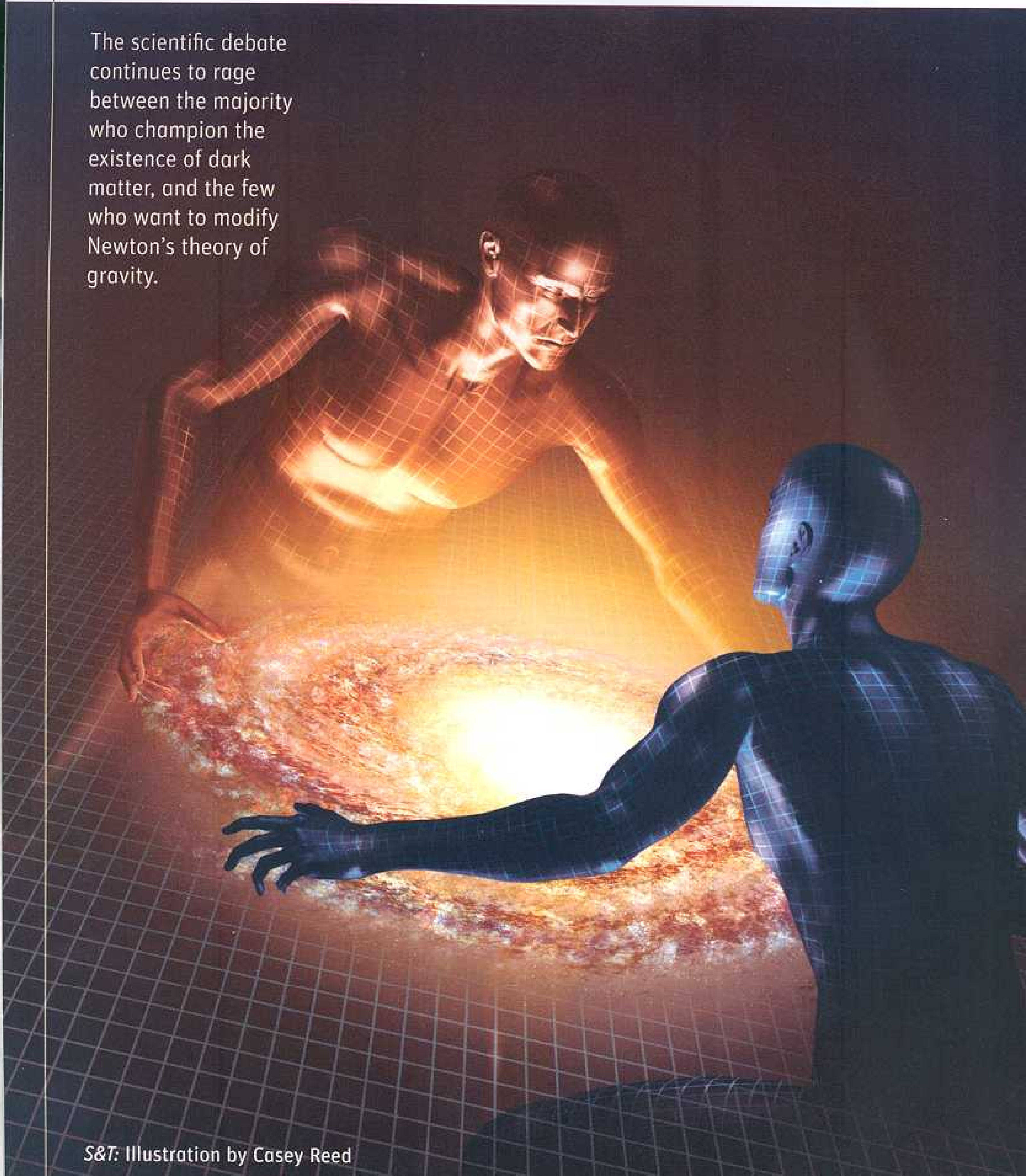


S&T: Illustration by Casey Reed

Battlefield Galactica: Dark Matter vs. MOND

By Govert Schilling

Dark matter is one of astronomy's biggest mysteries. Without its gravitational muscle, rotating galaxies would fly apart, galaxy clusters would dissipate, and the universe's large-scale structure would differ dramatically from what we observe. But no one knows what dark matter is, and laboratory experiments have failed to detect any. Does it really exist, or could there be something wrong with our ideas about gravity?

Physicist Mordehai Milgrom (Weizmann Institute, Rehovot, Israel) thinks it's the latter. And he's not alone. Twenty-five years ago Milgrom conceived Modified Newtonian Dynamics (MOND), a radical idea that gravity's behavior changes over galaxy-scale distances. Despite many attempts to squash the theory, it's still very much alive and kicking. "We're accumulating observational evidence," says Milgrom's collaborator Robert Sanders (University of Groningen, Netherlands), "and the theory is becoming stronger and stronger."

