BBC **ABSOLUTE BEGINNER? *YOU* CAN LEARN ASTRONOMY IN... 7 DAYS**

Sky at Night

THE WORLD'S ONLY ASTRONOMY MAGAZINE AND CD PACKAGE

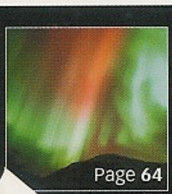
SEPTEMBER 2007 #28 ▸ £4.25
www.skyatnightmagazine.com

DARK MATTER IS DEAD

Why this distant galaxy cluster could overturn our view of the cosmos...

PLUS THE WORLD'S BIGGEST & BEST NIGHT SKY GUIDE

▼ MORE INSIDE



Airborne with the aurora
We take a flight to see the Northern Lights
Page 64

5-inch refracting scopes on test
Achromats from £369 reviewed and rated
Page 90

WIN! ASTRO IMAGING CCD CAMERAS WORTH £1,300

NO CD?
If this month's coverdisc is missing, please ask your newsagent for a replacement

9 771745 986003 09
FSC

DARK MATTER IS DEAD

Do the ideas contained in a new theory of gravity explain the Universe better than dark matter? **Marcus Chown** investigates

There is something odd about spiral galaxies like our own Milky Way. The stars in their outer regions are being whirled around far too fast. Like kids on a high-speed roundabout, they should be flung off into intergalactic space. To explain why this doesn't happen, astronomers have been forced to propose that the visible stars and nebulae are supplemented by invisible stuff, typically outweighing the luminous material by a factor of 10. The extra gravity provided by this 'dark matter' helps hold on to the fast-orbiting stars and stops them flying off into oblivion.

But not everyone is happy with this picture. "If Newton were alive today and saw the evidence," says Mordehai Milgrom of Israel's Weizmann Institute of Science in Rehovot, "he would have come up with a different law of gravity." In the absence of Newton, Milgrom has obliged. The new law is called Modified Newtonian Dynamics, or MOND, and a sizeable minority of astronomers think that he could be on to something. ▸

NASA/STSCI

◄ This X-ray image of the Bullet Cluster, taken by NASA's Chandra telescope, was taken as evidence for dark matter. But could MOND explain it too?

► For Milgrom, it all began at Princeton's Institute for Advanced Study in the early 1980s. While working on X-ray binary stars, he became intrigued by the mystery of fast-orbiting stars in spiral galaxies. According to Newton, the force of gravity weakens with an 'inverse-square law' – stars twice as far away from the concentration of mass at the centre of a galaxy should be experiencing gravity four times as weak; three times as far out, nine times as weak, and so on. Consequently, at greater and greater distances from the centre, the stars should be orbiting ever more slowly.

But this didn't match the observations. Far from falling with distance, the orbital speed of stars remained constant far out from the centres of observed galaxies.

A dark cloak

The extraordinary explanation that gained widespread acceptance among astronomers was that every spiral galaxy was embedded in an enormous spherical 'halo' of non-luminous matter. The gravity of this 'dark matter' enhances the gravity in the outer parts of spiral galaxies, enabling them to hold on to their stars. Nobody knows what the dark matter is made from, although possible candidates are hitherto undiscovered 'subatomic' particles left over from the Big Bang.

Milgrom thought the dark matter explanation perfectly reasonable. However, he thought that Newton wouldn't have bought it. And neither did he. His dissatisfaction with the dark matter idea led him to explore a radical alternative.

