

Ninety-five percent of the
universe has gone missing.
Or has it?

By Mordehai Milgrom

Does Dark Mat



ter Really Exist?

OF ALL THE MANY MYSTERIES of modern astronomy, none is more vexing than the nature of dark matter. Most astronomers believe that large quantities of some unidentified material pervade the universe. Like a theater audience that watches the herky-jerky gestures of a marionette and infers the presence of a hidden puppeteer, researchers observe that visible matter moves in unaccountable ways and conclude that unseen matter must be pulling the strings. Yet this dark matter has eluded every effort by astronomers and physicists to bring it out of the shadows. A handful of us suspect that it might not really exist, and others are beginning to consider this possibility seriously.

The dark matter problem arose because of a mismatch in the masses of galaxies and larger cosmic structures. The constituents of these systems—stars and gas in the case of galaxies, gas and galaxies in the case of galaxy clusters—move about but do not escape, because they are checked by the gravitational pull from the rest of the system. The laws of physics tell us how much mass has to be present to counterbalance the motions and thereby prevent the dispersal of the system. Disconcertingly, the tally of mass that astronomers actually observe falls far short of that.

This mass discrepancy is ubiquitous. It appears in practically all systems, from dwarf galaxies through normal galaxies and galaxy groups on up to the vast superclusters. The magnitude of the discrepancy ranges from a factor of a few to a factor of hundreds.

The need for extra matter arises not only in well-formed galactic systems but also through the universe at large. Long before galaxies even formed, the universe was filled with a plasma of atomic nuclei and subatomic particles. Radiation suffused the plasma and kept it extremely smooth. Fluctuations in the density of this plasma did not have a chance to grow and develop into galaxies until after the plasma had turned into a neutral gas, which does not interact with radiation as strongly. We know when this neutralization occurred and what the strength of the density fluctuations was then. The problem is that there just wasn't enough time for those fluctuations to become the galaxies we observe. Dark matter would help in that, being neutral by definition, it would not be homogenized by radiation. Therefore, it would have been contracting all along. Dark matter would have had enough time to form galaxy-mass bodies.

Common knowledge has it that part of this extra mass consists of ordinary matter that gives off too little radiation for present technology to detect: planets, dwarf stars, warm gas. Such material is more precisely called dim matter. It could represent up to 10 times as much matter as astronomers see, but even so it could account for only a small fraction of the missing mass. When researchers refer to dark matter, they usually mean an exotic breed of matter that makes up the difference. To add to the confusion, they also suspect the existence of dark energy, a distinct type of energy that would produce the observed accelerated expansion of the

universe, a phenomenon that neither normal nor dark matter can explain [see "The Quintessential Universe," by Jeremiah P. Ostriker and Paul J. Steinhardt; *SCIENTIFIC AMERICAN*, January 2001].

In sum, astronomers widely believe the current energy content of the universe to be roughly 4 percent ordinary (or "baryonic") matter, about a tenth of which is seen as stars and gas; a third dark matter in some unknown form; and two thirds dark energy, the nature of which is even less understood.

Under Cover of Darkness

DARK MATTER is the only explanation that astronomers can conjure up for the various mass discrepancies, if we cleave to the accepted laws of physics. But if we accept a departure from these standard laws, we might do away with dark matter.

The diverse appearances of the mass discrepancy, as reflected in the motions inside galactic systems, stem from the use of a single formula in Newtonian physics. This formula combines two basic laws: Newton's law of gravity (which relates the force of gravity between bodies to the bodies' masses and separation) and Newton's second law (which relates force to acceleration). The acceleration of a body in orbit depends on the velocity and size of the orbit. Putting all this together, one derives the connection among mass, velocity, and orbital size or distance.

These laws accurately explain the flight of a ballistic missile and the motions of the planets. But their extrapolation to galaxies has never been directly

tested. Might it go amiss? If the laws break down, then modifying them might obviate dark matter.

