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Reconstructing gravity

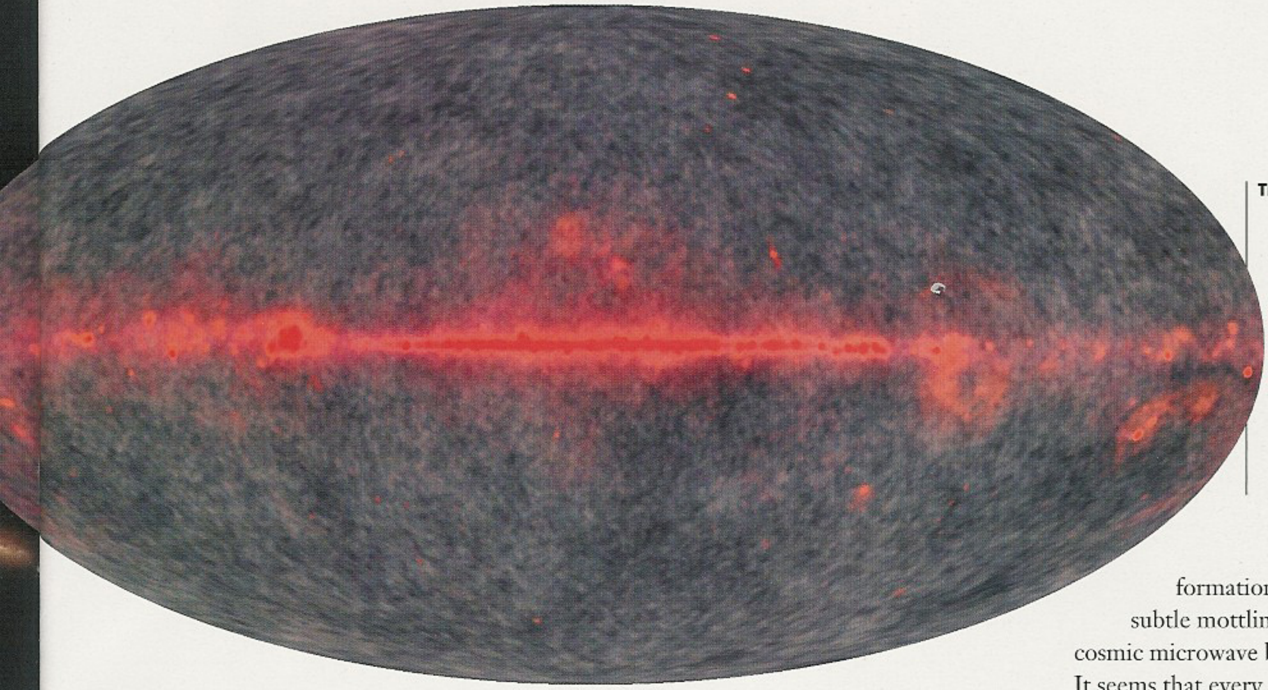
Just when you thought that dark matter was an established cornerstone of astronomy, along comes a theory that does away with it altogether. **Amarendra Swarup** meets the scientists who want to reconstruct gravity.

The rotation of spiral galaxies either means that vast amounts of dark matter lurk in space or our understanding of gravity is wrong. This is galaxy NGC1309, a beautiful face-on spiral galaxy, imaged by the Hubble Space Telescope. Image courtesy: NASA, ESA, The Hubble Heritage Team, (STScI/AURA) and A. Riess (STScI).

The philosopher Thomas Kuhn once described science as "a series of peaceful interludes punctuated by intellectually violent revolutions." To Kuhn, scientific progress was never a gradual accumulation of knowledge but an endlessly repeated battle between established theories and their upstart younger cousins. As dominant theories aged, anomalies would appear, battle lines would be drawn and intellectual blows traded until, finally, the mounting army of evidence caused a drastic paradigm shift from old to new.

