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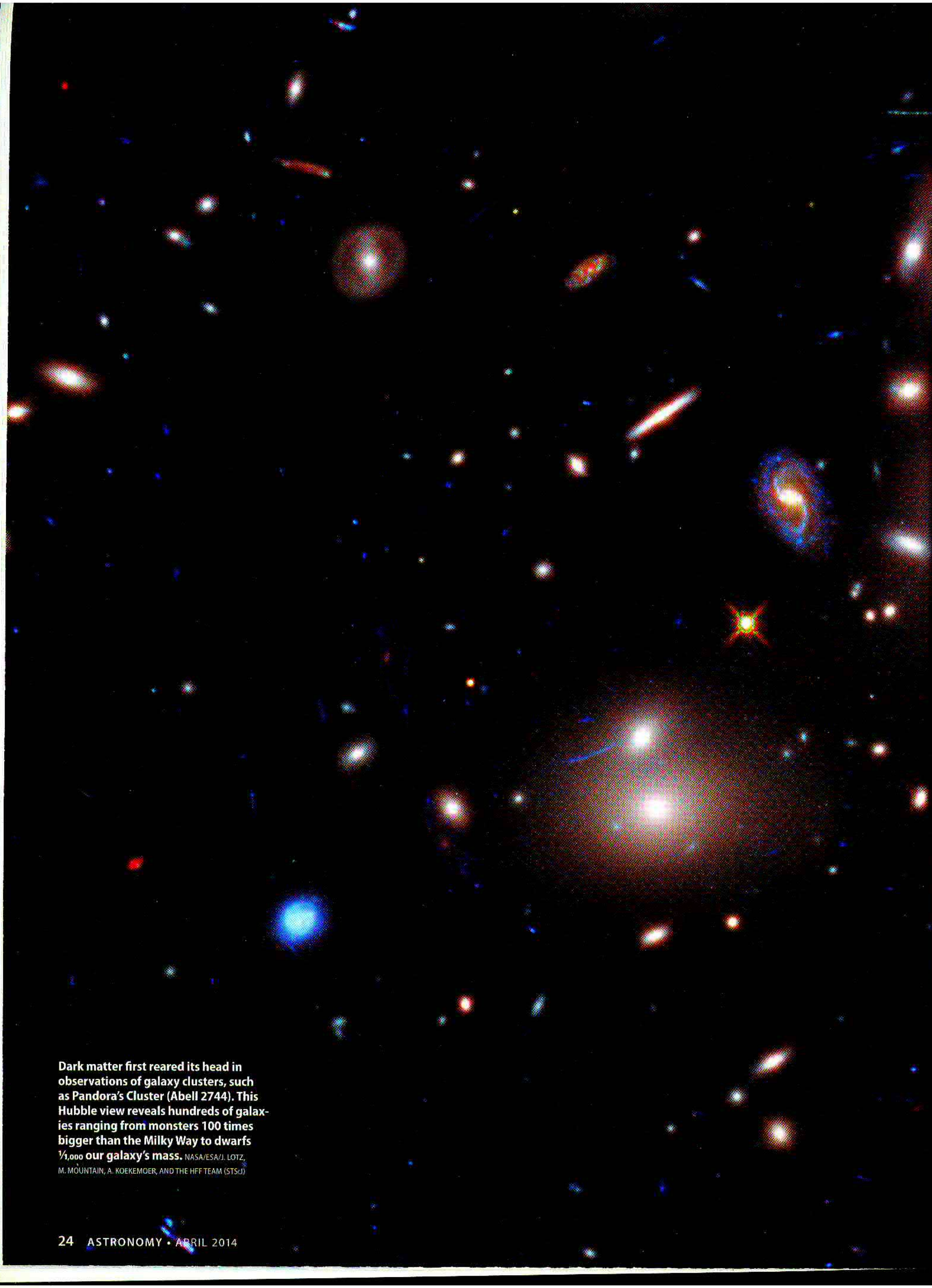