But the vast majority of astronomers and physicists strongly disagree. They accept the prevailing "concordance model" of a universe dominated by dark matter and an even more mysterious dark energy. One of the model's founding fathers, cosmologist Joel Primack (University of California, Santa Cruz), says the idea behind MOND is quixotic. He asserts, "Milgrom and his collaborators are on a quest that is not likely to succeed."

Astrophysicist David Spergel (Princeton University) agrees. "MOND has many observational failures," he says. Spergel argues that the concordance model beautifully fits all current data on the structure and dynamics of galaxy clusters, so there's no need for a new theory of gravity (see page 16).

Who is right, and how and when will scientists resolve the controversy?

According to Isaac Newton's famous inverse-square law, a foundation of modern physics, gravity's strength weakens with the inverse square of the distance from a central mass. Modified Newtonian Dynamics (MOND) changes Newton's inverse-square law by stating that as gravity falls below a certain strength, it becomes inversely proportional to distance, not to its square. The blue line shows how planetary orbital velocities depend on the Sun's gravity, whose strength falls off with distance according to Newton's inverse-square law. The strength of gravity at which MOND effects begin to show up is so weak that they would appear in planetary orbits only at thousands of astronomical units from the Sun.

Modifying Newton

Ironically, Milgrom became interested in galaxy dynamics during a sabbatical year in Spergel's hometown of Princeton, New Jersey, in 1979. A few years earlier Vera Rubin and Kent Ford had discovered that the outer, low-density regions of galaxies rotate much faster than expected, presumably under the influence of more gravity than that exerted by the visible stars and gas. Invisible (dark) matter could explain the observations. But, thought Milgrom, so could a different force law of gravity.

According to Isaac Newton's well-tested inverse-square law, gravity's strength falls off with the square of the distance. A planet three times farther from the Sun than another feels only one-ninth the gravity. As a result, Neptune orbits much slower than Saturn. But the outskirts of galaxies, where gravitational fields should be relatively weak, behave differently. There, stars and gas clouds generally have the *same* orbital velocities as objects much closer to the galaxy's center.

That's precisely what would happen if, below a certain field strength, gravity becomes inversely proportional to *distance*, not to its square. Milgrom wondered why hypothetical dark matter should be distributed in just such a way that its gravitational effect would mimic such a different but very simple force law. Astronomer Stacy McGaugh (University of Maryland) puts it this way: "Suppose Newton, upon studying the solar system, would have formulated an inverse-*cube* law, claiming that the observed inverse-*square* law is the result of some mysterious, undetected dark matter. That would clearly be less satisfying than simply adopting the observed force law."

Milgrom originally doubted his own idea. "I expected to be able to kill it in a few days," he recalls. But he never could. Instead, after the publication of the first MOND papers in 1983, the theory has steadily grown stronger. McGaugh at first thought he would be able to falsify Milgrom's idea with observations of low-surface-brightness (LSB) galaxies, which contain very little luminous matter. But to his surprise, MOND successfully predicted orbital velocities in these faint objects, which have proved particularly troublesome for dark-matter models. "All sorts of silliness has been published trying to explain this fact," says McGaugh.

McGaugh admits that Milgrom's original theory had some fundamental problems, but, he adds, "A lot of progress has been made since then." In 2004 renowned theoretical physicist Jacob Bekenstein (Hebrew University of Jerusalem) put forth a relativistic version of MOND, which, according to HongSheng Zhao (Scottish University Physics Alliance, St. Andrews), was "a crucial development to get people serious about this."

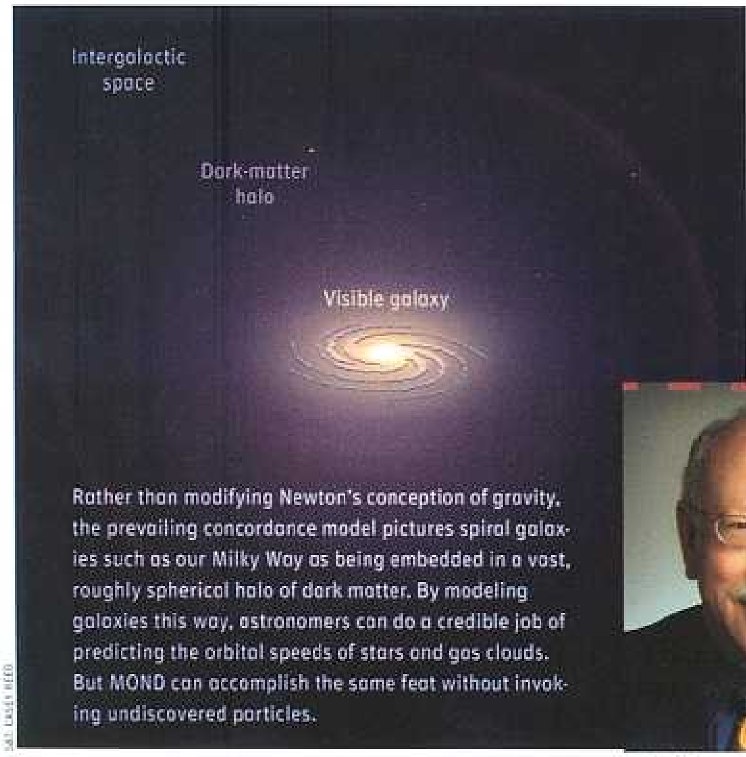
Bekenstein's relativistic version improves upon the original MOND theory, just as Einstein's general theory of relativity improves upon Newtonian gravity. Spergel admits that Bekenstein's theory (known as TeVeS, for tensor/vector/scalar) "is a much more interesting model from a theoretical point of view in that it can be tested against observations in modern cosmology." But, as the name implies, TeVeS introduces three different fields in space-time to replace one gravitational field, and many physicists feel uncomfortable with this contrivance. As Primack says, "Bekenstein's paper is monumentally complex and ugly."