Just such a battle took place in the early twentieth century between Newton's Universal Gravitation and Einstein's General Relativity. The simple case of Newtonian gravity was shown to be only applicable when moderate gravitational forces were at work. General Relativity describes gravity's behaviour when stronger forces come into play. Though talk of revolutions and dethronements may seem premature, a growing number of cosmologists are starting to believe that gravity needs to change again. This time, they think that it is the opposite end of the scale that needs adjustment and that gravity does not weaken with distance quite as simply as Newton or Einstein believed. If they are right, it challenges one of the foundations of modern cosmology – the hypothesis that for all the atoms we observe in the Universe today, over five times as much lies forever hidden as mysterious dark matter.

"Cosmologists assume General Relativity describes gravity, and so need to introduce an exotic form of matter, dark matter, to explain



The grey tones in this image show the subtle mottling of the cosmic microwave background radiation that will eventually betray the difference between dark matter theories and modified gravity theories. The red markings show contaminating microwave signals from our Galaxy. Image courtesy: NASA/ WMAP Science Team.

a whole range of observations," says David Mota at the University of Oslo, Norway. "But what if there is no such dark matter, but rather tha t the gravity law we are using is wrong?"

Mota is not the first to wonder this. Mordehai Milgrom of the Weizmann Institute in Israel proposed the theory of Modified Newtonian Dynamics (MOND) in 1980. It was the first attempt to do away with the need for dark matter by modifying gravity. Both MOND and dark matter have their genesis in the same problem: the strangely fast rotation velocities of stars in galaxies.

Gravitational glue

When one object is in orbit around another, the larger object's gravity pulls the smaller one around it. The more massive the central object, the faster the orbiting one goes. The same happens with stars orbiting in galaxies; only in this case it is the accumulated mass of the galaxy's other stars that swing them through their orbits.

Astronomers have long known that galaxies and galactic clusters are rotating too fast to be held together solely by the gravity that the visible matter generates. The stars are moving too fast and should simply fly off into space, creating a dilute sea of stars. Yet astronomers have never seen galaxies dispersing. The galaxies appear entirely stable. This has led many to infer the existence of vast amounts of unseen matter, which provides the extra gravitational glue needed to keep things together.

This extra mass cannot be normal atoms otherwise it would throw out the tidy theories astronomers have for the build up of the chemical elements in the Universe. So, most believe it consists of exotic particles. They call it dark matter because it is invisible and reacts with normal matter only through gravity.

But a growing number of sceptics are starting to find such a general explanation lacking in detail. Stacy McGaugh, University of Maryland says, "Everybody is using the words dark matter to mean different things. If you ask specific questions: how do galaxies form, how do they get these specific rotation curves, etc. then opinion quickly diverges."

Indeed, most talk of dark matter gives it the appearance of consensus but in reality, it is sadly lacking. The strange stuff has been variously proposed to be WIMPs (Weakly Interacting Massive Particles) predicted by theories that space contains more dimensions than the three we are used to, normal matter trapped in an alternate version of our Universe, even particles whizzing around at close to the speed of light. The possible candidates seem endless, each variety has its own champions and every year brings new ideas but little tangible progress.

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Despite this, cosmologists continue to invoke dark matter to answer a wide range of cosmological problems, from galaxy rotation velocities, to the formation of galaxies and the subtle mottling in the all-pervasive cosmic microwave background radiation. It seems that every cosmological problem can be solved by a suitable tweak of the hypothetical dark matter's properties. It is exactly this kind of tinkering that gives Mota, McGaugh and others pause for thought.

"Everybody is already convinced that there has to be dark matter," says McGaugh, even though not a single shred of direct evidence of its existence has been found.

