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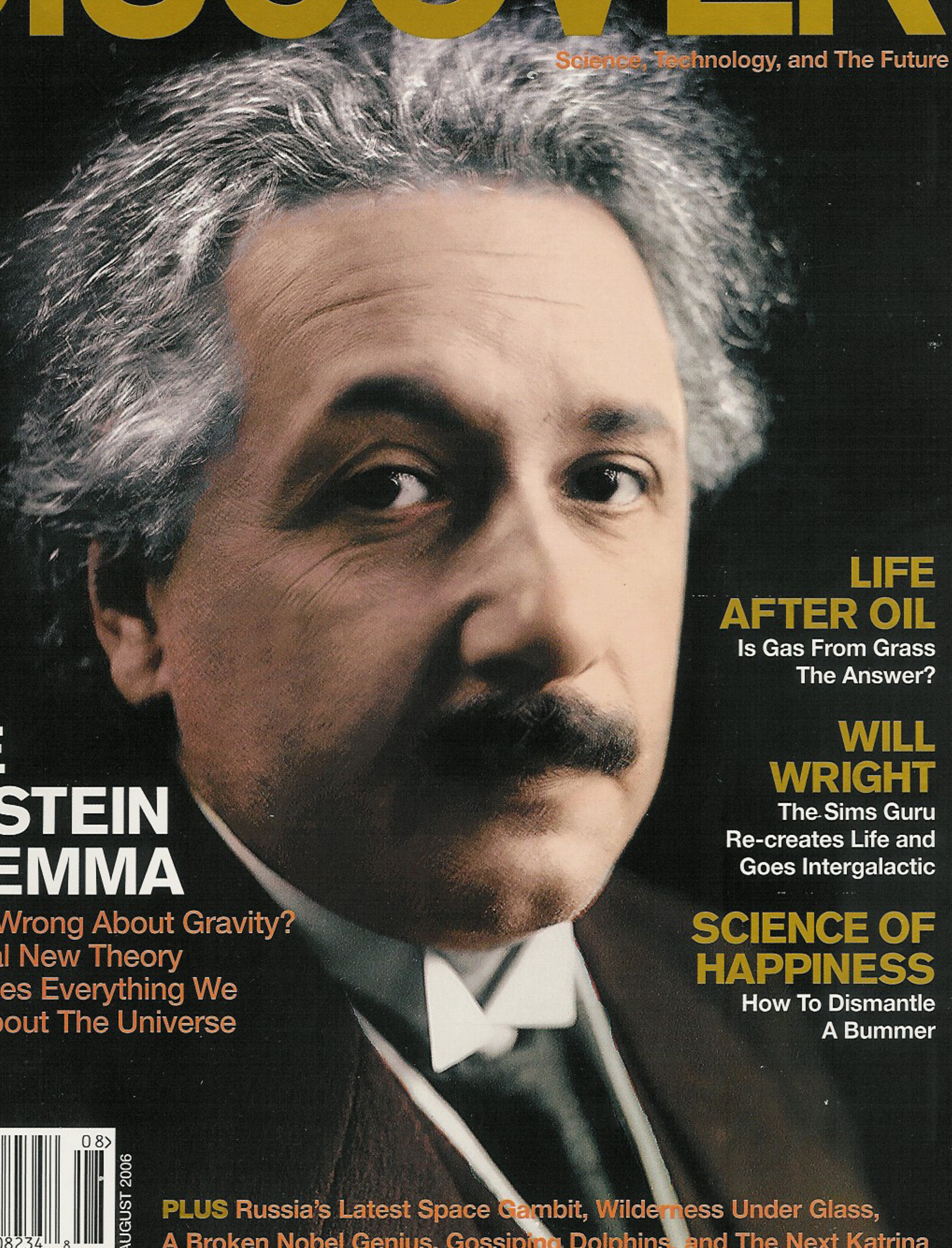

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Two spiral galaxies twist and pull at each other. Astronomers are still debating how gravity mediates such encounters.