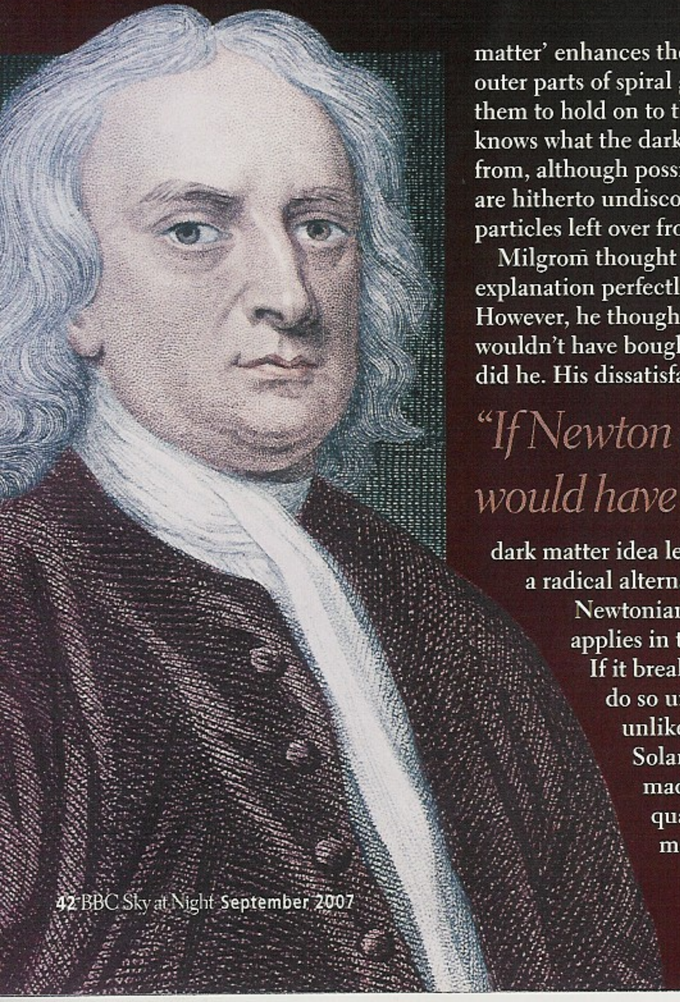
Newtonian gravity clearly applies in the Solar System. If it breaks down, it must do so under conditions unlike those in the Solar System. Milgrom made a list of physical quantities that differ markedly between the domain of the Solar System and that of spiral galaxies, and asked whether a change in the law of gravity when crossing a 'threshold' in any of them would explain the observations.

Could gravity be different over very large distances? Milgrom found that this idea didn't work. He tried other quantities and finally came to acceleration. Perhaps gravity behaves differently at low accelerations. Say there is a critical acceleration, and that at much greater accelerations than the critical threshold, gravity falls off with the Newtonian law, in other words with the square of the distance. But at much smaller accelerations gravity is stronger than expected, weakening more slowly. It weakens in proportion to the distance, not the distance squared.

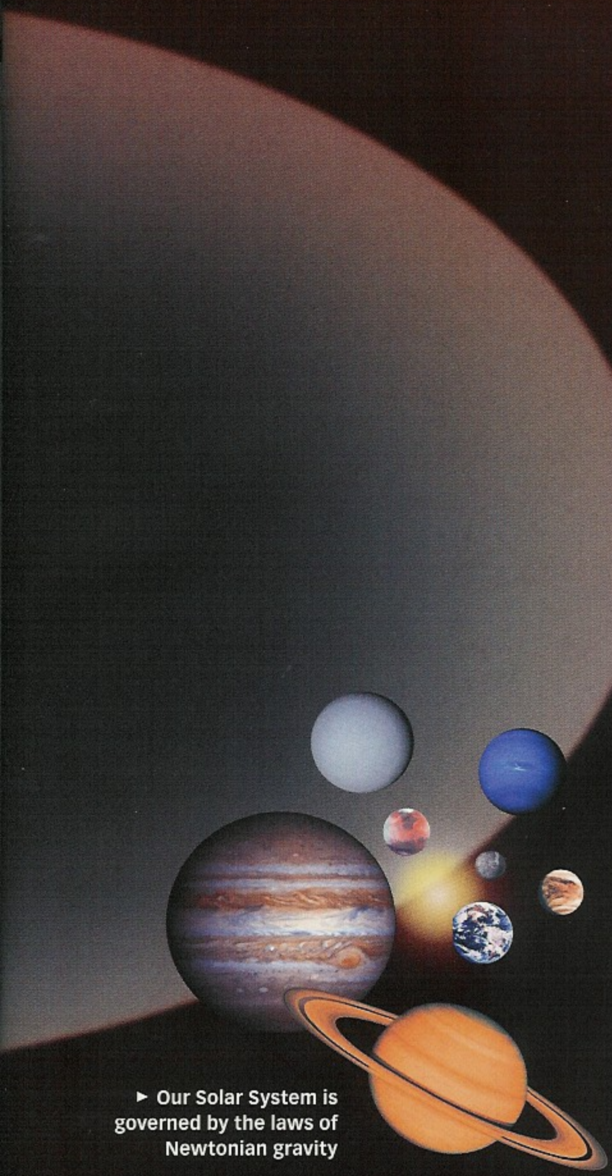
Milgrom applied his formula to the observations of spiral galaxies and was ►