Biting the Bullet

Spergel argues that recent observations of gravitationally lensed systems such as the Bullet Cluster of galaxies in Carina cannot be explained by MOND's relativistic incarnation. Indeed, in an August 21, 2006, NASA press release, Douglas Clowe (then at the University of Arizona) says that his team's X-ray observations of the Bullet Cluster constitute "direct proof that dark matter exists."

The Bullet (officially known as 1E 0657–56) is actually two clusters in collision. Clowe's team mapped the system's hot gas, which makes up most of the luminous material, using NASA's Chandra X-ray Observatory. The group charted the cluster's gravity with gravitational-lensing techniques. The two maps don't overlap, leading Clowe and his colleagues to conclude that most of the mass must be in an invisible, dark form (S&T: December 2006, page 46).

The failure of MOND to explain cluster observations on the basis of visible mass alone "is bad for the theory,"

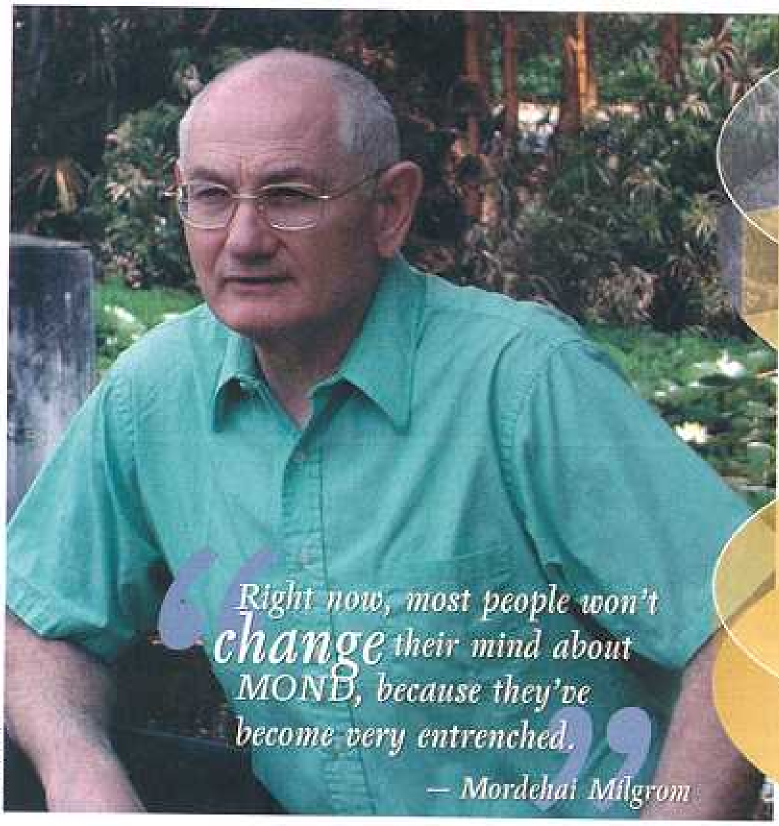


Rather than modifying Newton's conception of gravity, the prevailing concordance model pictures spiral galaxies such as our Milky Way as being embedded in a vast, roughly spherical halo of dark matter. By modeling galaxies this way, astronomers can do a credible job of predicting the orbital speeds of stars and gas clouds. But MOND can accomplish the same feat without invoking undiscovered particles.

