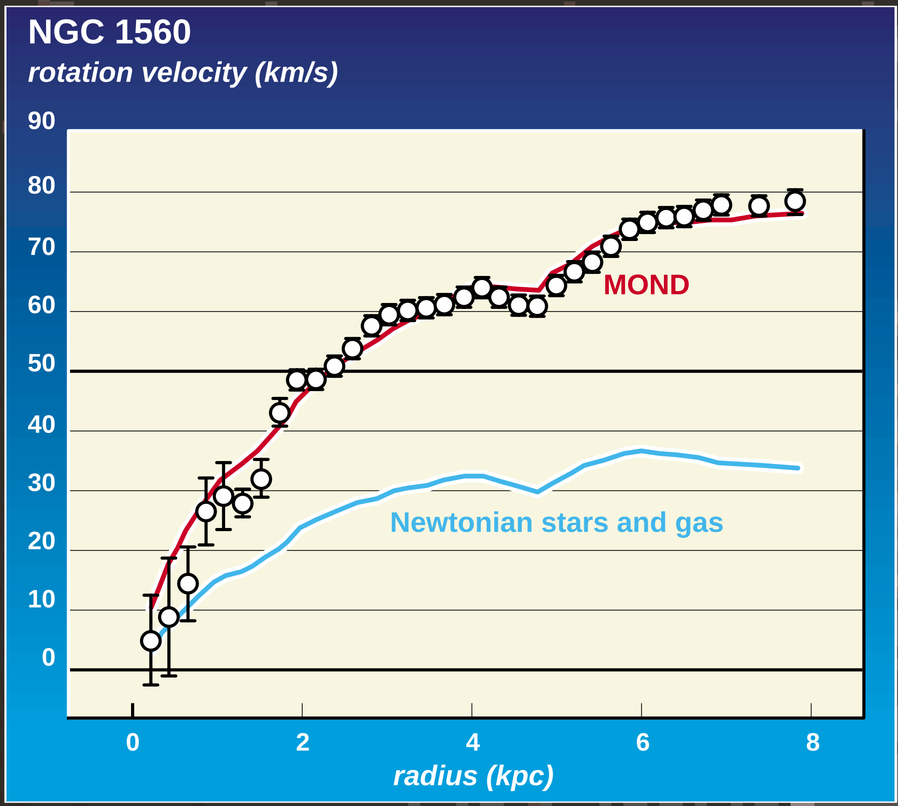
Mond over matter

A new way of looking at gravity, called 'MOND', could explain a slew of astronomical inconsistencies, and eliminate the need for dark matter. By Stacy McGaugh



The rotation curve of the dwarf galaxy NGC 1560. The data points are from 21 cm observations of hydrogen by K Begeman, A Broeils, and R Sanders. The lower line is the rotation curve predicted by Newtonian gravity. This falls well short of the observed rotation, leading to the inference of dark matter to make up the difference. The upper line shows the rotation curve predicted by MOND. Similar results are now known for over 100 galaxies. Note that in this case, even the kink observed in the gas distribution is reflected in the rotation curve. This is exceedingly difficult to explain with dark matter, which is not distributed in the same way as the luminous mass. AN graphic by Mark McLellan.

For many years now theoretical astronomers have wrestled with the problem of dark matter. Basically, there's a lot less matter visible in galaxies than is inferred gravitationally from the motion of their stars and gas. The usual solution is to top up the mass of the galaxies with unseen 'dark' matter. But what if the fault lies not with the amount of matter present, but with the law of gravity governing its motion?

The modern conception of gravity began in the 17th century with Sir Isaac Newton. At the heart of his universal law of gravitation is a simple empirical observation that everything happens as if the force between two bodies is directly proportional to their masses multiplied together and inversely proportional to the square of the distance between them.