▲ Most scientists think that galaxies are surrounded by a huge halo of 'dark matter'

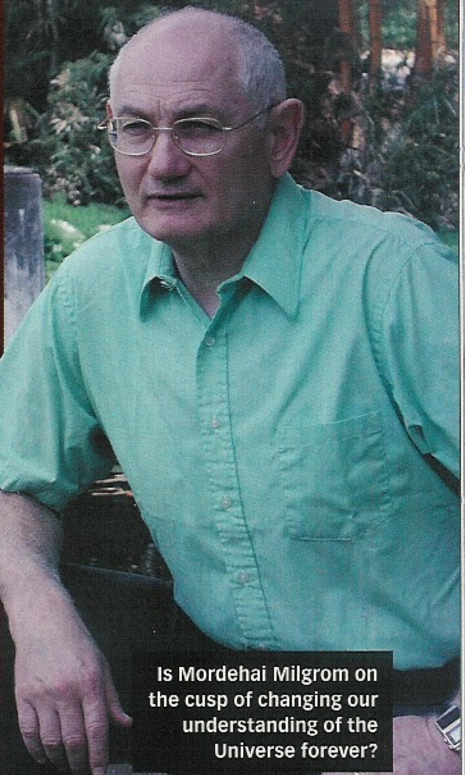
"If Newton were alive today and saw the evidence, he would have come up with a different law of gravity"



◄ Newton's laws of gravity struggle to explain the Universe on a cosmic scale



▸ stunned. "If the critical acceleration was a ten-billionth of a 'g', my formula fits all the existing observations," he says. His formula was beautifully simple, using just one free parameter. "By comparison, the dark matter people have to postulate a different amount of dark matter in each and every galaxy," he says.



Is Mordehai Milgrom on the cusp of changing our understanding of the Universe forever?

Dynamic thinking

The use of the word 'dynamics' rather than 'gravity' in Modified Newtonian Dynamics is important. It recognises the possibility that the faster-than-expected motion of stars in the outer regions of spiral galaxies could be due to either stronger-than-expected gravity, or to a reduction in the mass of the stars. In Milgrom's

"This is a clear-cut case of MOND describing what is seen and dark matter failing to describe it"

theory mass may depend on acceleration; under low accelerations mass decreases. "Both can explain the observations," says Milgrom.

For many years, MOND was ignored. According to Milgrom, dark matter is favoured largely because it is the explanation of minimum daring. However, when MOND was noticed, it received a mixed reaction. "I find the idea quite inspiring," said Jacob Bekenstein of the Hebrew University. Others disagreed: "I'm glad Milgrom is working on MOND, but I bet it's not right," said Craig Hogan of the University of Washington.

