FROM THE JULY/AUGUST 2015 ISSUE

Dark Matter Deniers

Exploring a blasphemous alternative to one of modern physics' most vexing enigmas.

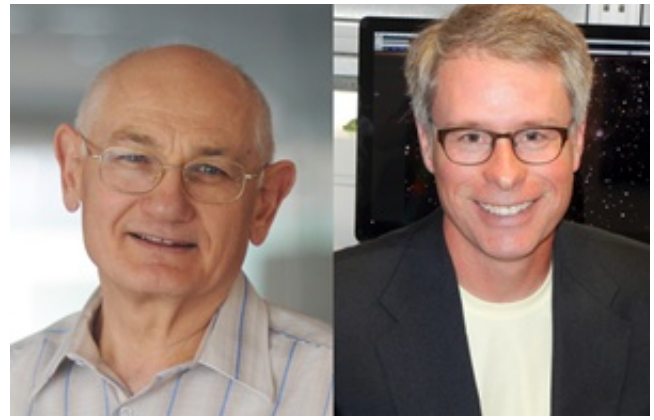
By Steve Nadis | Thursday, May 28, 2015

RELATED TAGS: DARK MATTER, COSMOLOGY

NASA/ESA/T. Megeath (University of Toledo) and M. Robberto (STScI)

When it comes to the universe, most cosmologists argue, what you see is not what you get. In fact, the latest survey of the Big Bang's residual light suggests that more than 84 percent of the matter in the cosmos is of the "dark" variety: exotic particles unlike the ordinary atoms that make up our everyday world and the objects therein.

Dark matter, according to current orthodoxy, is largely responsible for the formation of galaxies, galaxy clusters and larger entities, and it also provides the gravitational glue needed to keep these structures intact. In countless galaxies observed to date, stars orbit the galactic center so quickly that gravity alone shouldn't be enough to keep galaxies from flying apart. The picture makes more sense when you introduce hidden, invisible matter to hold the galaxies together. Furthermore, computer simulations of the universe have largely reproduced the cosmos we see today by following a recipe of roughly 5 parts dark matter to 1 part regular matter.



Mordehai Milgrom (left) and Stacy McGaugh

Milgrom: Weizmann Institute of Science; McGaugh: Case Western Reserve University

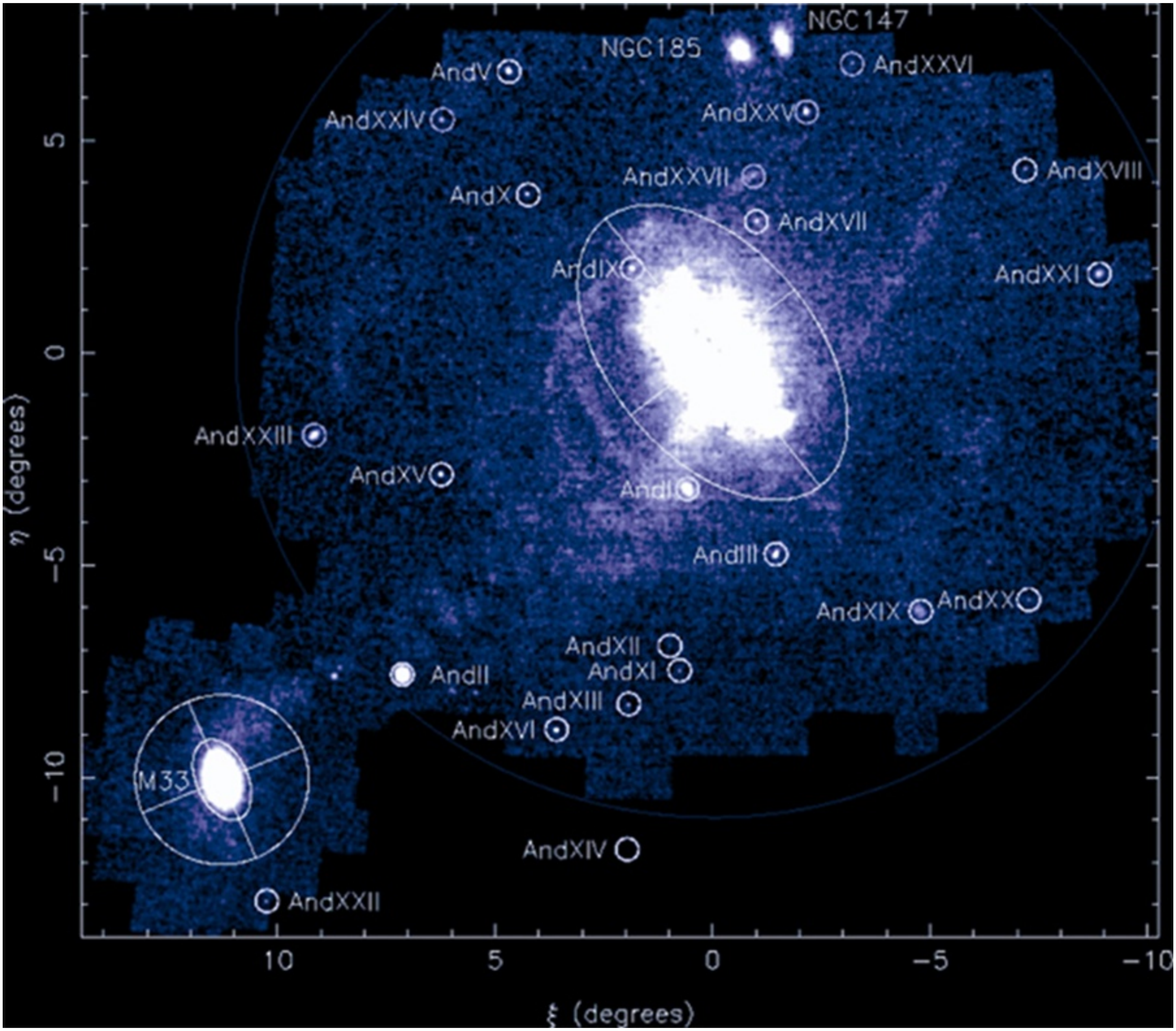
Yet there is a rather significant catch. No one has ever detected a single dark matter particle, and no one can say for certain what it would consist of. "Why are all the dark matter searches coming up empty-handed?" asks Stacy McGaugh, an astronomer at Case Western Reserve University in Cleveland. His answer runs contrary to the conventional wisdom: "It's possible it ain't there."