This plain fact explained the detailed motion of the Moon, encapsulated Kepler's Laws of planetary motion and, today, lets us navigate tiny spacecraft through the vast expanses of interplanetary space with remarkable precision. Never in history has any such plain-spoken observation carried us (literally) so far.

Newton's law of gravity has been tested over a wide range of scales – from distances of a fraction of a millimetre right out to the orbits of the furthest planets. It is rivalled by few other physical theories for its universality.

Indeed, the trust placed in Newton's 'clockwork' universe was such that when a tiny excess precession of Mercury's orbit – not predicted by Newton – was discovered, it constituted a major scientific crisis during the 19th century.

Enter Einstein

The problem of Mercury's orbit was resolved by Einstein's theory of general relativity, the only significant update to our understanding of gravity since Newton. General relativity has withstood many precision tests. The repeated successes of Newton-Einstein theory, coupled with the sheer eminence of its authors, has led to a widespread attitude among scholars that, when it comes to gravity, there is nothing new to learn. Yet, many of these same authors simultaneously adhere to the attitude that there must be a unified theory of the four fundamental forces – something which demands a rethink of gravitation.

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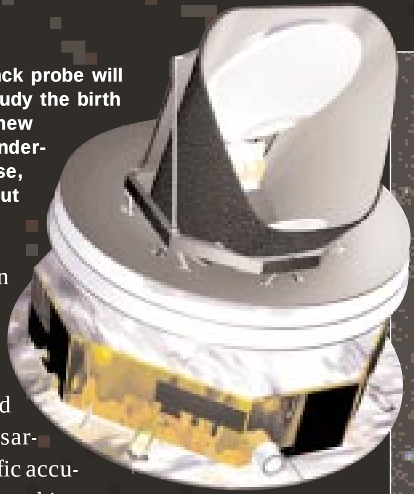
The trouble with this view is that so far gravity has steadfastly refused to be assimilated into the quantum mechanical picture, essential to the description of electromagnetism and of the two forces that operate within atomic nuclei. Therefore, it seems that there must be a quantum theory of gravity. Pursuing this to its logical conclusion, there must be yet more to learn beyond what Newton and Einstein have already told us.

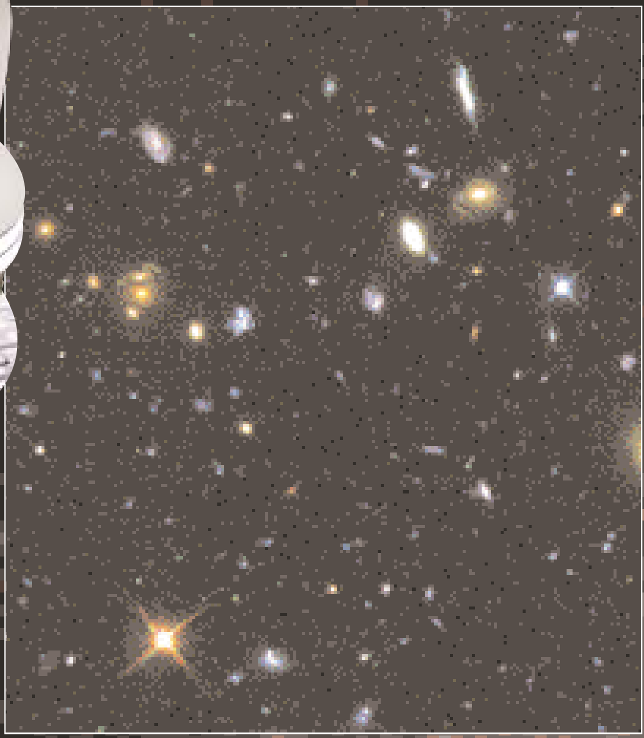
Even outside the quantum realm, there are other gravitational puzzles that remain to be explained. One of the most pertinent is commonly referred to as 'the dark matter problem'.