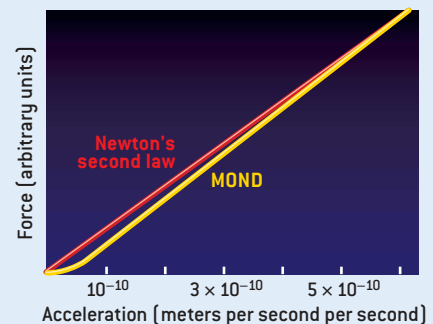
Such a modification would not be without precedent. Two drastic changes to Newtonian physics have already proved necessary. The first upgraded Newtonian dynamics to the theory of relativity—both the special theory (which changed Newton's second law) and the general theory (which altered the law of gravity). The second led to quantum theory, which accounts for the behavior of microscopic systems and even macroscopic systems under certain circumstances. The two proven extensions of Newtonian dynamics come into play under extreme conditions, such as extreme speeds (special relativity) or extremely strong gravity (general relativity). The bulk of the phenomena connected with galactic dynamics involves none of these particular conditions.

What attributes of galactic systems are so extreme that they might require yet another modification? The first possibility that comes to mind is size. Perhaps gravity departs from the Newtonian law at large distances. As early as 1923, English astronomer James H. Jeans proposed modifying the distance dependence of the law of gravity on galactic scales. But the discrepant observations he sought to explain were unrelated to dark matter and, in any event, were later refuted.

Another modified distance dependence was proposed in 1963 by Arrigo Finzi, then at the University of Rome, as a possible solution to the dark matter

Overview/*Alternative to Dark Matter*

- Astronomers have two ways to determine how much matter fills the universe. They tot up everything they see. And they measure how fast the visible objects move, apply the laws of physics and deduce how much mass is needed to generate the gravity that restrains those objects. Vexingly, the two methods give different answers. Most astronomers conclude that some invisible mass also lurks out there—the infamous dark matter.
- Perhaps the fault lies not in the matter but in the laws of physics. The author has proposed a modification to Newton's laws of motion (see graph at right)—or, equivalently, of gravity—that would explain away the discrepancy.
- The modification, known as MOND, does an amazingly good job of reproducing observations—better, in many ways, than dark matter does. That said, MOND has some problems, which may be unimportant or may be fatal.



NEW THEORY, known as MOND, changes Newton's second law of motion at low accelerations.

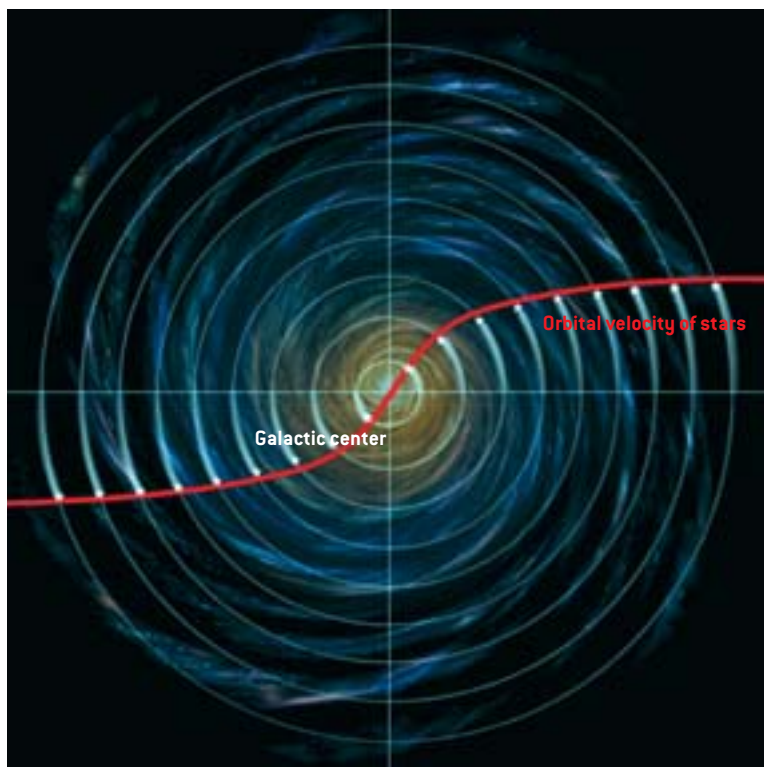
MAKING THE ROUNDS

JUST AS THE PLANETS in the solar system orbit around the sun, stars in a galaxy orbit around the galactic center. For example, the sun completes one circuit of the Milky Way every 200 million years or so. Stars in the disks of spiral galaxies have nearly circular orbits, and their orbital speed depends on their distance from the center.