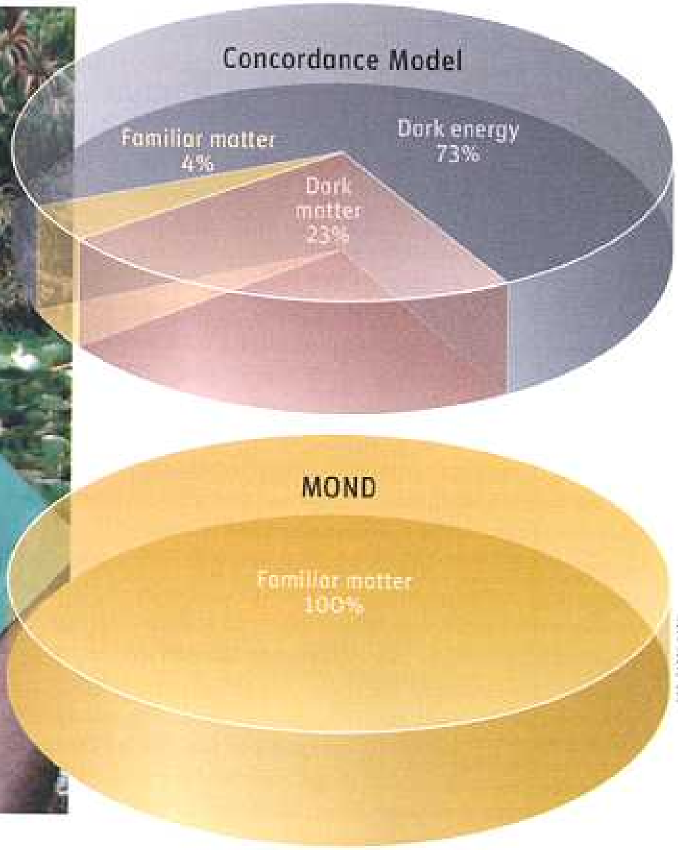
S&T: CASEY REED

PAUL SCHRAUB

"*If other cosmologists want to* ***waste*** *their time on MOND, that's great — it means less competition for me.* — Joel Primack"



"Right now, most people won't change their mind about MOND, because they've become very entrenched."
— Mordehai Milgrom



admits McGaugh, but it's not an insurmountable problem. If neutrinos — ghostly subatomic particles that emit no light — are a bit more massive than is generally thought, they could solve the cluster problem. Indeed, in a paper accepted for publication in *Astrophysical Journal Letters*, Zhao and his colleagues show that they can explain the Bullet Cluster with Bekenstein's TeVeS theory and neutrinos.

Sanders says that a large part of the Bullet Cluster's proof-of-dark-matter hype "is due to NASA's formidable public-relations machinery." Like most MOND adherents, Sanders thinks many astronomers are too strongly wedded to dark matter. "There's certainly a sociological effect involved. Paradigm shifts usually occur very gradually," he says.

McGaugh says that many mainstream scientists "have a predisposition to be disrespectful," but that the respective communities "are cordial socially as long as we don't talk science." He adds, "I often run into an irrational wall that sometimes has an almost religious feel to it. When I ask people what proof I could offer to convince them, they often say 'none.'"

Spergel is less dismissive. "If they came up with a relativistic version of the theory that fits cosmic-microwave-background data, large-scale-structure data, gravitational-lensing data, and matches solar-system tests of relativity, I would be very interested in exploring the theory," he says. "And if this new theory made predictions that were confirmed by experiment and contradicted the [concordance] model, it would be widely accepted by the scientific community."

But convincing evidence will be hard to come by. In science, you can never prove that a theory is right. You can only hope to gather more support for a theory, or to prove it wrong (March issue, page 8).

Falsifying MOND

Could anything convince MOND proponents to abandon their theory? "Of course," says Milgrom. "If dark matter is detected, the question will be answered." Also, if observations contradict a solid MOND prediction, that would settle the issue. For instance, if MOND predicted *less* matter in galaxy clusters than astronomers actually see, the theory would be dead.

In fact, MOND predicts that galaxy clusters should contain about twice as much matter as astronomers have detected. But this unseen stuff would consist entirely of matter that we already know about, such as neutrinos, protons, neutrons, and electrons. The Big Bang theory actually predicts that the universe should contain more familiar

"I often run into an irrational wall that sometimes has an almost religious feel to it. When I ask people what proof I could offer to convince them of MOND, they often say 'none.'"
— Stacy McGaugh

ELIZABETH WARNER

matter than astronomers have observed, which fits nicely with MOND. In contrast, the concordance model predicts about six times more unseen matter than MOND does, and most of this mass is in the form of particles that have never been detected.

Sanders isn't worried by the fact that MOND may also need some nonluminous matter. He points out that dark-matter proponents also have trouble explaining cluster observations. Indeed, Glennys Farrar and Rachel Rosen (New York University) wrote a paper, now being refereed, claiming that the velocities in the Bullet Cluster cannot be explained without invoking a new force that acts only on dark matter. "MOND needs some dark matter, but that could be in the form of neutrinos, which we know to exist," says Sanders. "But apparently, the concordance model not only needs mysterious dark matter, but also additional new physics. This makes you wonder what is worse."