When astronomers measure the motions of stars and gas in galaxies and yet larger systems, they find speeds well in excess of what can be explained by the application of Newton's universal gravitation to the mass in visible forms such as stars (see graph above). This has led to the inference that most (maybe 95 per cent) of the mass in the universe is dark.

There is a tremendous amount of evidence for dark matter. Yet all this evi-



The European Space Agency's Planck probe will be the first European mission to study the birth of the universe. It will also reveal new details about the force of gravity underpinning the evolution of our universe, and so could uncover the truth about MOND. Image: ESA.



A group of low-surface-brightness galaxies is picked out in this image, taken by the Hubble Space Telescope. Before galaxies of this type had even been discovered, MOND had accurately predicted many of their observable properties. Image: ASU/UAlabama/NASA.

dence is based on the assumption that Newton's theory can safely be applied to the scales of galaxies. Whilst this is an excellent starting assumption, we should not presume that it would necessarily hold true. Sticklers for scientific accuracy might object that, strictly speaking, we are faced not with evidence for dark matter, but rather for mass discrepancies. What we see doesn't add up, so either the universe is full of unseen mass, or the theory, which leads to the inference that mass is missing, needs revision.

Back to basics

It seems as if Newton's supposedly universal law of gravity is not universal after all. While it holds with great accuracy close to the Earth, it is patently false in galaxies and other extragalactic systems. But what if, instead of extra mass in the form of dark matter, there was extra gravity? In other words, over the scale of a galaxy, gravity pulled a little harder than we expect based upon our knowledge of its behaviour in and around Earth.

What if we could modify our laws of gravity so that they provide that extra force at long range, while leaving their behaviour on smaller scales untouched? If the idea holds, we would have no need for dark matter.

Many such attempts have been made, and many have failed. Indeed, these failures encouraged people in the direction of dark matter as the solution. Yet there is one idea that has yet to flounder. In 1983, Israeli physicist Moti Milgrom hypothesised a specific change in the equations governing particle motions at very low accelerations. He called the new theory modified Newtonian dynamics, or MOND. The theory reduces to the usual Newtonian form in the regime of 'high' acceleration, but at accelerations lower than a hundred-billionth of what we feel here on Earth things change in a way that might account for the mass discrepancy in galaxies.

This might all sound very contrived. But once the equations of MOND (or any other hypothesised modification) are written down, they leave little room for the theorist to manoeuvre. Each and every spiral galaxy provides a unique test of the hypothesis through its rotation curve – a graph showing the variation in the orbital speed of stars and gas with distance from the galaxy's centre.

Rotation curves calculated using MOND have now been compared with those observed in over 100 galaxies, with very favourable results. While there is certainly the occasional puzzle, there are no known cases where MOND clearly fails. In the vast majority, the theory clearly succeeds in explaining the motion of stars around the galaxy's heart without the need for dark matter.

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Explaining known phenomena is one thing, but it's more interesting when a theory predicts new ones as well. In his original 1983 papers, Milgrom made a series of predictions about a then unknown class of galaxies. At the time, such objects were thought to be rare or perhaps even non-existent. However, they have since been discovered and are now known as low-surface-brightness galaxies. In the process of studying these new objects for their own interest, astronomers gradually accumulated the data necessary to test Milgrom's largely forgotten, old predictions.

According to MOND, these dim and distant galaxies should exhibit even bigger discrepancies between their observed masses and those inferred by unmodified Newtonian gravity – their highly diffuse luminous material would generate even weaker gravitational acceleration than in brighter galaxies.