Two effects determine the speed: the distribution of mass and the weakening of the force of gravity with distance. The first effect is simply a matter of geometry—the amount of mass contained within a stellar orbit increases with distance. This effect dominates in the inner reaches of the galaxy. Farther out, the second effect becomes more important. The net result is that the orbital speed initially increases but then levels off and begins to decrease. This relation between speed and distance is known as the rotation curve.

According to Newton's laws, the rotation curve should continue to decrease forever. If MOND is correct, however, it should reach a constant value.

—M.M.



problem in clusters. But in the early 1980s I showed that such modifications of the distance dependence of gravity fail to reproduce the observations.

What, then, can work? After systematically considering different attributes, I zeroed in on acceleration. The acceleration in galactic systems is many orders of magnitude smaller than in everyday experience. The acceleration of the solar system toward the center of our galaxy (about one angstrom, or 10^{-10} meter, per second per second) is one hundred-billionth the acceleration of the space shuttle toward the center of Earth (about 10 meters per second per second). Nearly 20 years ago I proposed a modification to Newton's second law that changed the relation between force and acceleration when the acceleration is low. This was the beginning of the idea called MOND, for Modified Newtonian Dynamics.

Building Up Speed

MOND INTRODUCES a new constant of nature with the dimensions of acceleration, called a_0 . When the acceleration is much larger than a_0 , Newton's second law

applies as usual: force is proportional to acceleration. But when the acceleration is small compared with a_0 , Newton's second law is altered: force becomes proportional to the square of the acceleration. By this scheme, the force needed to impart a given acceleration is always smaller than Newtonian dynamics requires. To account for the observed accelerations in galaxies, MOND predicts a smaller force—hence, less gravity-producing mass—than Newtonian dynamics does [see *illustration on opposite page*]. In this way, it can eliminate the need for dark matter.

In the outskirts of galaxies, the acceleration produced by gravity decreases with distance and eventually goes below a_0 . Exactly where this happens depends on the value of a_0 and on the mass. The higher the mass, the farther out the effects of MOND set in. For the value of a_0 that is required by the data, and for a galaxy of typical mass, the transition takes place several tens of thousands of light-years from the center. For the mass of a typical cluster of galaxies, it happens at a few million light-years from the center.

