gravity extra strength in places such as the outskirts of galaxies. The vector field enhances gravitational lensing.

It may still sound ad hoc, but with the theory finally on a relativistic footing, even long-time sceptics are giving it a second look. "For me, MOND was a dirty word for years," says astrophysicist Pedro Ferreira of the University of Oxford. The big problem was that you couldn't address cosmology under MOND because it lacked a relativistic framework, he says. "What changed my mind was Bekenstein's paper."

Now several groups are using the theory to make cosmological predictions. Ferreira worked on a 2005 study led by Constantinos Skordis of the Perimeter Institute in Waterloo, Ontario, to predict how the large-scale structure of the universe would turn out under TeVeS following the big bang (*Physical Review Letters*, vol 96, 011301). Despite the cobbled-together nature of Bekenstein's theory, it naturally solves a fundamental problem in cosmology that is usually solved by invoking dark matter.

Galaxies are thought to have formed from relatively dense pockets of matter in the wake of the big bang. These dense patches were part of a pattern of giant acoustic waves that rippled through the universe, compressing and rarefying the soup of hot matter. The puzzle is how these variations could persist long enough for galaxies to form: in the white heat of this early era, countless photons zipped around and bounced haphazardly off particles of matter, and this should have blown the dense pockets apart before they could develop into galaxies. The standard explanation for what held the pockets together is – you guessed it – dark matter.

In Bekenstein's universe, however, the pockets survive even without dark matter. "The effect of MOND is to kind of sustain these structures through this smoothing phase, so the seeds of galaxies aren't wiped out through that period," Ferreira says.

The rivals

When it comes to alternative theories of gravity, MOND isn't the only game in town. Other proposed ideas:

Brans-Dicke theory (1961)
Carl Brans of Loyola University Chicago and Robert Dicke of Princeton University proposed that the gravitational constant of general relativity depends on an additional scalar field. The strength of gravity varies in time and space according to the strength of this field.

Scalar Tensor Vector Gravity (2005)
Joel Brownstein and John Moffat at the Perimeter Institute for Theoretical Physics in Waterloo, Ontario, described a theory in which quantum fluctuations alter the strength of gravity from place to place, giving rise to MOND-like effects.

Bi-Scalar Tensor Vector Theory (2005)
Robert Sanders of the University of Groningen in the Netherlands put forward this model, which is like Bekenstein's relativistic MOND, but with two scalar fields altering gravity instead of one. Vibrations in the second field give rise to a kind of dark matter.

"If the law of gravity doesn't work, our picture of the universe is going to change drastically"

With TeVeS, the extra scalar field develops variations of its own that reinforce the dense pockets of matter, preserving them long enough for galaxies to form.

Although the cosmic sound waves behave in roughly the right way under Bekenstein's theory, there is debate over whether their detailed behaviour is correct. To see how the real waves behaved, astronomers look at the cosmic microwave background, the radiation emitted by the hot matter at around that time in the universe's history. We can detect this faint glow all over the sky, but it is not uniform. It is finely mottled, with some areas slightly brighter than others, and these variations correspond to where the waves made matter denser in some regions (see Graph, page 54). This even allows us to see what different frequencies of wave existed.

Sceptics argue that relativistic MOND gives fewer high-frequency waves than is implied by observations. "I think it's very difficult to reconcile what we've observed in terms of the amplitude fluctuations in the microwave background with the MOND theory," says astrophysicist David Spergel of Princeton University. In particular, he says, the theory underestimates how strong acoustic waves with wavelengths of about 100,000 light years must have been.

MOND proponents counter that measurements in this wavelength region are not yet very precise, and so it's not clear that Bekenstein's theory is at odds with them. Future missions such as the European Space Agency's Planck spacecraft, scheduled to launch in 2007, will map out the microwave background to higher precision and should help resolve the ambiguity.

Who needs it anyway?

Scepticism, however, runs much deeper than that. Spergel doesn't see the need for the theory in the first place, even in the realm where MOND has traditionally been strongest. "I have not seen any really convincing case for the need for MOND-like physics on galaxy scales," he says, because the stability of galaxies can be explained with dark matter. Indeed, even if MOND does well in future tests, its creator Milgrom thinks many experts will continue to support dark matter. "This is their livelihood. This is their claim to fame," he says. "They will never change their mind."

Conversely, the only thing that could rule out MOND in the near future would be direct detection of dark matter. About 20 different experiments are under way, or about to begin, that could detect dark matter particles within five years. One group of US universities is running the Cryogenic Dark Matter Search II, which is monitoring silicon crystals to look for small vibrations created by the impact of dark matter. They have not detected any so far, but they are gradually improving the sensitivity of the detectors. If any experiment finds dark matter particles in sufficient abundance – whether neutrinos or something else – then out go the alternative gravity theories.

Until then, MOND will remain a thorn in the side of the astrophysics establishment. If the theory survives and garners supporting evidence from future missions (see "A good MOND is hard to find", page 51), astronomers will still face a long road ahead. Over the years, they have built a comprehensive picture of the universe using dark matter as a key ingredient. "That stuff rests on 25 to 30 years of laborious work," says Binney. "To do a comparable job with a much more tricky theory is going to be a long haul, and people are only beginning on it at this point."

Bekenstein concurs and goes even further. "All that we have learned about the universe in the last 300 years since Newton was learned really by combining the universal law of gravity of Newton with various pieces of physics," he says. "If you're going to change this, and you say that the law doesn't work, literally, in galaxies and bigger systems, then our picture of the universe is going to get changed drastically."

Either way, the picture will probably include a more fundamental theory of gravity. Even Spergel, despite his criticism of MOND, finds Bekenstein's theory interesting in a deeper sense, as a variation of relativity. "General relativity, while it's been a very successful theory, may not be the complete theory," he says. "Most people think it is not the final theory." When the dust settles, we may find that dark matter, Newton's law of gravity and even Einstein's most famous theory are all things of the past. ●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