GRAVITY'S GADFLY

Mordehai Milgrom's new physics could overthrow Newton and Einstein—and tear up our whole picture of how the universe is put together

BY **ADAM FRANK**

Mordehai Milgrom never wanted to be a heretic. Twenty-five years ago, while poking around for a meaty research problem, he found one that changed the course of his career—and that might yet transform our most fundamental understanding of the universe. His ideas, long relegated to the fringes of physics, where all but cranks fear to tread, have finally become too intriguing for his mainstream colleagues to ignore. Milgrom's heresy? He denies the existence of dark matter, the shadowy and thoroughly hypothetical stuff generally held to make up 80 percent or more of all matter in the universe. Even though dark matter has eluded all attempts at detection, most cosmologists are convinced it must be out there. Without it, there's no explanation for much of what they see in the cosmos.

Or at least there hadn't been until Milgrom's break with orthodoxy. His alternative not only eliminates dark matter, it strikes at the heart of modern physics. In short, Milgrom thinks that Isaac Newton's laws of gravity are incomplete. Unlike many radical alternatives to conventional physics, Milgrom's brainchild—known as modified Newtonian dynamics, or MOND—has not withered under scrutiny. Attacked? Yes. Ridiculed? Certainly. Refuted? No.

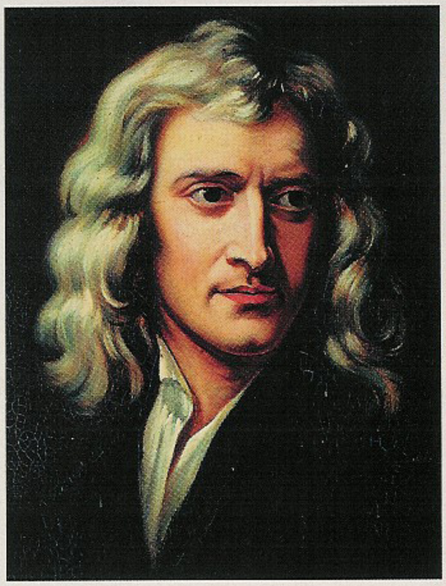
A little more than a year ago, Milgrom, a professor of physics at the Weizmann Institute in Rehovot, Israel, gained new support for his ideas when his longtime collaborator, Jacob Bekenstein, published a new, more powerful version of the theory, one fully consistent with Einstein's general theory of relativity. With this advance, MOND is poised to go head-to-head with dark-matter theories in describing how galaxies form and evolve. Should MOND prove successful, thousands of papers in mainstream cosmology will become obsolete overnight. And that is just half the story. If Milgrom can claim victory, he will have wrought the most dramatic revision of our understanding of gravity since Einstein's work of almost a century ago.

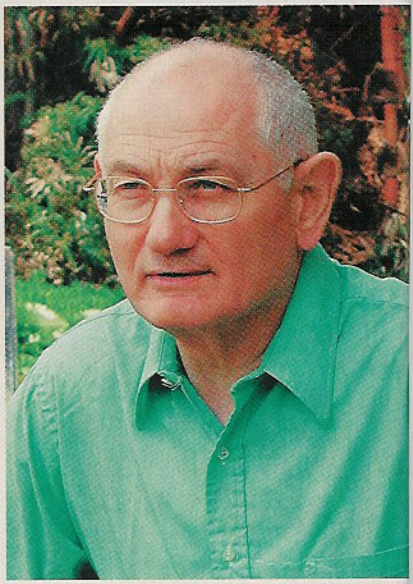
Mordehai Milgrom began his career studying objects called ultracompact neutron stars in binary star systems. In 1979, sensing the need for a new challenge, he bundled his family and headed on sabbatical to Princeton University, one of the world's leading centers for the study of galaxies. Even after half a century of unraveling the structure and evolution of galaxies, astronomers still had much to learn about them. Milgrom became particularly intrigued by one intractable problem. "I had heard there was this trouble understanding the so-called galactic rotation curves, which describe the way stars rotate around the centers of galaxies," he says. "I thought I would apply myself and try to think about this problem."

No one knew it at the time, but the problem posed a challenge to a cornerstone of physics, the fundamental relationship between mass and gravity. Isaac Newton figured out the rules for weighing orbiting bodies close to four centuries ago. The simplicity and accuracy of Newton's laws let any undergraduate transform observations of a satellite's orbit into a direct measurement of the parent body's mass. It is Newton's laws that tell us the sun weighs a thousand trillion trillion tons.