Suppose the bulk of a galaxy is con-

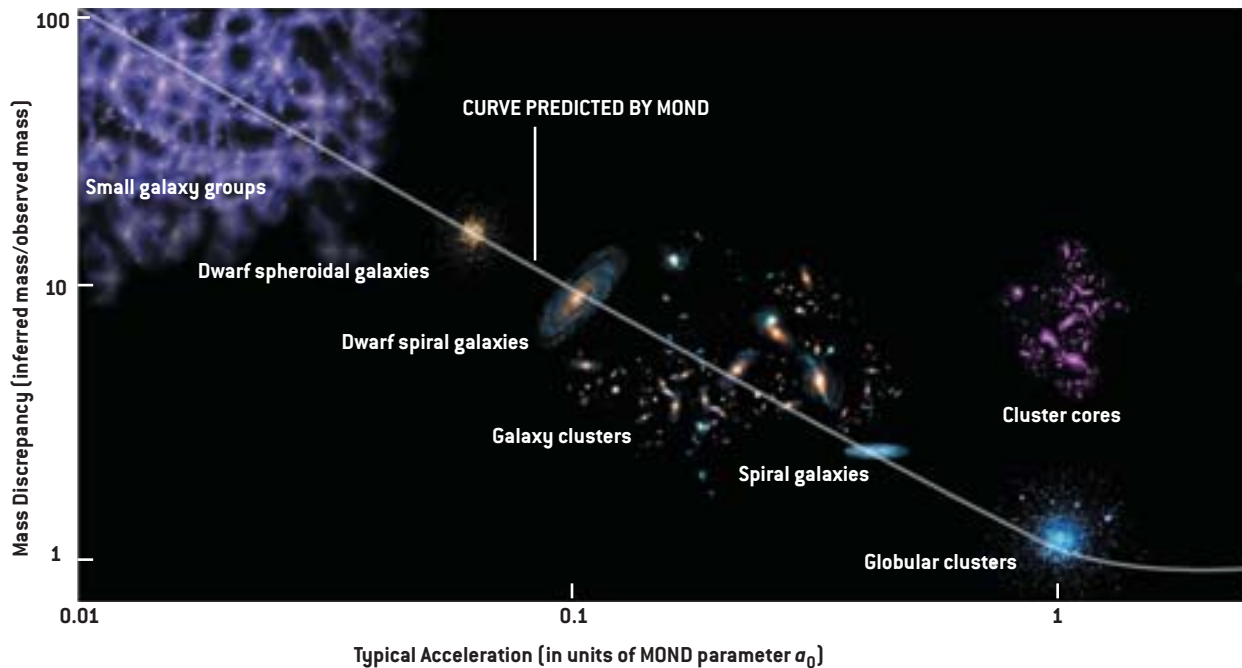
tained within a certain radius. Then, by Newtonian dynamics, beyond this radius the speed of objects in circular orbits (such as gas or stars) should decrease with increasing radius. This is what happens in the solar system. The bulk of the solar system's mass is contained in the sun, and the orbital velocity of the planets decreases with distance. Mercury trundles around the sun much faster than Earth does, for example. Where MOND applies, however, the situation is radically different. At sufficiently large distances from the center of a galaxy, the orbital velocity should stop decreasing and reach a constant value. This constant velocity should be proportional to the fourth root of the galaxy's mass.

How does MOND fare when confronted with the data? Orbital velocities in spiral galaxies, instead of declining with increasing distance from the galactic center, flatten out to a constant value, as predicted by MOND. Moreover, according to an observed correlation known as the Tully-Fisher relation, this constant velocity is proportional to the fourth root of the galaxy's luminosity. This, too, emerges naturally from MOND. The key

MOND IN GALACTIC SYSTEMS

ALL TYPES OF GALACTIC SYSTEMS—ranging in size from globular star clusters to dwarf galaxies to galaxy groups and clusters—suffer from a discrepancy between the observed and the inferred mass. This discrepancy scales

inversely with the characteristic acceleration, just as MOND predicts. Dark-matter models have no explanation for the correlation. MOND's main failure occurs in the cores of large galaxy clusters. —M.M.



assumption is that the luminosity, in turn, is proportional to mass or nearly so. Recent observations vindicate the assumption: a direct velocity-mass correlation is even tighter than the velocity-luminosity correlation.

Glimpses of these regularities were already in sight when I proposed MOND; indeed, they furnished clues for its construction. What makes MOND particularly intriguing is that it predicted many effects that could not even be tested when I formulated it. One example is the nature of low-surface-brightness galaxies—stellar agglomerations so wispy that they can barely be seen at all. Whereas the acceleration in ordinary galaxies exceeds a_0 toward the center and drops below a_0 in the outskirts, the acceleration in low-surface-

brightness galaxies is smaller than a_0 everywhere. According to MOND, the mass discrepancy should be seen throughout such a galaxy. At the time I propounded MOND, astronomers knew of only a few low-surface-brightness galaxies and had analyzed none in any detail. Since then, they have discovered that the mass mismatch is indeed disproportionately larger in these galaxies than in ordinary galaxies [see “The Ghostliest Galaxies,” by Gregory D. Bothun; *SCIENTIFIC AMERICAN*, February 1997]. MOND correctly anticipated this. It also foresaw the magnitude of the discrepancies.