MOND and dark matter don't just confront each other in spiral ▸

▸ Our Solar System is governed by the laws of Newtonian gravity

MOND breakthrough

The theory has so far failed to acknowledge Einstein's masterwork, until now…

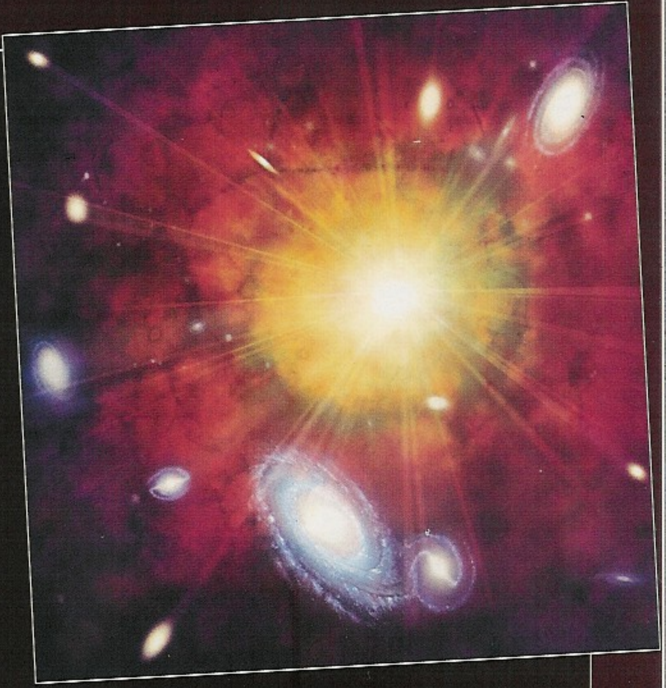
MOND, like Newtonian gravity, describes a force of gravity that reaches out and tugs on massive bodies instantaneously. This is synonymous with a force that travels at infinite speed. However, Einstein's special theory of relativity recognises that no influence – including gravity – can travel faster than light. As long as MOND so blatantly ignored Einstein's cosmic speed limit, no theorist would take it seriously.

However, in 2004 there was an important development. Jacob Bekenstein, of the Hebrew University, devised a theory that he called Tensor-Vector-Scalar gravity, or TeVeS. It introduced twin force 'fields'. One gave rise to gravitational phenomena like the ones found in Einstein's theory, while the other served as an arena for things involving other interactions – the electromagnetic, weak nuclear and strong nuclear forces.

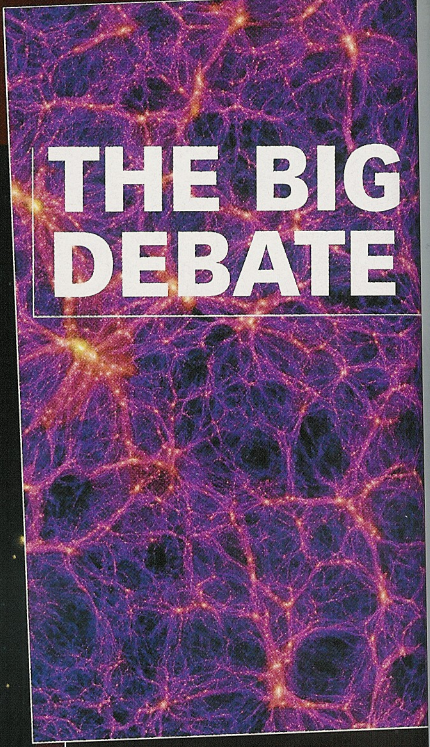
At high speeds and accelerations that were well above the critical threshold, Bekenstein's theory reduced to Einstein's theory of gravity. At low speeds and accelerations above the critical threshold, it reduced to Newtonian gravity. And at accelerations below the threshold it reduced to Milgrom's MOND.

Milgrom's original MOND theory, by not taking into account relativity, had no predictive power in situations where speeds were close to that of light. This meant it was fundamentally incapable of describing anything involving light itself – a serious deficiency. The bending, or 'gravitational lensing', of light coming from a distant object, is of particular importance in astrophysics.

MOND wasn't equipped to predict the degree to which this light would bend. However, Bekenstein's theory predicted this effect precisely. It also enabled theorists to describe events in the Big Bang that led to the formation of galaxy clusters. Like dark matter, the theory appears to create a distribution of galaxies much like we see today. According to Bekenstein, it conflicts with no observations of the Solar System or elsewhere.



▴ Bekenstein's altered theory of MOND explains how the Big Bang led to the formation of galaxy clusters



▸ galaxies; they also clash in the cosmological realm. In the 1930s, the Swiss-American astronomer Fritz Zwicky first noticed that galaxies within clusters were orbiting so fast that by rights they should be ejected. He postulated the existence of a large amount of dark matter, typically many times the mass of the visible material, whose extra gravity was preventing this from happening.