Throughout the 1970s, astronomers applied these laws to galaxies, hoping to extract a measure of their total mass. The orbital speed of stars circling a galaxy can be teased from an analysis of their combined light. Repeating this process for a sequence of positions from the center of the galaxy out to its visible edge allowed astronomers to determine rotation speeds at various distances. Placing these points on a graph produced the galactic rotation curves that Milgrom had heard about. The data were new and messy, but by the end of the disco decade it was clear that something was terribly wrong.

The skinny black line on a plot of stellar rotation speed versus distance was expected to go down—stars close to the galactic center should orbit faster than stars at the edge because all the mass concentrated at the center of the galaxy pulls most powerfully on the closest stars. The same thing happens in the solar system: Mars moves faster than Jupiter because the sun's gravity pulls harder on it, Jupiter orbits faster than Saturn, and so on, out to Pluto and beyond. A plot of orbital speeds and distance—a rotation curve of the solar system—does decrease with distance. The skinny black line falls, just as Newton's laws say it should.





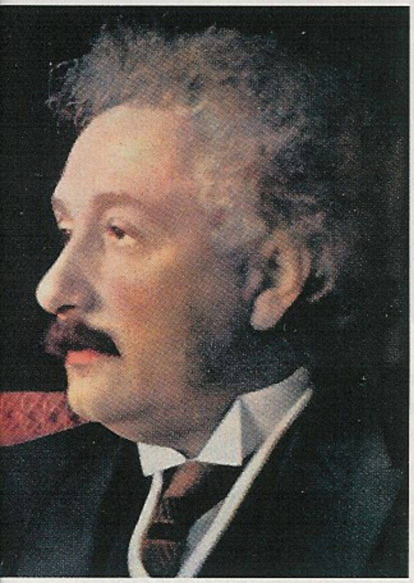
Images of Isaac Newton (left) and Albert Einstein (far right) flank Mordehai Milgrom, a physicist who has boldly updated Newtonian motion and, in doing so, has reconceived Einsteinian gravity.

The rotation curves for spiral galaxies do not. At a certain distance from the galactic center, the rotation curves for stars in most every spiral galaxy simply do not fall; instead, at some point they flatten. All the stars in the middle and outer parts of these galaxies orbit with the same speed, in seeming defiance of Newton's laws. Why don't the outer stars move more slowly than the inner ones?

When confronting such a paradox, scientists have only a few options: Question the data, question the theory, or invent something new, maybe even something invisible, to explain the effect. In the late 1970s, astronomers were beginning to line up behind the last alternative. Faced with flat rotation curves that seemed to flout Newton's laws, astronomers assumed the existence of a halo of dark matter around every spiral galaxy. Whatever the stuff was, it did not emit light, but it did exert a gravitational pull. The dark matter tugged on the stars, cranking up their speeds and creating the flat rotation curves.

The choice was reasonable, but it was still a choice. "Science does not emerge in some perfect, complete crystalline form," says Princeton University cosmologist James Peebles. "Sometimes one must make extended conclusions from limited data. Why should all matter be in the visible sector? Dark matter was a simple solution to the problem." It was a solution, however, that Milgrom could not accept. He took a shot at the second alternative. Milgrom decided to retrofit Newton.

He set out to modify aspects of Newton's laws of motion so that they could naturally yield the flat rotation curves for galaxies. "I was systematic," he says. "I knew Newton's laws worked for the solar system, but they didn't seem to work for galaxies. So I made a table of solar system properties and galaxies' properties to see which one might present the best road to modifying the equations."



Milgrom's systematic method was critical. Spiral galaxies can be a hundred million times larger than the solar system. A naive approach would simply change Newton's gravitational force law at large distances, but this attack fails to describe accurately other properties of large systems like galaxies. Milgrom then tried modifying the gravitational force based on the spin of the galaxy. No dice. "The last property on my table was acceleration," Milgrom says, "and that one worked."

If you took high school physics, you may remember having Newton's most important equation pounded into your head: $F = ma$. With this simple formula, known as Newton's second law, Newton forever linked forces (F) to their action on mass (m) in the form of acceleration (a). We all experience the relation between force and acceleration whenever we're in a car. As the car accelerates, we're forced back in our seats; when it decelerates, we're forced forward. Milgrom found that the best way to resolve the problem of the flat rotation curves was to modify this hallowed equation.