Another success concerns the shape of galactic rotation curves—that is, the precise variation of orbital velocity with distance. Only since the late 1980s have astronomers made observations detailed enough to compare with theoretical predictions. And the correspondence with MOND is remarkable [see *illustration on page 50*]. These comparisons involve one parameter that must be adjusted for each galaxy: the conversion factor from starlight to mass. The inferred value of this pa-

rameter agrees with theoretical expectations. For dark matter, in contrast, the comparisons involve at least two additional adjustable parameters per galaxy—namely, the extent and mass of the dark matter. Despite this flexibility, current dark matter theories do not explain the rotational data as well as MOND does.

Exception to the Rule?

IN OTHER GALACTIC systems, when one plots the mass discrepancy against the typical acceleration, the pattern almost completely agrees with MOND's predictions [see *illustration above*]. The one exception is found in rich galaxy clusters. If we consider the clusters at large, they typically show a mass discrepancy of about a factor of five to 10, which MOND can explain. If, however, we concentrate on the inner parts of these clusters, we find that a mismatch remains. MOND does not sweep away all the invisible mass. Perhaps the theory itself fails, but perhaps the observations are incomplete. Significant amounts of dim matter—ordinary matter in the form of feeble stars or lukewarm

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gas—could be lurking in these systems.

Ideally, one would like to check MOND using physics experiments as well as astronomical observations. Unfortunately, laboratory tests are infeasible. The acceleration that enters the MOND criterion is the full acceleration with respect to an absolute frame of reference. On Earth or in the near solar system, the large background acceleration—caused by Earth’s gravity, its rotation, its revolution around the sun and myriad other factors—would mask the effects of MOND even if we could create a setup with small relative accelerations internally. Similarly, it would be hard to test MOND by studying the motions of the planets. The acceleration of bodies orbiting the sun does not fall below a_0 until one goes about 10,000 times as far from the sun as Earth is, far beyond the orbit of Pluto. To be sure, the structure of MOND for high accelerations—where the theory departs only minutely from Newtonian dynamics—is not yet known. It might be that the departure, though very small, is still large enough to produce observable effects. The claimed anomaly in the motions of certain spacecraft, if verified, could be naturally explained within MOND [see “Pioneering Gas Leak?” by George Musser; *Science and the Citizen*, *SCIENTIFIC AMERICAN*, December 1998].

Just as Planck’s constant appears in many roles in quantum theory, so does a_0 appear in many ways in MOND’s predictions for galactic systems. It is part of the success of the theory that the same value—approximately one angstrom per second per second—works for all these diverse appearances.

Successful as it may be, MOND is, at the moment, a limited phenomenological theory. By phenomenological, I mean that it has not been motivated by, and is not constructed on, fundamental principles. It was born from a direct need to describe and explain a body of observations, much as quantum mechanics (and, indeed, the concept of dark matter) developed. And MOND is limited, because it cannot yet be applied to all the relevant phenomena at hand.