More importantly, dark matter – typically outweighing the visible stuff by a factor of about six – is also needed to explain the very existence of galaxies such as our own Milky Way. According to the standard view, galaxies and then galaxy clusters grew from regions of the Big Bang fireball that were ever-so-slightly denser than average. Because they had slightly stronger gravity, they pulled in matter more effectively than surrounding regions, enhancing their gravity so they pulled in yet more. However, this process – akin to the rich getting ever richer – couldn't possibly have created today's galaxy clusters in the 13.7 billion-year history of the Universe. Enter dark matter. Its extra gravity, say the theory's proponents, speeded up the process of galaxy formation.

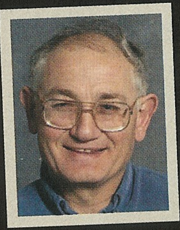
Apply the ideas in MOND, of course, and you get a similar effect to dark matter because MOND fundamentally enhances gravity – or, by reducing mass, achieves the same

▲ MOND explains why stars on the outer edges of spiral galaxies such as M33 above, aren't flung off into intergalactic space

MOND fundamentally enhances gravity – or, by reducing mass, achieves the same end

MOND

Mordehai Milgrom, Weizmann Institute of Science

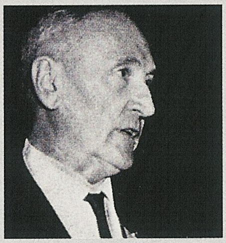


"In more than 100 spiral galaxies, MOND correctly describes the way the speed of orbital material changes at different distances from their centres. It therefore demonstrates that there is a very tight correlation between the mass of the visible material and their motion. This must be explained even if you do not believe in MOND. In other words, supporters of the dark matter idea must explain why there is a connection between the distribution of dark matter and visible matter. However, this is impossible in the dark matter picture. The standard view of galaxy formation involves mergers, cannibalism, ejection of visible matter by supernovae and so on. These processes should affect visible and dark matter differently.

Galactic systems aside, I freely admit that the MOND idea isn't fully developed enough to make predictions that can be checked against observations. But there is hope, since [Jacob] Bekenstein is making progress with MOND-TeVeS gravity."

[TIMELINE]

1933
Fritz Zwicky notices that galaxies in clusters appear to be moving so fast they should fly off into oblivion. He postulates that clusters are dominated by a large amount of 'missing mass'.

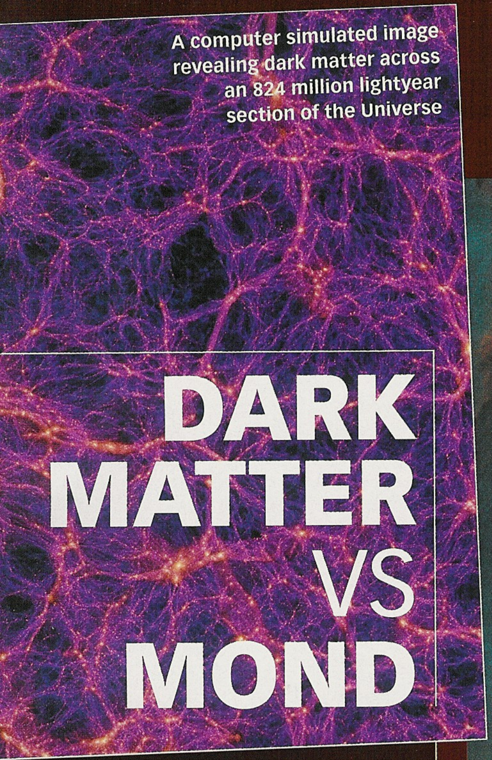


1978
Vera Rubin begins measuring the velocity of gas orbiting in spiral galaxies. After analysing 200 galaxies, it is clear that the velocity does not drop off with distance from the centre, as Newton predicted, but stays constant. The idea gains currency that every spiral galaxy is embedded in a spherical cloud of non-luminous 'dark matter' that outweighs the normal matter by a factor of about 10.