"I assumed that when the accelerations due to gravitational forces became very small, the formula changes to $F = ma^2/a_0$," Milgrom says. According to Milgrom, this change holds only when accelerations fall below one 10-billionth of a meter per second every second. Not only does this modification work best with the data, he adds, but the new constant, a_0, may be of cosmological significance: Accelerating at this rate will take you from a resting state to the speed of light in the lifetime of the universe. Otherwise Newton's law operates as usual. So with MOND, stars in the outer reaches of galaxies move faster than expected, not because of the influence of some invisible matter but because Milgrom's amended version of Newton's second law increases the force acting on them.

When he used this modified equation to plot the rotation curves, the flatness at the outer distances was predictable, not puzzling. Nothing else was needed to explain it. To a layperson, Milgrom's innovation might seem like a negligible tweak, but to his colleagues, it was bold to the point of foolhardiness. He was changing a cornerstone of physics. Opposition was a given.

In 1981 Milgrom began working on papers to publicize his idea. He was laboring alone—since returning from Princeton, he had told no one of his work but his wife. He sent drafts of his papers to a few mentors and colleagues. Their reactions were muted but encouraging. "None of them reacted violently," Milgrom says. "I even got some helpful comments."

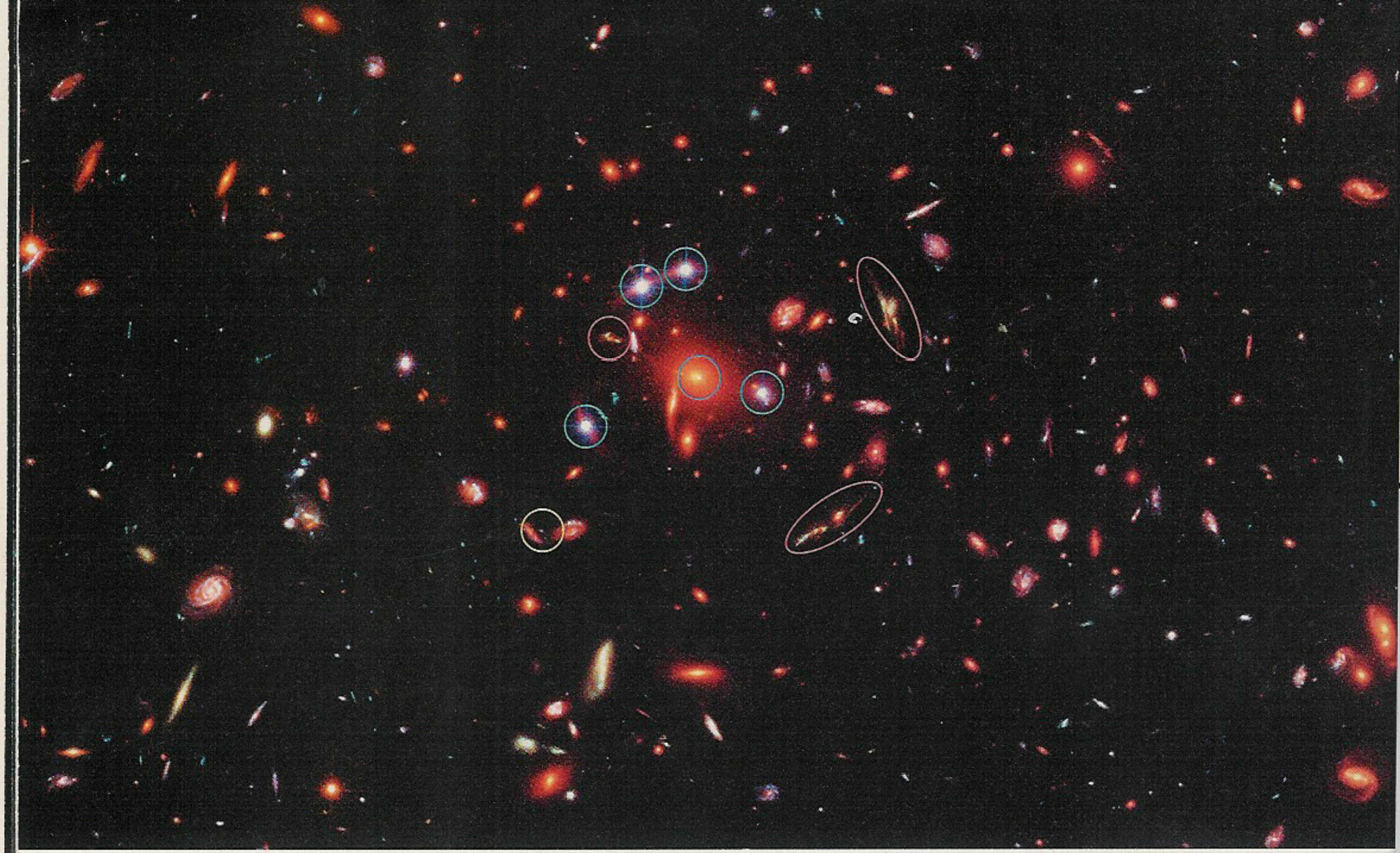
In spite of the suggestions Milgrom had received—all from world-class scientists—getting the papers published became an ordeal. "I was a little naive," Milgrom says. "I thought the papers would be welcomed. They were rejected by the journals at first. The reasons varied: 'It was all nonsense'; 'It's too early to consider an alternative to Newton'; 'There is no trouble yet; the flat rotational curves will be resolved in other ways.' "