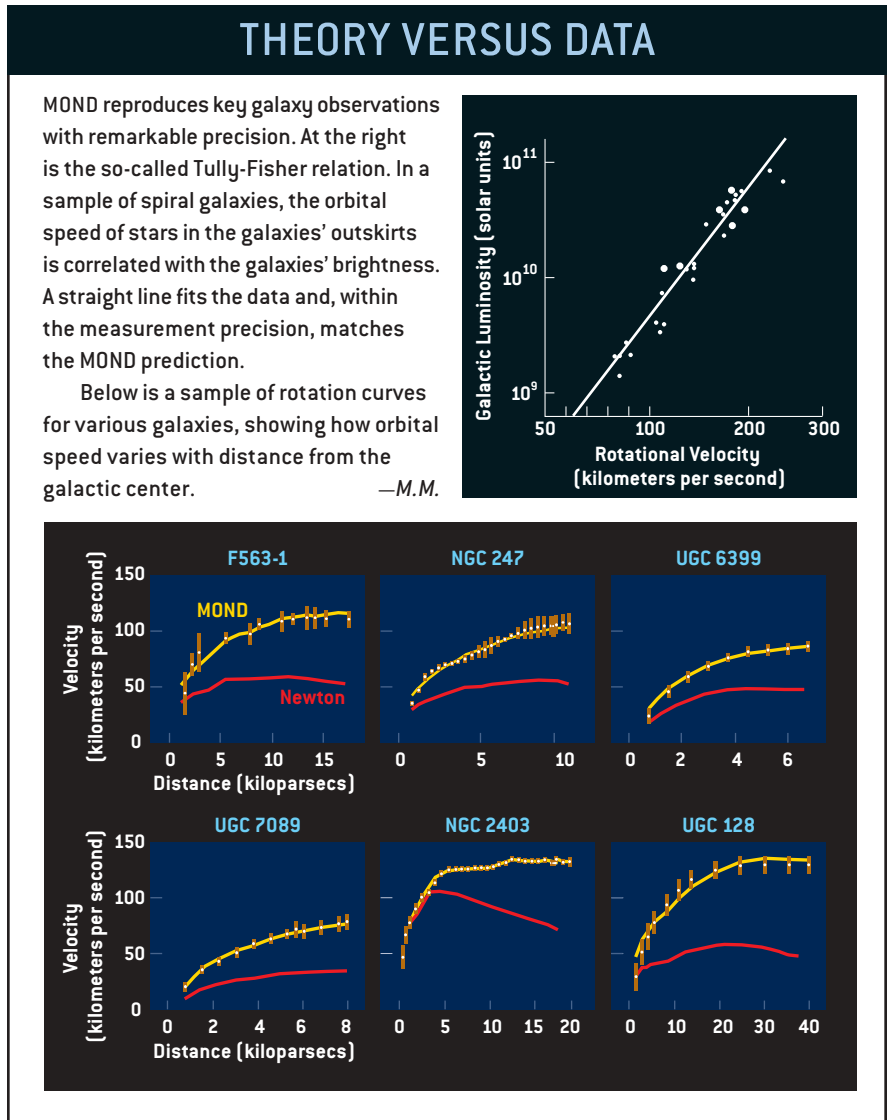
The main reason is that MOND has

not been incorporated into a theory that obeys the principles of relativity, either special or general. Perhaps it is impossible to do so; perhaps it is simply a matter of time. After all, it took many years for the quantum idea, as put forth by Max Planck, Einstein and Niels Bohr, to be encapsulated into the Schrödinger equation, and more time still to be made compatible with special relativity. Even today, despite long, concentrated efforts, theorists have not made quantum physics compatible with general relativity.

Beyond the Ken

THE PHENOMENA that fall outside the present purview of MOND are those that involve, on the one hand, accelerations smaller than a_0 (so that MOND plays a

role) and, on the other, extreme speeds or extremely strong gravity (so that relativity is also called for). Black holes meet the second criterion but fail the first: for the acceleration near a black hole to be smaller than a_0 , the hole would have to be larger than the observable universe. Light propagating in the gravitational fields of galactic systems, however, does satisfy both criteria. MOND cannot properly treat this motion, which pertains to gravitational lensing [see “Gravity’s Kaleidoscope,” by Joachim Wambsgans; *SCIENTIFIC AMERICAN*, November 2001]. Observations that make use of gravitational lensing exhibit the same mass disparity that observations of galactic dynamics do. But we do not yet know whether MOND can explain the disparity in both cases.



top: DON DIXON; SOURCE: ROBERT H. SANDERS, Kapteyn Astronomical Institute AND MARC A. W. VERHEIJEN, University of Wisconsin—Madison; bottom: BRYAN CHRISTIE DESIGN; SOURCE: STACY S. MCGAUGH, University of Maryland

Not a Bad Idea

MOND is out of the mainstream, but it is far from wacky

By Anthony Aguirre

Although the great majority of astronomers believe that dark matter exists, an alternative hypothesis—a modification of Newtonian gravitational dynamics (MOND)—has quietly endured since its proposal in 1983. As Mordehai Milgrom discusses in the accompanying article, MOND can claim an impressive number of correct predictions regarding the dynamics of galaxies. The reactions of most astronomers fall into three categories:

1. MOND is a tautology. It explains only what it was expressly designed to explain. It has made a few fortuitous predictions, but the success of those predictions has been exaggerated by its proponents.
2. MOND describes a surprising, even mysterious, regularity in the formation and evolution of galaxies. The standard theory of gravity still applies and dark matter still exists, but somehow the dark matter emulates MOND. When applied in detail to unusual galaxies or to systems other than galaxies, MOND will eventually be shown to fail.
3. MOND replaces Newtonian dynamics under certain conditions. It is one aspect of a theory of gravitational dynamics that will supplant Einstein's general theory of relativity.

The first view, through uncharitable, was the one held by most astrophysicists for much of MOND's history. In recent years, however, outright rejection has become much less tenable. MOND's myriad predictions have been confirmed. Many of these studies have been performed by those critical of, or neutral toward, Milgrom's hypothesis. Moreover, MOND reproduces the statistics of galaxy properties at least as well as dark matter models do, even though these models describe crucial aspects of galaxy formation in an ad hoc way.

Most impressively, MOND can predict the details of galaxy rotation using only the distribution of visible matter and an assumed (fixed) ratio of mass to luminosity—a feat beyond the ability of dark matter models. These predictions and the observations they are compared with go far beyond what was available at the time of MOND's formulation. MOND is no tautology.

Meanwhile standard dark matter theory has run into difficulty when applied to galaxies. For example, it predicts that the dark matter cores of galaxies should be far denser than observations indicate. Such problems could be an artifact of computational limitations; researchers still lack computers powerful enough to simulate galaxies in full. But many theorists have taken the discrepancies seriously enough to consider modifications of the properties of dark matter.

The successes of MOND and the difficulties for dark matter have converted a number of astronomers from the first view to the second. Relatively few, though, have gone from the first

or second view to the third. Why? I think there are three reasons.

First, as both its opponents and proponents point out, MOND is a modification only of Newtonian dynamics. Despite some effort, MOND's proponents have yet to formulate it in a way that can be applied to post-Newtonian phenomena such as gravitational lensing and cosmic expansion. Either no such theory exists or it is inherently difficult to develop. Whatever the reason, MOND has been unable to confront—and hence pass or fail—some key tests.

Second, it is not clear that MOND works well in systems other than galaxies. For example, its predictions about the temperature of hot gas in clusters of galaxies disagree starkly with observations, unless clusters are dominated by—what else?—undetected matter. One might hope (as do MOND's proponents) that this matter could take a recognizable but hard-to-see baryonic form such as small stars or warm gas. Those possibilities are not currently ruled out, but they are strongly constrained both observationally and theoretically. And it is rather disquieting that dark matter (even if in a prosaic form) must be postulated to save a theory devised to eliminate dark matter.

The third reason, related to the first two, is that standard dark matter theory has scored some impressive triumphs in recent years. Numerical simulations predict a spatial distribution of intergalactic gas that is in exquisite agreement with observations. Independent estimates of the mass of dark matter in clusters all agree with one another. The predicted growth of structures correctly links the galaxy distribution we see on large scales today with the tiny temperature fluctuations in the cosmic microwave background radiation from 13 billion years ago.

So what are astronomers to do? Those who are most sympathetic to Milgrom's hypothesis should continue the search for a fundamental theory of MOND, without which the idea will never draw the majority of physicists away from the standard paradigm. For others, I think that it is productive to study, test and use MOND as a convenient rule of thumb whether or not one accepts a modification of Newtonian dynamics. Perhaps we could call it Milgrom's Fitting Formula, or MIFF, to emphasize that we are using it as a practical tool while reserving judgment about whether standard physics is indeed wrong.

If general relativity is correct, and dark matter real, then as the precision of measurements increases, MIFF will ultimately fail. In the meantime, MIFF can provide a compact summary of a great deal of knowledge concerning galaxy formation and evolution.