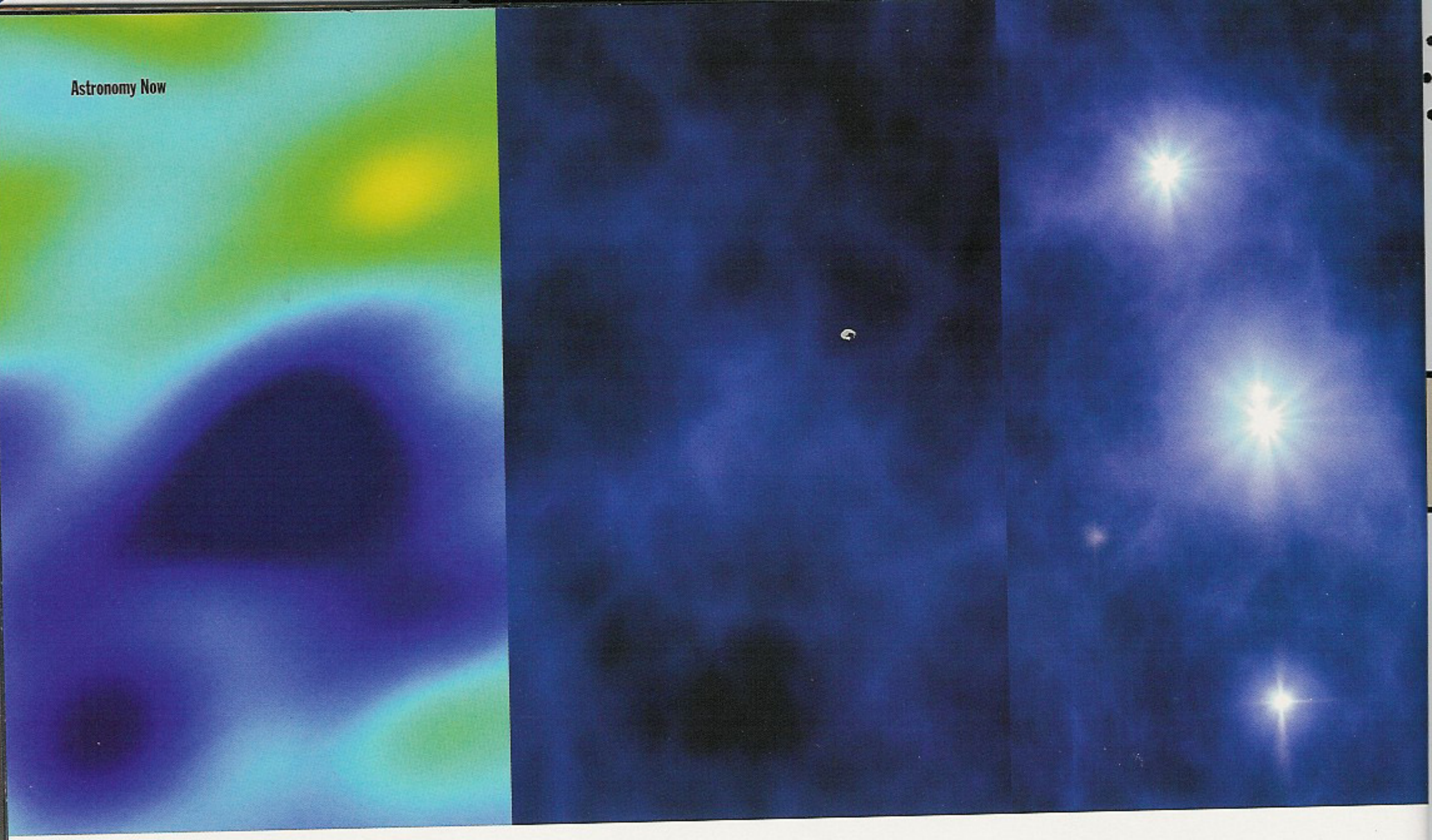
There is a resonance here with the last decades of belief in the supremacy of Newton's gravity. In the 1800s it was discovered that Mercury's orbit did not follow the path Newton's work predicted for it. So astronomers postulated an undiscovered planet, Vulcan, whose gravity pulled Mercury off course. When Einstein presented General Relativity, a new calculation of Mercury's orbit showed the planet behaving perfectly as normal.