Dark matter first reared its head in observations of galaxy clusters, such as Pandora's Cluster (Abell 2744). This Hubble view reveals hundreds of galaxies ranging from monsters 100 times bigger than the Milky Way to dwarfs 1⁄1,000 our galaxy's mass. NASA/ESA/J. LOTZ, M. MOUNTAIN, A. KOEKEMOER, AND THE HFF TEAM (STScI)

THE MISSING UNIVERSE

Most astronomers think unseen matter permeates the universe, but some researchers suspect we don't quite understand gravity.

by Bob Berman

Eighty-one years ago, most of the universe went missing. According to many astronomers, it's *still* missing. And it's making some of them uncomfortable.

The problem started with the famous Swiss physicist Fritz Zwicky. It was he who first theorized the existence of neutron stars. He also coined the word *supernova*. Cantankerous and crotchety, he was such a heavy hitter that everyone paid attention when his brain went *boing*.

It did exactly that in 1933 when he was studying speeds in the giant Coma galaxy cluster. What he perceived was astonishing. Each member moved so quickly, it should have had no problem escaping the gravitational glue of the entire assembly. Zwicky realized that this galaxy cluster — and all others, it soon turned out — shouldn't even exist. Yet there they were.

Extra gravity must lurk within and among the galaxies. The conclusion was bewildering: Some invisible substance boasting an enormous gravitational pull apparently dominates the universe. Zwicky called it "dark matter," and the name stuck.

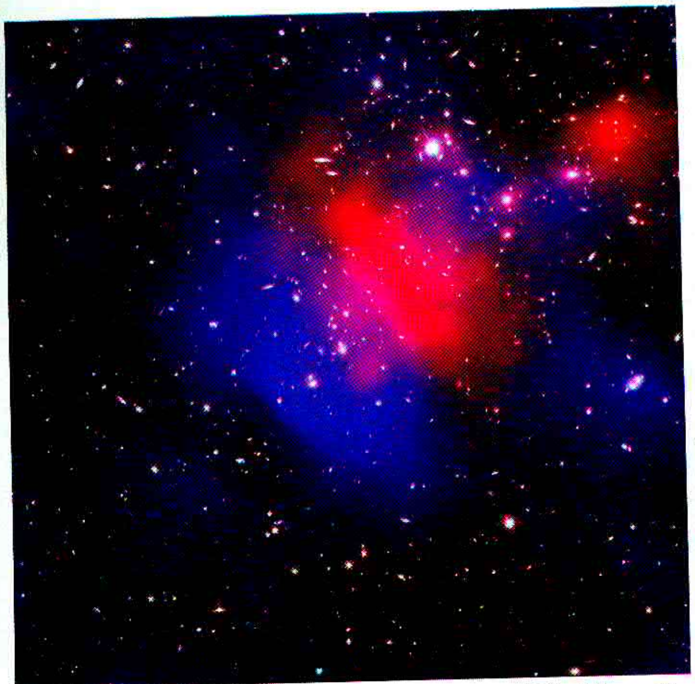
Problems closer to home

Actually, a year earlier Dutch astronomer Jan Oort had noticed the same thing on a much smaller scale in our Milky Way Galaxy. Logic demands that stars near the galactic core quickly whirl around the nucleus while stars at the edges move more slowly. The situation ought to be akin to that in our solar system, where Mercury zooms around the Sun in just three months while poor demoted Pluto requires a quarter millennium. Gravity rapidly grows weaker with distance, so objects farther away must move more slowly. But that's not what happens in our galaxy — or any other.