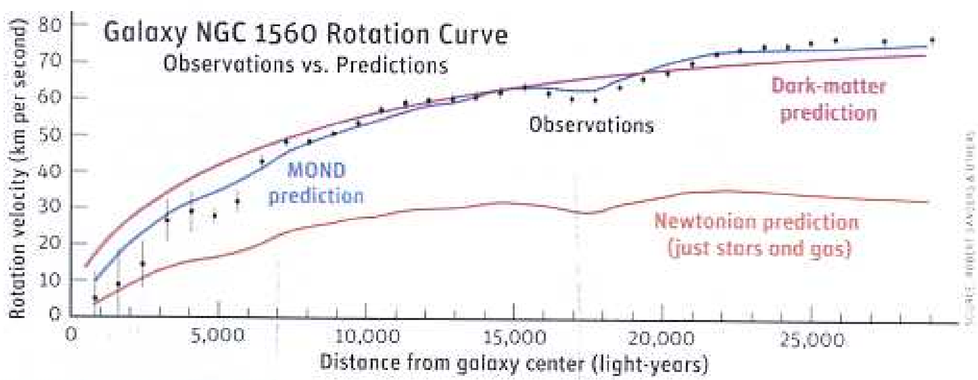
All MOND researchers agree that the theory's strongest point is its huge phenomenological success in explaining and predicting the orbital velocities in galaxies. "Even if MOND is incorrect," says Zhao, "we have to understand its predictive power." Zhao also thinks it's much easier to prove MOND wrong than to prove dark matter wrong. "The theory has made itself vulnerable and falsifiable," he says. "In fact, it's amazing that it has survived for so long."

To illustrate this point, McGaugh and Erwin de Blok (Mount Stromlo Observatory, Australia) constructed a "fake" galaxy, combining the light distribution of one galaxy with the velocity distribution of another. Since MOND has no free parameters, it would not be able to explain this object, so if such a galaxy were ever found, MOND would have to be discarded. But this crazy galaxy would not falsify dark-matter models, since a theorist could concoct a particular mix of dark-matter particles to explain the "observed" velocities.

A Waste of Time?

Primack concedes that MOND does a remarkably good job of explaining the velocity distributions of galaxies, but, he adds, "attempts to turn this into a successful theory have failed. Clearly, MOND doesn't work at other scales." The fact that only a few researchers are involved in MOND reveals that it's "an irrelevant theory," he says. "If other cosmologists want to waste time on it, that's great — it means less competition for me."

Primack points to the concordance model's phenomenal success in explaining a wide variety of observations, including the dimming of supernovae at large distances (March issue, page 20), large-scale clustering of galaxies (*S&T*: December 2006, page 19), gravitational lensing, and the cosmic microwave background (*S&T*: June 2006, page 22). "We now have what appears to be a totally reliable theory," he says. "As far as I know, there is no single piece of contradicting evidence. It's a continuous success story.



MOND's greatest strength is its ability to accurately predict the rotation curves of galaxies, such as the "normal" spiral galaxy NGC 2903 in Leo *(left)* and the low-surface-brightness galaxy NGC 1560 in Camelopardalis *(right)*. Dark-matter models can be tweaked to provide reasonably good fits, but not as good as those using MOND.

Meanwhile, we're making new predictions, so the theory sticks its head out."

Spergel disputes Milgrom's charge that the concordance model is a loose concept. "Once you have fit the latest observations of the cosmic microwave background, you have basically determined *all* of the parameters in the model to an accuracy of 5 to 10%, and there's no flexibility left to fit the astronomical data," he says. "Yet, remarkably, the model fits a host of observations."

Moreover, MOND's physical basis remains an utter mystery. Why would gravity change its apparent behavior below a certain field strength? The lack of a known physical basis might be due to a lack of interest in the theory. As Zhao points out, "There haven't been too many brains working on this problem."

Sanders expresses optimism that this situation might change. "Young people are far more open to the idea of modifying gravity than older people," he observes. And Milgrom himself is confident: "I like to read about the history of science, and it's always like this. It's going to be a gradual process, but I'm patient." If dark-matter particles continue to elude laboratory physicists, says Milgrom, people will gradually take MOND more seriously.

Worst Nightmare

New evidence supporting MOND may come from studies of globular clusters, which are presumably not dominated by dark matter. If gravity behaves in a non-Newtonian way in the outskirts of globulars, where gravity is weak, that would be good news for MOND. Riccardo Scarpa (European Southern Observatory) and his colleagues have already tested this idea in five globular clusters, including Omega Centauri (NGC 5139). Although the team's results have been challenged, Scarpa sticks to its original claim that a MOND-like velocity distribution has indeed been observed in the cluster's outskirts.

Meanwhile, theorists Bekenstein and João Magueijo (Imperial College, London) have pointed out that MOND could be tested in our solar system. There are various wandering points where the gravity of the Sun and the planets cancel out one another. In very small bubbles around these points, MOND effects might become observable. A relatively inexpensive space mission might be able to test this idea. But McGaugh doubts such a mission will happen anytime soon, because "there is a huge funding bias against MOND."