1983
Mordehai Milgrom looks at the evidence of gas orbiting in spiral galaxies and postulates that at a critical acceleration of one ten-billionth of a 'g', gas experiences a stronger pull than predicted by Newton. MOND, which explains observations of all spiral galaxies, is born.

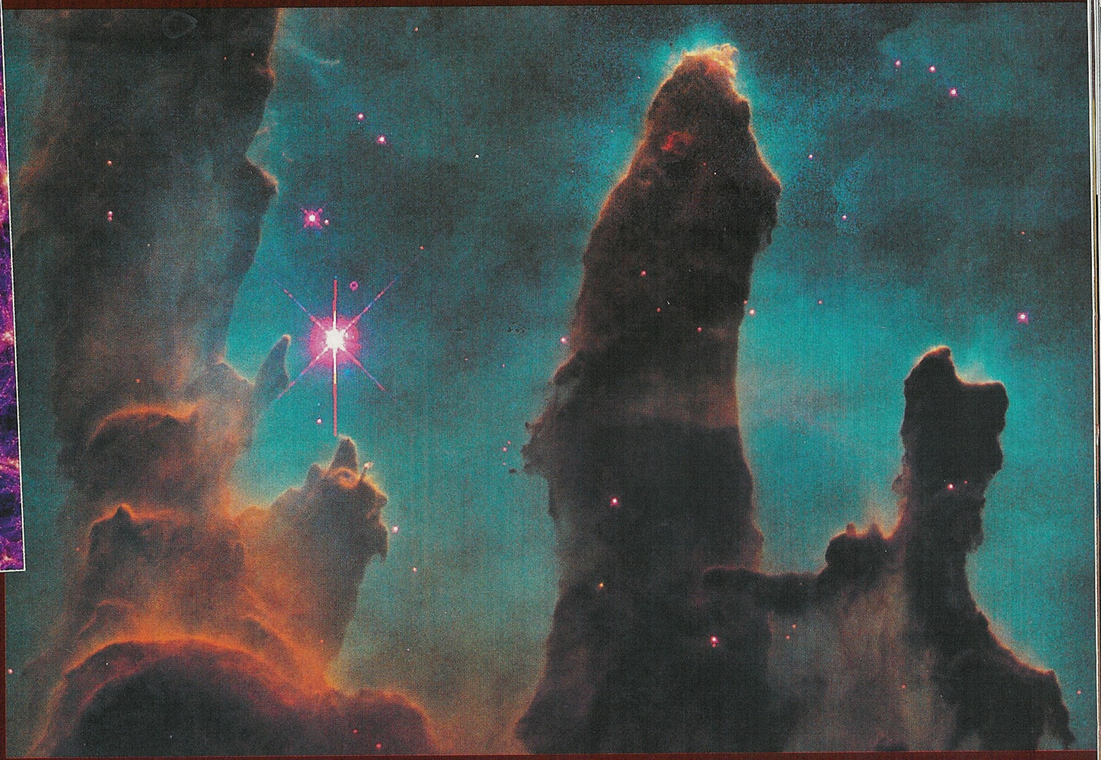
1930 — 1970 — 1980 — 2000 — 2001 — 20

SCIENCE PHOTO LIBRARY X 4, PROFESSOR MORDEHAI MILGROM, PROFESSOR SIMON WHITE, NASA/JPL-CALTECH, NASA/STSCL, P-A DUC/CEA-CNRS/NRAO/AUI/NSF/NASA NASA X 3



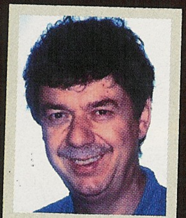
A computer simulated image revealing dark matter across an 824 million lightyear section of the Universe

DARK MATTER VS MOND



Dark matter

Simon White, director of the Max Planck Institute for Astrophysics



"I have considerable sympathy for Milgrom's programme and would love to see a fully consistent MONDian theory that could simulate the evolution of the Universe from shortly after the Big Bang to the present day. Despite the important steps taken by Bekenstein and others, however, such a theory does not yet exist.