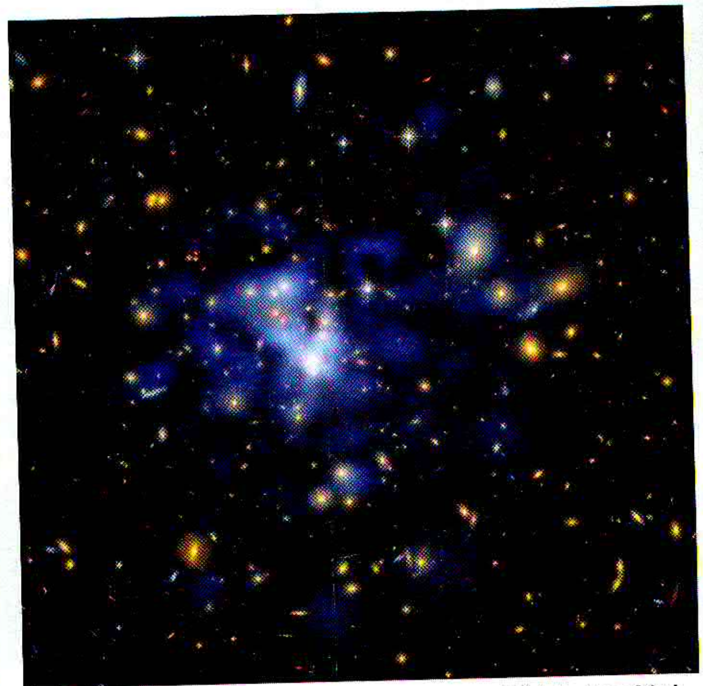
Except for the stars whirling frantically around the supermassive black hole near the Milky Way's core, the rest of the galaxy spins as if each star's accelerator is frozen at the same setting. The Sun orbits our galaxy's nucleus at a speed of approximately 135 miles per second (220 kilometers per second). If you visit a star much closer in or farther away, nothing changes. In other words, the galaxy's rotation curve is flat. This would happen only if the Milky Way were enveloped in an enormous ball of invisible matter containing at least a half-dozen times more mass than our entire galactic inventory.

So, within galaxies and between them, everywhere we gaze, lurks more gravity — and thus more mass — than makes sense. Scientists quickly dubbed this the "missing mass problem."

Bob Berman *is the author of the column "Strange Universe."*



Four separate galaxy clusters came together over a span of 350 million years to form Pandora's Cluster (Abell 2744). In this image, hot gas emitting X-rays has been colored red, and the deduced distribution of dark matter appears blue. NASA/ESA/J. MERTEN (INSTITUTE FOR THEORETICAL ASTROPHYSICS)/D. COE (STScI)



Hubble Space Telescope scientists mapped the expected distribution of dark matter (blue) in galaxy cluster Abell 1689 based on its gravitational effects on more distant galaxies. NASA/ESA/D. COE (JPL-CALTECH/STScI)/N. BENITEZ (INSTITUTE OF ASTROPHYSICS OF ANDALUSIA)/T. BROADHURST (UNIVERSITY OF THE BASQUE COUNTRY)/H. FORD (JOHNS HOPKINS UNIVERSITY)

It would not go away. As telescopes got bigger and astronomers observed more of the universe, the situation stubbornly endured. Years and then decades passed. Some astronomers brought up the problem from time to time; others ignored it. By and large, the major media and non-scientists shrugged it off. OK, we get it: There's more stuff than meets the eye. What's the big deal? Maybe there are more stars than we know of. Or more dust clouds. Or nebulae. Maybe all that unseen gravity lurks in black holes. Why is this so profound?

But it *is* a big deal. Stars are luminous — and massive ones especially so. There simply cannot be many unseen stars. That goes for the failed stars known as brown dwarfs as well — there aren't enough of them. Dust clouds reveal themselves by blocking or reddening everything behind them, and astronomers don't see this either. Nebulae show themselves by imposing spectral lines on the light arriving at Earth from more distant objects, so that's not the case.

As for black holes, they affect everything in their 'hood. The black hole known as Cygnus X-1 whirls in tandem with a visible star once every 5.6 days like sumo wrestlers. Black holes betray their presences. They are not there — not enough of them, anyway.

On the dark side of matter

So the problem is deep. There's far more gravity in the universe than astronomers can account for. What's creating it? What is this strange, unseen stuff?

Most astronomers assume dark matter (DM) consists of undiscovered particles that only interact anemically with planets, stars, and ourselves. Because scientists love acronyms, they call these "WIMPs," for weakly interacting massive particles.