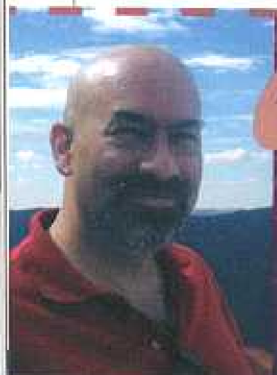
DANIEL VERSCHATSE

MOND's next great challenge will come from studies of stellar motions in globular clusters, such as Omega Centauri (NGC 5139), which are thought to contain very little dark matter.

For Primack, decisive proof of dark matter will come in future particle experiments, such as the Large Hadron Collider at the European CERN laboratory in Switzerland. "If dark matter consists of weakly interacting massive particles such as predicted by the theory of supersymmetry," he says, "they should be detected within 10 years or so" (see "A Particle Physicist's Perspective on Dark Matter," page 35). Another dark-matter candidate, the axion, should also show up in at most 10 to 15 years. And even though creative physicists have proposed many weird dark-matter candidates that could easily elude detection, Primack says not finding dark matter in the laboratory within two decades is "one of my worst nightmares." But he is confident the new particles will eventually turn up.

Milgrom also expects the issue to be settled within 20 years or so. "Right now," he says, "most people won't change their mind, because they've become very entrenched" in the idea of a universe dominated by dark matter. "But there's now a new generation of scientists willing to at least consider MOND as a serious option." MOND's founding father, who turns 61 this month, says he's not distressed by the fact that his idea is still up in the air, 25 years after its original conception. But, he adds, "I hope to see an answer within my lifetime." ∗

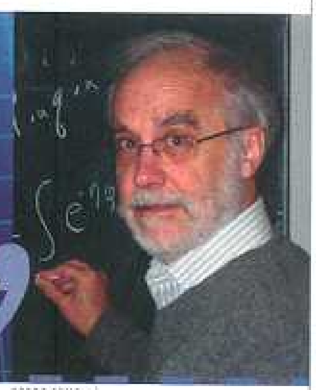
Contributing editor Govert Schilling *covers modern mysteries of astronomy from his hometown Amersfoort in the Netherlands.*



JULIAN SPERGEL

"*MOND has many observational* **failures.**" — *David Spergel*

"*We're accumulating observational evidence for MOND, and the theory is becoming stronger and* **stronger.**" — *Robert Sanders*



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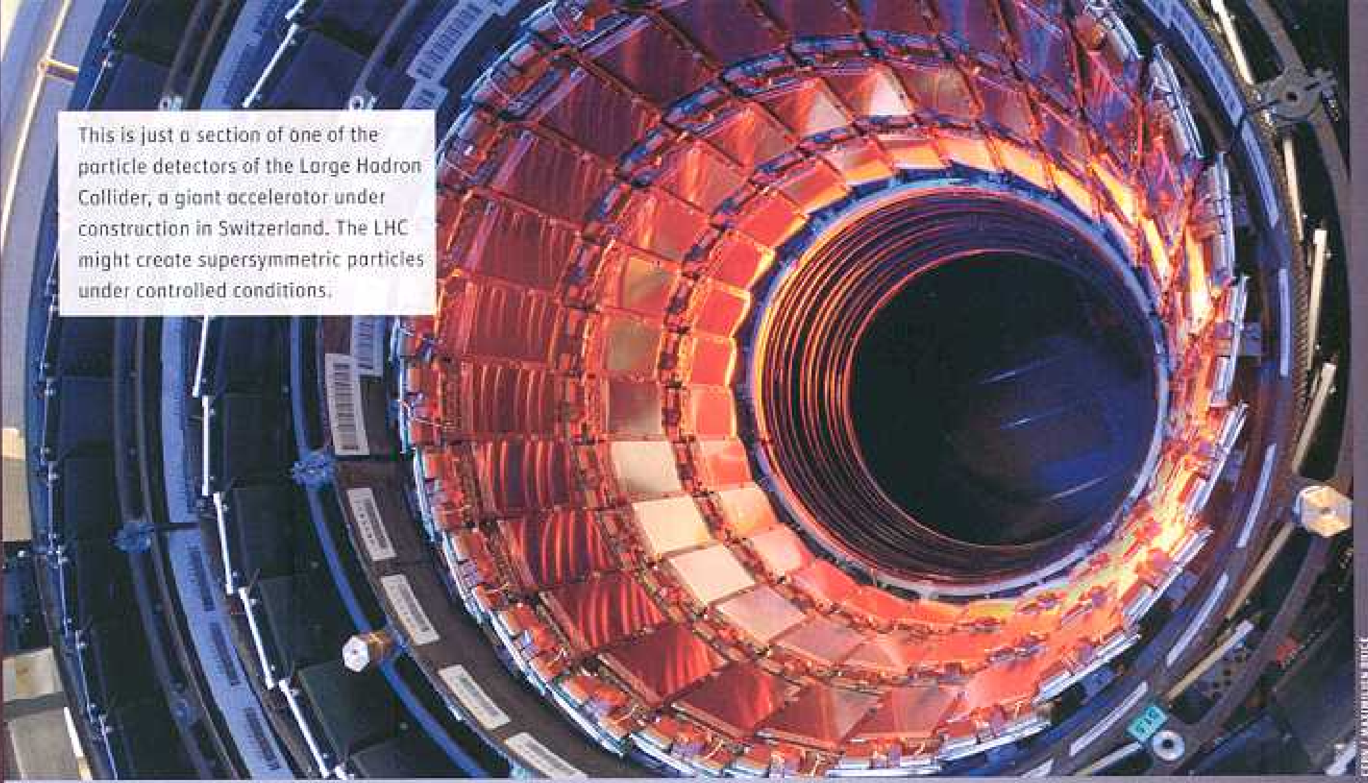