Looking back on this period, Milgrom betrays no bitterness. "I went back and looked at the history of science and saw this happens again and again. The marketplace can only handle so many heretical ideas at one time. I think on the whole I have been treated fairly." After Milgrom's dogged persistence, all three of his original papers on modified Newtonian dynamics were published side by side in 1983 in Volume 270 of *The Astrophysical Journal,* a premier publication in the field.

As is often the case with radical ideas, the community's reaction was not scorn but silence. "At first the work was not accepted, not even really looked at," Milgrom recalls. By this time he had begun collaborating on MOND with fellow Israeli theorist Jacob Bekenstein. Bekenstein, who had already won some acclaim for his work on black holes, became a hard-core MONDista. "In 1986 we were invited to present a talk at a meeting in Princeton," says Milgrom. "This made us really happy. At least we were getting noticed." MOND began to make inroads. Its solution to the galaxy-rotation-curve problem was too elegant to ignore. For most galaxies it explained observations better than dark matter did.

But why did MOND work? What was the justification for changing Newton's law other than that it made the rotation-curve problem disappear? There was no reason, and Milgrom knew it. His solution wasn't a theory; it was simply a description and did not explain anything from first principles. Meanwhile, the dark-matter hypothesis had become ever more sophisticated. So while Milgrom and a handful of true believers continued to work on MOND, dark matter had attracted legions of supporters and became the subject of hundreds of research papers.

Where dark matter once seemed as ad hoc as Milgrom's proposal, it had over the past decade morphed into a full-blown theory that explained far more than just the peculiar movement of stars in galaxies. Dark matter had become crucial to understanding the entire large-scale structure of the universe and how galaxies formed in the first place. One of the most striking astronomical discoveries of the past 20 years is that galaxies are not randomly scattered.



They're organized in vast sheets hundreds of millions of light-years in extent. Huge expanses devoid of visible matter separate the sheets. The only explanation cosmologists can offer for this structure is that the enormous galactic sheets must themselves be embedded in even larger agglomerations of dark matter.

Supporters of dark matter draw their most convincing evidence from the early universe. For the past few years, a NASA spacecraft called the Wilkinson Microwave Anisotropy Probe, or WMAP, has been studying the cosmic microwave background radiation, which is a relic of the Big Bang. The fine details of the radiation hold clues about how matter was distributed when the universe was only a few hundred thousand years old. Dark-matter models have predicted what WMAP has seen with such stunning accuracy that cosmologists now rely on dark matter to explain the entire evolution of the universe.

"The big difference between now and 20 years ago," James Peebles says, "is the quality of cosmological data [from WMAP]. I am deeply impressed with the way dark matter has explained cosmological observations."