By contrast, the theory of dark matter – plus dark energy, the stuff that appears to be speeding up the expansion of the Universe – is sufficiently developed to simulate the evolution of the Universe. And the predictions match observations at a range of different cosmic epochs.

The dark matter picture makes detailed predictions that agree qualitatively, and often quantitatively, with a wide range of data. As long as the MOND model is unable to do the same, most astronomers will not be sufficiently impressed by a few examples of apparent discrepancies to abandon dark matter."

end. However, in galaxy clusters, unlike in spiral galaxies, it falls just short of explaining the orbital speeds of galaxies. Milgrom postulates the existence of mundane matter – perhaps in the form of gas or dim stars – that has so far escaped detection.

▲ **Could difficult-to-detect, dim matter such as these dark dust clouds account for the orbital speeds of galaxies?**

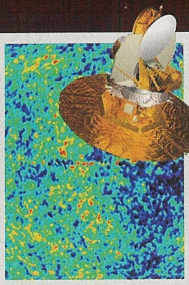
Bullet battleground

Over the years, the battleground between dark matter and MOND has shifted. Last year, it was the Bullet Cluster, 1E 0657-56, so-called because a small galaxy cluster has thudded – like a bullet – into a much larger cluster. A characteristic of dark matter is that it can't slow down easily because it is unable to lose energy in the form of light (or heat). In the case of the Bullet Cluster, the prediction was therefore that the gas in the two clusters would collide and heat up, but the dark matter in one cluster would simply pass through the dark matter in the other, ending up on either side of the hot gas. Indeed, this is what is seen. X-ray observations reveal hot gas at the impact point in the centre. And observations of the distortion of background galaxies by the gravity of mass in the Bullet Cluster show two large concentrations of dark matter on either side – roughly six times the mass of the hot gas.

Milgrom is perplexed, however, that this has been heralded as a triumph of the dark matter picture. "MOND predicts pretty much the same thing!" he says. "The only difference is that it requires some missing dim stuff about as massive as the hot gas rather than dark matter six times as massive."

However, recent observations that were only published in May this year ▸

2002
Data from NASA's Wilkinson Microwave Anisotropy Probe is compatible with a Universe containing, by mass: 4% atoms, 23% dark matter and 73% dark energy.



2004
Jacob Bekenstein finds a relativistic theory that reproduces MOND-like behaviour. For the first time it is possible to apply the theory to light – gravitational lensing – and the Big Bang.

2006
There's a storm in a teacup over the Bullet Cluster of galaxies, which dark matter proponents claim supports their idea. Milgrom says MOND explains it too.

2007
Tidal dwarf galaxies around NGC 5291 appear to have a large amount of dark matter, whereas dark matter theory predicts they should have none. MOND predicts the observations.

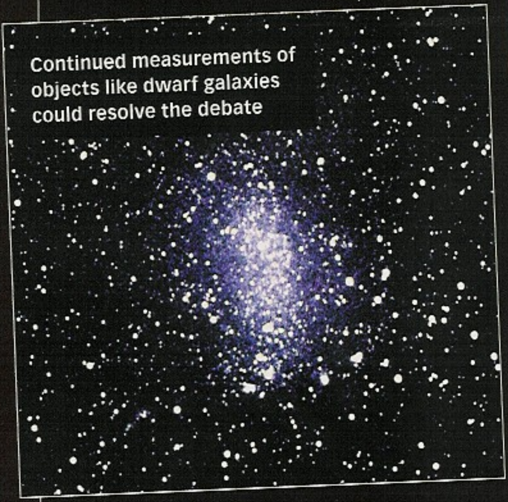
2003 | 2004 | 2005 | 2006 | 2007

How rival theories are tested

Future observations may provide evidence to support either dark matter or MOND

MORE MEASUREMENTS

Precise velocity measurements in an increasing number of systems, from dwarf galaxies to clusters of galaxies, are continuing. If MOND works in all of them, the view will strengthen that it can't be just a clever way of summarising what dark matter does. Rather, it would be a fundamentally correct description of reality.