This is just a section of one of the particle detectors of the Large Hadron Collider, a giant accelerator under construction in Switzerland. The LHC might create supersymmetric particles under controlled conditions.

CERN / MAXIMILIEN BRICE

A Particle Physicist's Perspective on Dark Matter

By Dan Hooper

For decades a large and growing body of observational evidence has convinced most astronomers that dark matter exists. But this is not the only reason to suspect that our universe would be filled with invisible matter. Particle physicists have long held very different reasons for anticipating dark matter's reality.

Since the 1970s physicists have been studying a theory that naturally leads to the existence of dark matter. They began working on this theory, known as supersymmetry, for reasons that have nothing to do with dark matter. Supersymmetry can solve problems associated with many aspects of theoretical physics, from the origin of mass to unifying the forces of nature. The fact that supersymmetry explains astronomical dark matter is just an added bonus.

Supersymmetry is a fundamental relationship between matter and force. All types of particles fall into one of two categories: fermions and bosons. Fermions are particles such as quarks and electrons, which make up the type of matter we're familiar with. Bosons, in contrast, are the particles responsible for the forces. Photons — particles of light — are bosons, for example. Electrically charged particles "feel" the electromagnetic force by emitting and absorbing photons. Without photons, there would be no electromagnetic force.

According to supersymmetry, each type of fermion must have a corresponding boson with many of the same properties, and vice versa. Every particle thus has a supersymmetric counterpart, called its "superpartner." The electron's partner is the super-electron, and the photon's superpartner is called the photino. Through supersymmetry, matter and force are intertwined and inseparable aspects of nature, each unable to exist without the other.

Most superpartner particles are thought to be considerably heavier than their known counterparts, making them difficult to produce and study in experiments. To date, no superpartners have been discovered. Despite this lack of experimental confirmation, supersymmetry is such an alluring concept that many particle physicists feel confident that superpartners exist. And the field has a remarkably successful track record of predicting new particles.

One superpartner in particular is thought to be stable and unaffected by the electromagnetic and strong nuclear forces — exactly the characteristics required of a dark-matter candidate. Such particles, collectively known as WIMPs (weakly interacting massive particles), would interact only through gravity and the weak nuclear force, and would thus emit no light. The specific supersymmetric particle, the neutralino, is a kind of combination of the photino and other electrically neutral supersymmetric particles. Neutralinos may very well make up our universe's dark matter.

As we speak, an extensive experimental search for supersymmetry is under way outside Chicago, at the world's biggest and most powerful particle accelerator, the Tevatron. With a little luck, the physicists operating the Tevatron could be the first to create and observe superpartners. An even larger accelerator in Switzerland, the Large Hadron Collider, is planned to begin science operations in 2008. If supersymmetry exists in nature, this colossal facility is almost guaranteed to see it.

Experiments in deep underground mines are trying to detect supersymmetric dark-matter particles passing through Earth. Telescopes on the ground and in space are also looking for signatures of such particles. Other experiments are looking for evidence of dark matter being captured in the Sun's core.

Today, we do not yet know what makes up dark matter. With this array of experiments under way, the elusive identity of dark matter may soon be revealed.

DAN HOOPER *is a theoretical physicist at Fermilab and author of the new book* Dark Cosmos: In Search of Our Universe's Missing Mass and Energy *(HarperCollins, 2006).*