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A second system that requires MOND and relativity is the universe at large. It follows that cosmology cannot be treated in MOND. This incapacity extends to questions relating to incipient structures in the universe. MOND can be applied to well-formed systems that are detached from the global cosmological soup, but it cannot describe the early moments before galactic systems became distinct.

Researchers have made preliminary

This idea falls within the framework of an old concept, Mach's principle, which attributes inertia to such an interaction.

Physics abounds with instances in which the effective inertia of particles is not an inherent property but rather is produced by their interaction with a background medium. For example, electrons in solids sometimes behave as if their inertia has been greatly modified by the rest of the solid. Might an analogous effect be

year Manoj Kaplinghat and Michael S. Turner, both then at the University of Chicago, claimed that the appearance of a characteristic acceleration akin to a_0 occurs naturally in dark matter models. According to their scenario, these models predict the formation of dark matter halos of a restricted type around galaxies.

Subsequently, however, I pointed out that this scenario does not work. Kaplinghat and Turner based their work on

If we accept a departure from the standard laws of physics, we might do away with dark matter.

attempts to deal with what these phenomena might look like in a MOND-inspired theory. For example, Robert H. Sanders of the Kapteyn Astronomical Institute in Groningen, the Netherlands, and Adi Nusser of the Technion-Israel Institute of Technology have devised scenarios of galaxy formation by supplementing MOND with further working assumptions. But it must be said that without an underlying theory, none of these efforts can be fully trusted.

In what directions should one look for the needed underlying theory? A clue may come from the value of a_0 . One angstrom per second per second would take a body from rest to near the speed of light in the lifetime of the universe. In other words, a_0 is roughly the same number as the product of two important constants: the speed of light and the Hubble constant, the present-day expansion rate of the universe. It is also near the (unrelated) acceleration produced by the dark energy. This numerical proximity, if it is not just a coincidence, may tell us either that cosmology somehow enters local laws of physics, such as the law of inertia, to produce MOND or that a common agent affects both cosmology and local physics so as to leave the same mark on both of them.

Resistance

MOND APPEARS to suggest that inertia—the responsiveness of a body to a force—is not an inherent property of bodies but is acquired by the body by dint of its interaction with the universe at large.

responsible for genuine inertia? If so, what could be the agent whose presence impedes acceleration and thus produces inertia?

An exciting possibility is the vacuum. The vacuum is what is left when one annihilates all matter (or, equivalently, energy) that can be annihilated. According to quantum theory, the remnant is not a complete void but rather a minimal representation of all the forms of energy. The interaction of the vacuum with particles might contribute to the inertia of objects. Intriguingly, the vacuum also enters cosmology as one explanation for dark energy. It remains unknown, however, whether the vacuum can be fully responsible for inertia and whether it can indeed account for MOND.

Many researchers maintain that although MOND neatly reproduces galactic phenomenology, it does not constitute a fundamental truth. The argument goes that MOND is perhaps an economical and useful summary of what we see in nature but that these relations and regularities will one day emerge from the complexity of the dark matter paradigm. Last

crude approximations that disagree with observed dark matter halos and with detailed numerical simulations of dark matter behavior. Those simulations, as they now stand, do not reproduce any aspect of MOND phenomenology. To boot, their claimed result accounts for only a small fraction of the successes of MOND. But it is possible that MOND follows from the dark matter paradigm in a different way. Time will tell.

In the meantime, work is proceeding on understanding the observational consequences of MOND and improving the theory itself, with contributions from Sanders, Jacob D. Bekenstein of the Hebrew University in Jerusalem and Stacy S. McGaugh of the University of Maryland. MOND continues to be the most successful and enduring of the alternatives to dark matter. Observations, far from ruling it out, seem to prefer it over dark matter. Although people are right to be skeptical about MOND, until definitive evidence arrives for dark matter or for one of its alternatives, we should keep our minds open. SA

MORE TO EXPLORE

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Stacy S. McGaugh's MOND Web site is at www.astro.umd.edu/~ssm/mond