With hindsight, one of the obvious flaws with the Vulcan theory, was that different astronomers proposed different properties for the hypothetical planet. Its proposed size and orbits varied enormously. Now, similar discrepancies might be showing up in dark matter theory.

Prodigal problems

Astronomers are murmuring about contradictions in the implied distribution of dark matter in galaxies. To counter these objections, theorists have tweaked their models or blamed flaws in the experimental data. But at least one of these problems may not be so easy to explain.

A detailed study of more than 60



spiral galaxies by McGaugh shows that there is a fine balance between the proportions of supposed dark matter and conventional matter. The nature of this balance stands in stark contradiction to one of the founding principles of dark matter theories. It is assumed that the amount of normal matter reflects the amount of dark matter. This is because galaxies are thought to form from dark matter conglomerations in the early Universe. The greater the amount of dark matter, the higher its gravitational field, the more normal matter it can attract and the bigger the resulting galaxy.

However, McGaugh's study shows the opposite. As the contribution of normal matter to the rotational velocity of the galaxy increases, there is a corresponding decrease in the dark matter contribution.

Hongsheng Zhao at the University of St Andrews admits the observations are troublesome. "The mysteriously tight correlations of baryons [normal matter] with the supposed dark matter seen in McGaugh's data should be taken very seriously by anyone trying to model or find dark matter," he says.

Neverthless, most dark matter theorists are still sceptical. "I am not too worried about dark matter theories yet," says Ben Wandelt at the University of Illinois at Urbana–Champaign. "There are many unanswered questions, but galaxy formation is complicated."

Ken Freeman at the Australian National University also believes that the explanation is more likely to be found in unknown aspects of galaxy formation, such as star formation.

McGaugh is dismissive, saying, "There are all sorts of buzzwords thrown around but nobody has come close to giving a satisfactory explanation. What we observe is the last thing we'd expect from basic physics."

Instead of assuming that the cause of the problem is missing matter, McGaugh argues that the purest statement of the problem is that there is too much gravity. "When it first became apparent things didn't add up, there was a choice. Either lots of matter is present which happens to be dark, or gravity has to be amended."

Astronomers and physicists of the time chose to believe that the laws of gravity were sound and so went down the dark matter route. McGaugh believes this solution is now untenable and so he is prepared to think that it is our understanding of gravity that is wrong. Without dark matter, the observations imply that we misjudge how quickly gravity weakens with distance.

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Modifying gravity

Suggesting that we do not understand gravity is a dangerous path to take. The most successful attempt to recast our theories on gravity has been MOND. However, it causes strong emotions among cosmologists.

Cristian Armendariz–Picon at Syracuse University, New York, still remembers attending a workshop in Chicago where a colleague attempted to present the successes of MOND. "When it became clear where his talk was heading, the audience nearly revolted," he recalls. "My impression is that MOND is not particularly popular among astronomers."

Nevertheless, MOND has hung in there for over twenty years, especially as it seems to accurately predict much of the behaviour seen in galaxies, including McGaugh's latest galactic observations. In fact, by replacing dark matter and Newton's gravity with MOND, the new observations are not only reproducible, they were actually predicted. "MOND is the only theory that predicted this ahead of the fact, so that deserves respect," says McGaugh. "It would be intellectually dishonest to ignore this dramatic possibility."

Supporters of MOND point out that in galaxies everything happens as if MOND were right, making it the most natural interpretation. Critics say that MOND is simply an effective theory without any underlying physical justification. "MOND is more a description than a theory," contends Freeman.