Continued measurements of objects like dwarf galaxies could resolve the debate

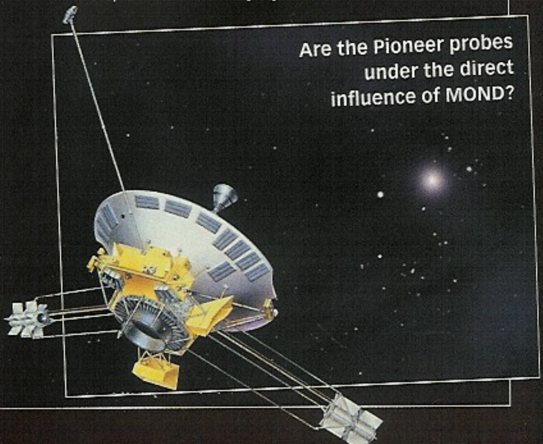

Will the particle accelerator at CERN create dark matter?

FINDING THE INVISIBLE

Experiments are attempting to detect dark matter directly. Several experiments, such as the one run by the UK Dark Matter Collaboration in Boulby Mine in North Yorkshire, have been working for 10 or more years. If one of these experiments finds dark matter in the correct quantities, it would rule out MOND. Even if dark matter isn't found, people may still say that it interacts weakly with matter, thereby eluding the experiments. Another experiment is the Large Hadron Collider at CERN, the European centre for particle physics. It may conceivably create hitherto unknown subatomic particles such as the neutralino, a possible candidate for dark matter.

PROBE MYSTERY

Scientists are seeking confirmation of the Pioneer anomaly. NASA's Pioneer 10 and 11 spacecraft, launched in 1973 and 1974, are experiencing an unexplained acceleration, directed towards the Sun. The acceleration is close to the critical acceleration in MOND. Nobody knows whether this is significant. However, a serious proposal has been made to send a space probe to measure gravity in the outer Solar System and confirm, or refute, the Pioneer anomaly. If it turns out to be an effect of some unknown new physics, it could be explained naturally by MOND.


Are the Pioneer probes under the direct influence of MOND?

► have really stirred things up. A team led by Frédéric Bournaud of the Commissariat à l'Énergie Atomique (CEA) in Paris, France, looked at three dwarf galaxies that were formed in galactic collisions near the galaxy NGC 5291. The key thing is that in such collisions, dark matter – as in the Bullet Cluster – tends to be separated from the visible matter. In fact, there should be no dark matter whatsoever in the three 'tidal dwarf' galaxies. The trouble is that the observations appear to show that there is – about three times as much mass tied up in the visible material. To explain this and save the dark matter picture, astronomers have postulated the existence of a new type of dark matter, 'cold molecular gas', that wouldn't get separated in a collision. Milgrom sees this as an act of desperation. "MOND predicts what is observed," he says. "This is a clear-cut case of MOND describing what is seen and dark matter failing to describe it."

To save the dark matter picture, astronomers have postulated the existence of a new type of dark matter

▼ Galactic collisions such as this one create dwarf galaxies that should be devoid of dark matter

A confusing past

If MOND is a manifestation of new physics, then at the least, proponents of dark matter must explain how in spiral galaxies, dark matter clumps together in a way that mimics the MOND formula. The problem, according to Milgrom, is that most galaxies have already undergone mergers in which dark matter has been separated from ordinary matter. "With each galaxy experiencing a different and complex history, it's hard to see how dark matter could produce such similar, MOND-like behaviour, in every galaxy."

Until 2004, the biggest objection to MOND was that it didn't incorporate the principles of the theory of relativity, which forbids anything – including gravity – from travelling faster than light. However, that year there was a breakthrough, when Bekenstein found a relativistic form of the theory (see *MOND breakthrough* p43). Could it be that MOND's time has finally come? ✪

[FIND OUT MORE]

The MOND pages: www.astro.umd.edu/~ssm/mond/litsub.html

Jacob Bekenstein: www.phys.huji.ac.il/~bekenste/

UK Dark Matter Collaboration: http://hepwww.rl.ac.uk/ukdmc/ukdmc.html