To make MOND a serious alternative to dark matter, Milgrom's inspired guess needed to mature into a true theory, with a firm foundation in modern physics. And that meant confronting not just Newton but his wild-haired offspring, Einstein. It was Einstein who divined the interconnections between gravity, space, and time. For MOND to make headway in the field, someone was going to have to find a way to reconcile it with Einstein's masterpiece, the theory of general relativity.

"You can compare the first version of MOND to Kepler discovering the shape of planetary orbits," says Mario Livio, the senior astronomer at the Space Telescope Science Institute in Baltimore. In 1605 Kepler figured out that planets have elliptical orbits, but he could not explain why. It took the genius of Newton, in his 1687 *Principia Mathematica*, to finish what Kepler started and provide a complete theory, including the nature of the gravitational force.

Milgrom needed to do the same for MOND to expand its explanatory power. "Of course I knew a relativistic version of MOND was needed," he says, "but, hey, there is no theory of quantum gravity yet either. MOND had survived so many other tests over the years that my confidence had grown with time. There has never been anything drastically wrong found with the MOND framework. It simply was not equipped to deal with cosmology and galaxy formation."

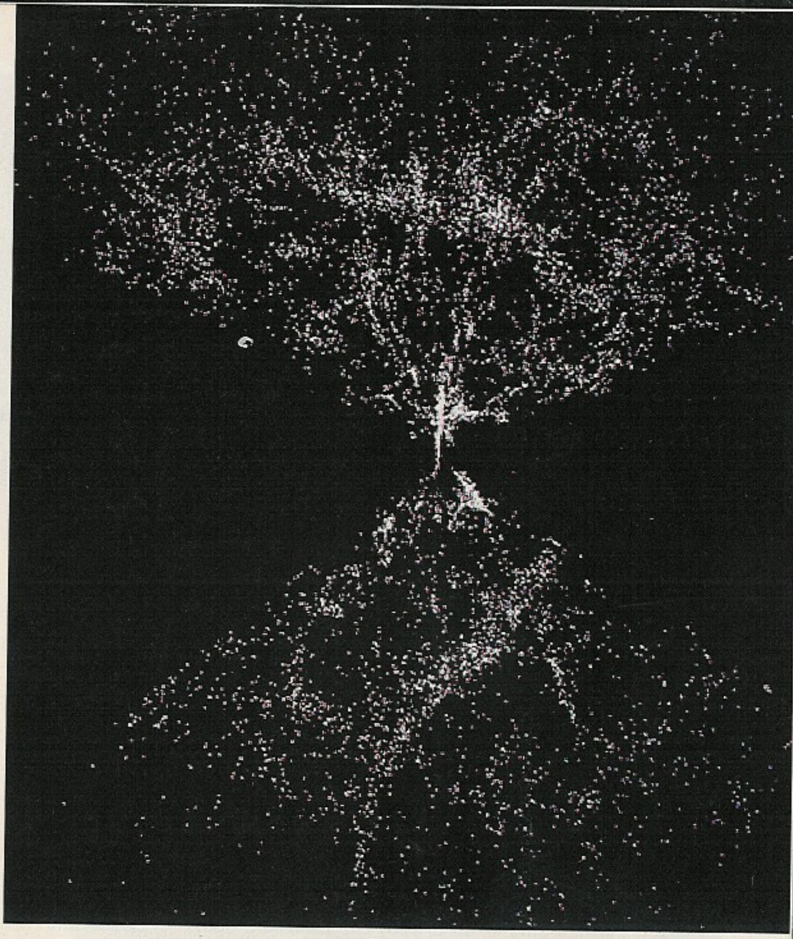
Michael Turner, a cosmologist at the University of Chicago, sees the contrast more starkly. "MOND was a clever idea, but we are pretty far down the path in cosmology now, and the simpler solution is to assume that there are just particles out there that don't give off light." Turner says he will always keep an open mind to interesting new theories, but the successes of dark matter are just too hard to ignore. "It's like you're at a baseball game, and it's the ninth inning, and dark matter has a 14-run lead over MOND, which isn't even on base yet. The game may not be over, but people are heading for the parking lot."