Wandelt agrees. "It explains one thing,

Starting from temperature fluctuations in the sea of gas that filled the early Universe (left, frame one), matter began to pull itself together (frame two). About 200 million years after the big bang, this gravitational contraction caused the first stars to shine (frame three) and a subsequent burst of star formation activity (frame four). In the modern era (frame five), galaxies form chains that stretch across the Universe. The only problem with this picture is that gravity, as we understand it, is too weak to pull these structures together. Either dark matter exists, contributing gravity, or our understanding of the way gravity decays over vast distances is wrong.
Images courtesy: NASA/WMAP Science Team.

galaxy rotation curves, by modifying another, Newton's gravity law. But modern cosmology has come a long way since Newton." By this, Wandelt means that any competing theory must also encompass General Relativity.

Modifying MOND

Taking on Einstein's theory is not for the faint hearted. Any contending theory must not only reproduce general relativistic effects, such as the bending of light, but also provide answers to the cosmological problems of large-scale structure formation and the subtle patterns in the microwave background revealed by experiments such as NASA's Wilkinson Microwave Anisotropy Probe (WMAP). So it's not surprising that supporters of MOND have taken a while to place their ideas in a broader cosmological context.

Enter Tensor–Vector–Scalar (TeVeS) theory, developed by Jacob Bekenstein at the Hebrew University of Jerusalem, Israel. "TeVeS answers all prior criticisms of MOND and incorporates relativity," explains Mota. "It explains a whole range of phenomena occurring on galactic scales and also other observations, in particular the bending of light."

With these successes, TeVeS is beginning to look a credible alternative and cosmologists are beginning to concede that the theory has merit. "There may be other theories more compelling than anything current. The fact that a different theory can give definite predictions is very interesting," says Wandelt.

Sean Carroll at the University of Chicago agrees that these ideas should be pursued, given no one knows for sure there is dark matter. "We have to keep an open mind," he says. "However, relativity and dark matter have a long string of incredibly impressive successes, and it's becoming ever harder to imagine credible alternatives."

Not everyone is convinced though. Some, such as Chuck Bennett, the Principal Investigator on the WMAP project, have pointed out that TeVeS is more complex than relativity and dark matter put together. Others, including Sir Martin Rees, the former Astronomer Royal, would rather that all conceivable dark matter candidates were excluded first.

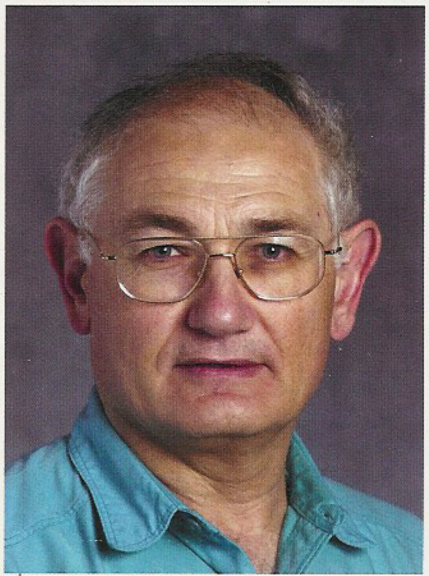
TeVeS supporters, however, may just have found a way to end-run that long and lengthy process.

Who dares wins?

Calculations by Mota and colleagues point to a crucial test, which could settle the issue. TeVeS produces a unique signature on the cosmic microwave background radiation. Although it is too small to be reliably measured at present, most expect the next generation of WMAP data, due to be released this year, to put stronger constraints on both dark matter models and TeVeS. Certainly, ESA's upcoming Planck mission should be able to clearly differentiate between them.

Until then, the speculations and implications will multiply. A recent paper suggested that TeVeS might provide an explanation for dark energy – the mysterious accelerating expansion of the Universe.

"Cosmology becomes a much more open game in TeVeS," says McGaugh.



The proposer of Modified Newtonian Dynamics (MOND), Mordehai Milgrom. Image courtesy: Mordehai Milgrom, Weizmann Institute of Science, Israel.

Amarendra Swarup is a freelance science journalist.

ESA's Planck spacecraft should provide a definitive answer about whether dark matter theories are correct when it launches in 2008. Image courtesy: ESA 2002. Illustration by Medialab.