It's not far-fetched. The universe's most common particles are neutrinos. They are invisible, too. They also are numerous and interact only weakly with normal matter. A trillion neutrinos pass through each of your fingernails every second. Yet statistically, despite their omnipresence, you'd have to wait a century before a single atom in your body was jostled by a neutrino. Even hypochondriacs ignore them.

Yet statistically . . . you'd have to wait a century before a single atom in you body was jostled by a neutrino. Even hypochondriacs ignore them.

So it's not much of a stretch to imagine a kind of souped-up neutrino. To achieve the observed gravitational effects, huge numbers of these particles would have to dwell mostly in a halo surrounding each galaxy. Meaning, galaxies are like ships in bottles, enclosed by unseen spheres. But DM also would have to lurk everywhere else, too. It would have to coexist with us, occupying the same room you are sitting in.

DM particles — unlike neutrinos, which weigh virtually nothing — would each have a mass at least that of a lead atom. Hundreds

THE KNOWN MATTER IN THE UNIVERSE

The stable of stable particles:

Heavyweights: Baryons, meaning quarks. They gather in threes, forming neutrons and protons — the stuff of normal matter.

Middleweights: Leptons, such as electrons. Each electron weighs 1,836 times less than a proton.

Lightweights: Neutrinos, which are omnipresent but weigh next to nothing.

Every particle has an antimatter twin that possesses identical properties but opposite electrical charge and other properties.

Numerous transient, unstable particles of various masses also come and go.

The gravitational pull of unseen matter likely warps the light from more distant objects in the galaxy cluster MACS 1206, although some scientists think a change to Isaac Newton's law of gravity better explains the observations. NASA/ESA/M. POSTMAN (STScI)/THE CLASH TEAM

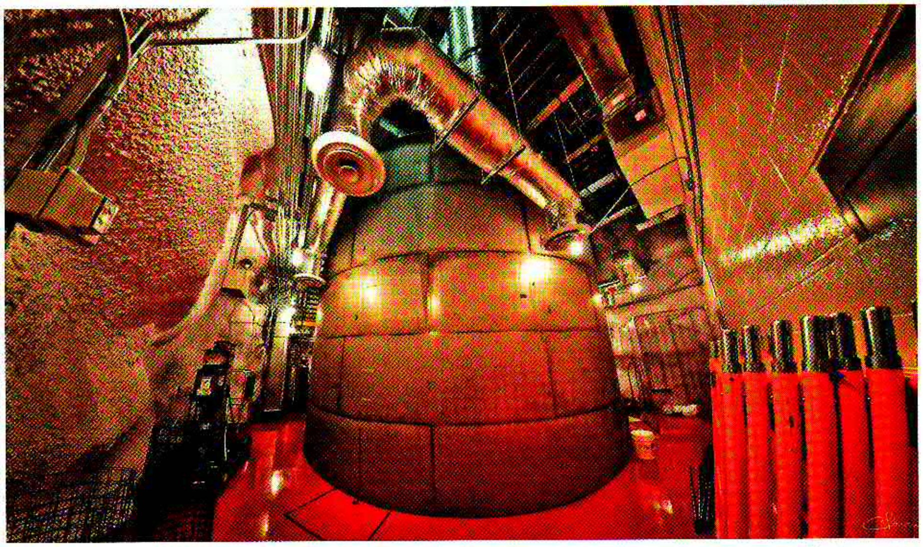
must be passing through your body each second. They'd be the majority material in the cosmos and likely form structures. An entire DM universe would coexist with ours like a zombie empire. Yet despite their crowded presence, they must neither help us nor harm us.

A gravitational twist

Every few years, researchers think they've spied traces of WIMPs, but the hopes have never panned out. Nonetheless, most astronomers are convinced that they'll ultimately find these particles — and then we'll know what most of the material universe is made of. And that's where this story would end — if it weren't for "MOND."