Turner's analogy drives home the role that human resources play in developing a theory. For whatever reason, MOND had remained a wallflower at the astrophysics ball. It was hard to find dance partners, physicists willing to devote the long hours to figuring out the gritty mathematical details by which the theory would live or die. String theory, for example, is an exceedingly abstract piece of work, but because of its perceived promise, armies of talented young physicists are drawn to it. MOND had no such fan base.

To Turner, this makes perfect sense. "As a theorist you see that

LEFT: The gravitational pull of a galaxy cluster has bent and split light to create multiple images of a quasar (blue circles) and multiple images of a galaxy (red). The yellow circle shows a supernova.

RIGHT: This image shows 11,000 galaxies, depicted as dots, with the Milky Way at the center. Cosmologists typically attribute the latticelike distribution to the pull of dark matter.



... COURTESY OF MARGARET GELLER AND JOHN HUCHRA, SMITHSONIAN ASTROPHYSICAL OBSERVATORY.

MILGROM SAYS HIS THEORY HAS PASSED A CRUCIAL FIRST TEST. IT CAN EXPLAIN THE PHENOMENON OF GRAVITATIONAL LENSING, A COSMIC OPTICAL ILLUSION IN WHICH MATTER BENDS LIGHT

with a really good idea, you put a quarter in and you get 10 dollars out, and people should flock to your idea," he says. "I just have not seen that with MOND."

With only a few diehards working on MOND, progress was necessarily slow. Peebles applauds the existence of MOND as an alternative to dark matter, but he points out its recruitment problems. "With so much success happening with dark matter and cosmology, if you were a young scientist, would you bet your career on MOND?" In the face of such pressure, it was left to the old guard to find a way forward.

On March 25, 2004, a paper from *Physical Review Letters D* appeared on the Los Alamos preprint server, a Web site where physicists post their newest articles. The paper, titled "Relativistic Gravitation Theory for the MOND Paradigm," was written by Jacob Bekenstein, Milgrom's collaborator since the 1980s. Building on earlier attempts, Bekenstein was finally able to generate a MOND theory that Einstein might have loved. The new theory was called TeVeS, an acronym for tensor, vector, and scalar—mathematical terms that describe how matter and energy interact with space and time in general relativity.

"TeVeS does everything," says Mario Livio with enthusiasm. A self-described agnostic in the MOND debate, but one with an obvious love for the underdog, Livio says that Bekenstein's work is "a phenomenal paper." In TeVeS, he adds, all the right things happen. Its results mesh with what physicists know about gravity from Einstein, and when gravity is very weak, it reduces to the behavior Milgrom envisioned in his first MOND papers. "With Bekenstein's theory we should now be able to explore all aspects of relativistic behavior," Milgrom says, unable to hide his pride. "This includes the bending of light by gravity, and in principle, the new theory should be OK for galaxy formation."

TeVeS may not be the final word on making MOND jibe with relativity, but it is a critical first step. "Perhaps there are more beautiful and elegant forms of the theory out there," Livio says. What matters most is that now the contest between MOND and dark matter can really get started. "With MOND you could not do cosmology," he says, "but you can do it with TeVeS."

TeVeS has already passed a crucial first test, Milgrom says, because it can be used to explain the phenomenon of gravitational lensing, a cosmic optical illusion in which matter bends light. It's one of the stranger predictions of general relativity, and astronomers have confirmed it many times over. When observing a distant galaxy, for example, massive objects between Earth and the galaxy act like a giant lens and bend the galaxy's light, creating multiple images of the single galaxy. Dark-matter models have been used to explain the lensing of many distant galaxies. If Milgrom can convince his colleagues that TeVeS does it just as well, it's a whole new ball game, and maybe some of the fans will start returning to their seats.

Papers comparing TeVeS and dark matter are just beginning to appear, and it is far too soon to say how the new work will ultimately be judged. While TeVeS and all the other MOND approaches may fall into the trash bin of scientific history, the same fate may await dark matter. Expensive and elaborate searches for dark-matter particles have come up empty-handed. If those ongoing hunts continue to fail, and if the momentum for MOND-inspired theories continues to build, the tide may turn, and the entire elaborate cosmological scaffolding may be rocked from its foundations. It's a startling thought that dark matter, now such an integral if mysterious part of the modern picture of the universe, might simply vanish overnight. That wouldn't be heresy. That would be a revolution. ■