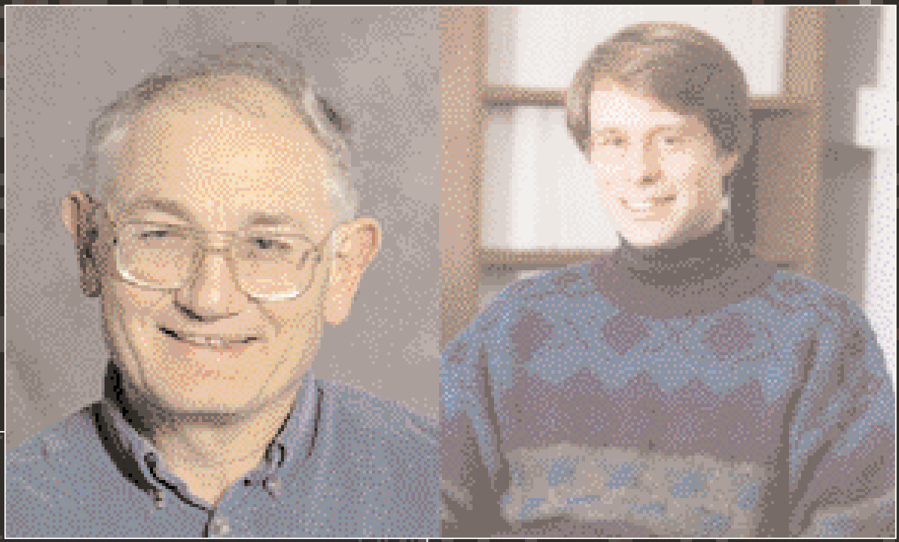
Milgrom listed a number of specific, testable consequences of the prediction. And it came as quite a shock when every one of them was borne out by observations. While, in principle, science advances by the construction of hypotheses that make predictions, which can subsequently be tested, it is rare indeed that the observations actually follow a hypothetical model so cleanly.

Accurate observations

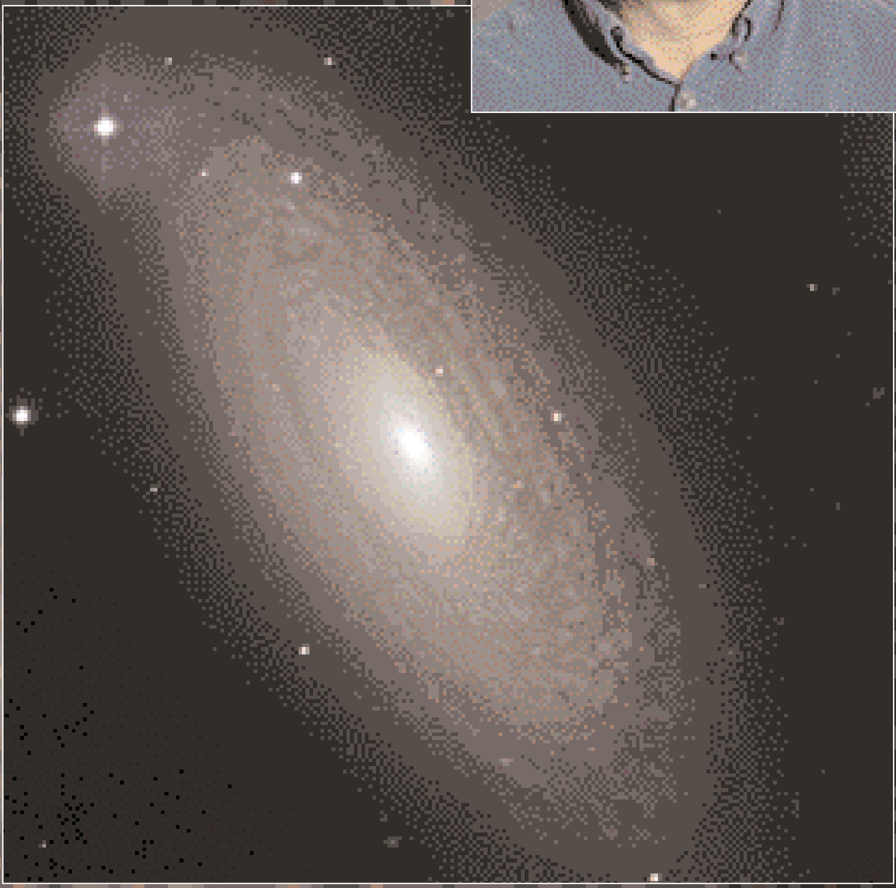
The success of MOND is most obvious in places where astronomers possess the most accurate dynamical data. However, there are other systems where the picture is less clear. Any modification of physical laws must explain the mass discrepancy everywhere – it is not sufficient to explain just spiral galaxy rotation curves; it must also work for the velocity dispersions of elliptical galaxies, the gas temperatures of clusters of galaxies, and the peculiar motions of galaxies in the large-scale universe.