Thirty-one years ago, the prestigious *The Astrophysical Journal* published three articles by Israeli physicist Mordehai Milgrom, who proposed an entirely different solution to the crazy galaxy motion problem. Instead of seeking missing mass that tugs at everything, Milgrom mathematically showed that we'd see the same effects if gravity itself behaves differently at its weakest.

A modification of Isaac Newton's law of gravity is not something many scientists were willing to accept — then or now. Yet the principle is sound: What if there's a lower limit on how weak gravity can become? What if gravity, whose strength falls off inversely with the square of the distance between two objects, operates with more oomph than expected in places where it accelerates objects most feebly — like the outskirts of galaxies? (Such a tweak would not be unprecedented — Albert Einstein showed in his general theory of relativity



Ongoing searches for dark matter include the Large Underground Xenon experiment, located in an abandoned gold mine in the Black Hills of South Dakota. LUXDARKMATTER

FIVE STATES OF MATTER

Matter can exist either as a plasma, gas, liquid, solid, or Bose-Einstein condensate.

Quarks combine into protons and neutrons to form atomic nuclei held together by the strong force, and these can join with electrons into atoms held together by the electromagnetic force.

A cloud of electrically charged atomic nuclei (ions) and electrons is a **plasma**.

When atoms float loose, they form a **gas**.

When atoms attach weakly to neighbors, they form matter's rarest state, a **liquid**.

When atoms rigidly bond to neighbors, they constitute a **solid**.

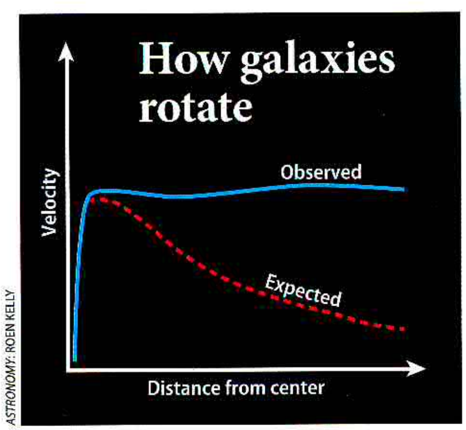
At temperatures colder than any natural place in the universe, atoms can merge spookily into a single state, the **Bose-Einstein condensate**.

that in the strongest fields, gravity behaves differently from what Newton thought. And essentially no scientist doubts that fundamental change to gravity.)

If that's true, then dark matter need not exist at all.

This MOdified Newtonian Dynamics (MOND) theory takes scientists to a key investigative area, something called the Tully-Fisher relation. Proposed in 1977 by American astronomers R. Brent Tully and J. Richard Fisher, it shows that the rotational speed of a spiral galaxy is related to its brightness. Luminous galaxies spin faster. This makes sense because a brighter galaxy has more stars and hence probably more mass, which defines how much gravity drives the rotation.

But finding that Tully-Fisher works with virtually all galaxies, even when their surface brightnesses (the average glow from an object's total area) vary, supports MOND theory better than it supports the existence of dark matter. Indeed, the rotation curves align so well for MOND that some former DM supporters, like astronomer Stacy McGaugh at Case Western Reserve in Cleveland, left the congregation.



A galaxy's rotation curve compares the velocities of stars in the disk with their distances from the galaxy's center. Observed curves appear flat, suggesting that a halo of unseen matter or gravity behaves differently in weak fields. Without dark matter or Modified Newtonian Dynamics, the curve would drop off at increasing distances.

"I believed in dark matter as much as anybody," McGaugh says. "In fact, since we all called the whole thing 'the missing mass problem,' we were predisposed toward the dark matter solution. But which is simpler — a new kind of particle that fits nowhere in the standard model of particle physics and shows itself more in some places than others? And for which there's no evidence at all? Or, instead, simply sticking with a single force — gravity — that behaves a bit differently from what we thought?"

McGaugh and other members of the MONDian minority have a point. Of the four fundamental forces in the universe, gravity is the most mysterious. No one knows why it is the way it is, and there's no absolute reason — no writing on stone tablets — that it must fall off with the inverse square at every possible level of strength or acceleration.