Lost in Translation

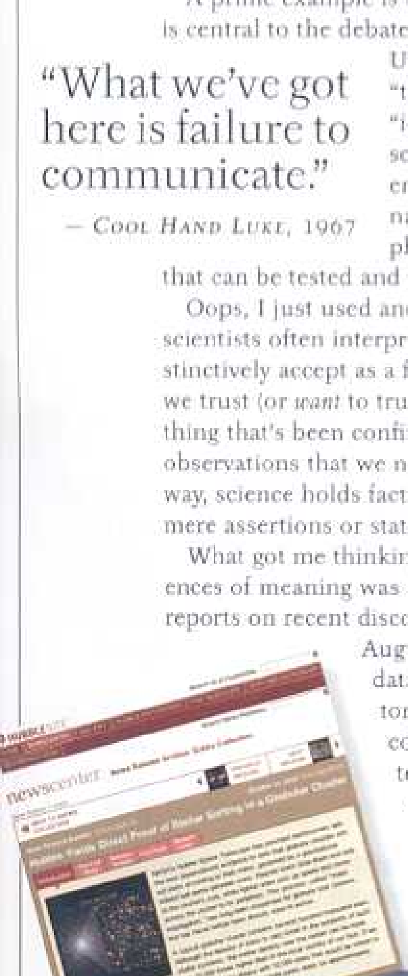
BRITISH PLAYWRIGHT George Bernard Shaw once famously quipped, "England and America are two countries divided by a common language." This also could be said of scientists and nonscientists. We use the same words, but not always with the same meanings.

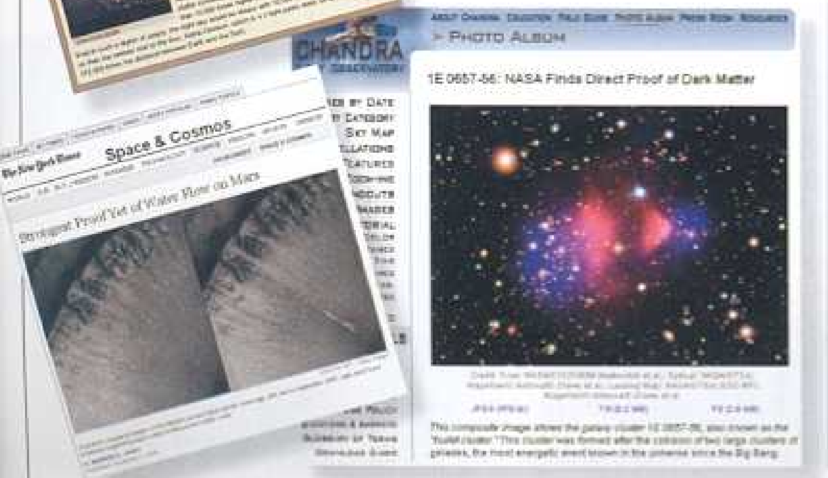
A prime example is the word "theory," whose definition is central to the debate over how evolution is taught in the United States. Most people consider "theory" to be synonymous with "idea," "hunch," or "guess." But to a scientist, a theory is a logical, coherent set of facts and principles that naturally explains multiple observed phenomena and makes predictions that can be tested and thereby confirmed or refuted.

> "What we've got here is failure to communicate."
>
> — COOL HAND LUKE, 1967

Oops, I just used another word that scientists and nonscientists often interpret differently: "facts." Lots of us instinctively accept as a fact any assertion made by someone we trust (or *want* to trust). But to a scientist, a fact is something that's been confirmed through so many independent observations that we no longer question it. Put another way, science holds facts to a higher standard of truth than mere assertions or statements.

What got me thinking about these not-so-subtle differences of meaning was a string of press releases and media reports on recent discoveries in astronomy. It started last August, when NASA claimed that new data from the Chandra X-ray Observatory and the Hubble Space Telescope constituted "direct proof" of the existence of dark matter (S&T: December 2006, page 46). Then, in October, the Space Telescope Science Institute trumpeted Hubble's "direct proof" of mass segregation in globular clusters (that is, massive stars move slowly and sink to the cluster's center, while stellar flyweights pick up speed and zoom into the outskirts). Finally, in early December, the *New York Times* ran a story about recent changes in two Martian craters (see page 17 of this issue), under the headline "Strongest Proof Yet of Water Flow on Mars."





If you ask a jury of astronomers whether the existence of dark matter in galaxy clusters, mass segregation in globular clusters, and running water on Mars are established beyond a reasonable doubt — the same standard used in criminal trials — you'll probably get an acquittal, or perhaps a deadlock. We have no proof of any of these things. What we *do* have is some very compelling evidence — enough to convince many astronomers, but not enough to convince all. In the stories cited above, "direct proof" or "strongest proof" should properly have been written "best evidence yet."

In science, proving an idea to be right is very difficult, sometimes impossible. But proving an idea wrong is easy — a single counterexample will suffice. As in law, we're almost always dealing with evidence, not proof. In science, as in law, some cases are decided beyond a reasonable doubt and others by preponderance of the evidence. Especially in astronomy, where we study objects far removed in space and time, absolute proof is rare indeed. There's nothing wrong with that; it's just the way science works.

I think the best way to bring everyone's understanding of concepts like "fact," "theory," "evidence," and "proof" into concordance is to teach young people to think more scientifically. Here in the US, though, we seem to be doing the opposite. Some authorities want to change the definition of "science" itself to make it more consistent with specific religious tenets. If that scares you, as it does me, you might want to sign and circulate the Defend Science statement at www.defendscience.org. In the meantime, watch your language!

Rick Fienberg

EDITOR IN CHIEF

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