One place where MOND appears to have serious difficulties is in rich clusters of galaxies. The luminous mass in these clusters is only half of what is needed to explain the observations. On the one hand, this may not seem so bad. Coming within a factor of two in astronomy is often viewed as a great success. But on the other hand, the discrepancy does appear genuine. This implies that there remains some additional mass yet to be discovered in clusters. This, in effect, invokes some form of dark matter – hardly a selling point for a theory that seeks to do away with the stuff.

That might be considered fatal for MOND, were it not for the fact that the dis-



LEFT Moti Milgrom, the Israeli physicist who devised the theory of modified Newtonian dynamics (MOND). **RIGHT** The author, Stacy McGaugh. Images: Weizmann Institute of Science (left) and University of Maryland (right).



Do spiral galaxies, like NGC 2841, pictured here, contain huge amounts of dark matter? Or, are their rotation curves caused by gravity deviating from Isaac Newton's long-standing law. Image: Nik Szymanek, based on information from the ING Archive.

covery of huge reservoirs of mass in clusters has happened before. It was long thought that the stars in the galaxies that made up the clusters were the biggest reservoir of normal matter there. But about a decade ago, it became apparent that the mass of hot, diffuse gas spread between the cluster galaxies greatly exceeds the mass in stars. It's hard to be confident that more mass won't turn up again.

Another problem is cosmology. Unmodified general relativity provides a satisfactory interpretation for the empirical aspects of the hot big bang cosmology: an expanding universe, nucleosynthesis of the light elements, and the relic radiation from the big bang – the cosmic microwave background. The success of standard cosmology is often equated with evidence against MOND. Yet the standard cosmology – ie, the one based on unmodified general relativity – is only viable if 90 percent of the mass indeed exists in an as yet hypothetical form – hardly a great boasting point. Worse, in recent years it has become necessary to revive Einstein's self-described 'greatest blunder' – the cosmological constant. One might wonder if these strange turns are hinting at some greater truth.

The cosmic microwave background may help to decide this issue. A universe full of dark matter leaves a signature on this echo of the big bang that's subtly different to one devoid of dark matter. Recent observations came tantalisingly close to distinguishing between the two cases. New space missions, like NASA's MAP and ESA's forthcoming Planck, could now do the trick.

Refusing to go away

Regardless of whether MOND is correct as a theory, there remains a real conundrum for the dark matter picture. MOND's predictions for the rotation curves of galaxies are borne out well by astronomical observations. But those based on dark matter theories are not. Yet many researchers in the field still cling to dark matter. They agree that MOND fits the rotation curves, but steadfastly refuse to think through the deeper consequences.

Nevertheless, the debate between dark matter and MOND is refreshing. There has been some concern expressed in recent years that science is at its end. All the fundamental discoveries have been made; there is nothing truly new left to discover. This sentiment echoes the words of British physicist Ernest Rutherford nearly a century ago, who said something to the effect that all that remains is to fill in the last few decimal points. Now, as then, the rumours of the end of fundamental science are greatly exaggerated.

Stacy McGaugh obtained his doctorate from the University of Michigan in 1992 and is currently Assistant Professor of Astronomy at the University of Maryland. More information about MOND can be found at his web site www.astro.umd.edu/~ssm/mond/.