"Years ago, in trying to make dark matter work, I had to add all sorts of patches and assumptions when dealing with varying galaxy surface brightnesses," McGaugh says. "With dimmer surfaces, dark matter just couldn't fit. I tried to make it work, but the data apparently didn't get that memo. I found I was simply adding epicycles." He chuckled at that image, which alludes to 16th-century and earlier efforts to make planet orbits fit an Earth-centered doctrine.

Moreover, says McGaugh, "With dark matter, there's nothing in it you can't fudge. You have endless freedom to try to make it fit. One group ran a thousand simulations and simply picked the one that worked."

Test the nearly untestable

It is true that MOND does away with the need for an entirely new form of matter. Nonetheless, a true MOND test would require placing an experimental apparatus far from any gravity field.

"We'd need to go about a tenth of a light-year from Earth, or 7,000 astronomical units [AUs, or Sun-Earth spans]," says McGaugh, sighing. He knows this is as likely as teaching cats to learn their own names. No space probe will venture anywhere near that far in our lifetimes. The farthest Voyager spacecraft, for comparison, now lies 127 AU away.

A fly in the ointment?

But MOND enthusiasm comes with caveats. Why gravity should have this low-intensity anomaly is anyone's guess. Moreover, MOND works well in predicting how galaxies rotate, but it doesn't work as well in explaining motions at much larger scales, such as those between galaxy groups. So, most astronomers remain in the DM camp.

One of them is astrophysicist Hongsheng Zhao at the University of St. Andrews in the United Kingdom. He compares the

The Whirlpool Galaxy (M51), like all other spirals, seems to possess about 10 times more gravity than its visible contents can account for. Either dark matter surrounds these galaxies or gravity operates differently than most scientists think.
NASA/ESA/S. BECKWITH (STScI)/THE HUBBLE HERITAGE TEAM (STScI/AURA)

current battle between the two camps to a four-dimensional board game, with MOND owning the within-galaxy territory and DM calling the shots on the largest scales. He concedes that for his beloved DM to work within dense star concentrations like globular clusters, the theory would have to "appeal for some magic." But Zhao believes DM's alternative fails on the largest scales: "MOND predicts galaxy clusters should behave as if just the known stars and nebulae influenced their motions — which is wrong by a factor of 10."

"It's more like a factor of two," McGaugh says in rebuttal. But either way, MOND doesn't really shine once you're floating beyond the galaxies.

These two opposing researchers are witty and gentle. But that's not the case everywhere. Much emotion and tension exist over this issue. Many DM advocates regard MOND as akin to a flat-Earth hypothesis. Yet it also appears some are unaware of powerful recent evidence that points MONDward.

"With dimmer surfaces, dark matter just couldn't fit. I tried to make it work, but the data apparently didn't get that memo." — Stacy McGaugh

For example, McGaugh wrote a paper that appeared in *The Astronomical Journal* in 2012 showing that low-mass galaxies fall along the Tully-Fisher relation precisely as MOND predicts. That was new, unexplored territory; it didn't have to work out so. Better still, the data "scatter" is negligibly small, posing another fine-tuning problem for DM models.

Then, too, in 2013 the rotation curves for the Andromeda Galaxy's recently discovered dwarf spheroidal satellites matched MOND predictions. Last year also brought proof that Milky Way stars hovering far above and below the galaxy's disk move in accordance with MOND. They don't seem the least nudged by all the theoretical DM that supposedly occupies that very region.

Put it all together, and the odd-gravity MOND idea certainly seems compelling, at least in our neighborhood. At the largest scales, so does DM, although its advocates do take more parameter-tweaking liberties to make the data fit.

The food fight between the two sides is likely to rage for years. It will end with finality only if scientists actually discover DM particles, or some as-yet-undreamt-of gravity experiment clinches MOND.

Until then, astronomers can only keep gazing into the night sky, conducting their experiments, and wondering, as Zwicky did 81 years ago, whether most of the cosmos is really missing.

READ MORE ABOUT ASTRONOMERS' SEARCH FOR DARK MATTER AT **www.Astronomy.com/toc.**