For the past two decades, McGaugh has reluctantly played the role of the doubter. He was a dark matter enthusiast like most of his peers, but he started losing faith in the mid-1990s when he realized that models predicated on the invisible stuff didn't match up with the phenomena he was witnessing in galaxies.

Instead, McGaugh is considering an idea called Modified Newtonian Dynamics, or MOND. Although many astronomers regard it as blasphemous, MOND has consistently outperformed dark matter models in describing the motions of stars and gases in galaxies. Instead of relying on new, hypothetical types of matter, this alternative theory merely tweaks Isaac Newton's laws of gravity to strengthen the gravitational pull as needed. If gravity plays by different rules than we thought, MOND advocates suggest, we might be able to explain galaxy dynamics, and other puzzling aspects of the universe, without having to invoke dark matter at all.

Changing the Rules

Mordehai Milgrom, a theoretical physicist at the Weizmann Institute of Science in Israel, came up with MOND more than 30 years ago as an alternative to dark matter. At the time, Milgrom was studying star velocities in other galaxies. Normally, he says, "you expect objects near the center of a galaxy to rotate faster and objects farther from the center to go slower and slower, but this wasn't observed." Instead, velocities flattened out, staying constant as one moved farther from the galactic center.



The Pan-Andromeda Archaeological Survey has revealed several new targets for tests of MOND: dwarf galaxies around Andromeda (center). The controversial theory consistently makes accurate predictions.

Geraint F. Lewis, from an original presented in Richardson, J., et al. (2011), Astrophysical Journal, 732, 76

If dark matter is responsible for such uniform rotation speeds, it would require an extraordinarily precise distribution of the invisible stuff — "fine-tuning in the extreme," as Milgrom calls it. "It's like taking 100 building blocks and throwing them on the floor, and lo and behold, I see a castle." MOND offers an explanation he finds more plausible: "You don't need the hidden mass." The desired effects can be explained by modifying our understanding of gravity.

Milgrom's brainchild, MOND, builds on Newton's laws of gravity in a similar way as Einstein's gravitational theory, general relativity. General relativity predicts the same thing as Newton's laws wherever gravity is not overly strong, but it yields different answers in extreme environments, such as in the vicinity of a black hole. MOND does something similar, except that it takes over for Newton somewhere different — in places where gravitational forces are weak.

Newton’s laws, for example, work well near Earth’s surface and in describing planetary motions in the solar system, where the gravity is moderately strong. Those laws don’t work so well, however, in describing the motions of stars in a galaxy where gravitational forces are much weaker because the stars are widely scattered. Milgrom noticed that in diffuse systems like this, Newton’s laws begin to falter — and make untrustworthy predictions — whenever gravitational acceleration dips below a specific threshold, 10-10 meters per second per second, 100 billion times weaker than the force of gravity felt on Earth.

Milgrom devised a straightforward equation, the so-called MOND formula, to describe how fast objects should move depending on the gravitational forces and accelerations exerted on them. Simply put, above the 10-10 threshold, you get Newton’s gravity, and below it, you get MOND’s modified version. The formula also provides for a smooth transition between these two physical regimes.

A Guarded Reception

When Milgrom introduced MOND to the world in a 1983 paper, it was greeted with indifference — a reaction that largely persists to this day. “In the beginning, MOND was ignored by almost everyone,” Milgrom recalls. “That wasn’t unfair. It was the correct attitude. Heretical theories should be given a hard time.”

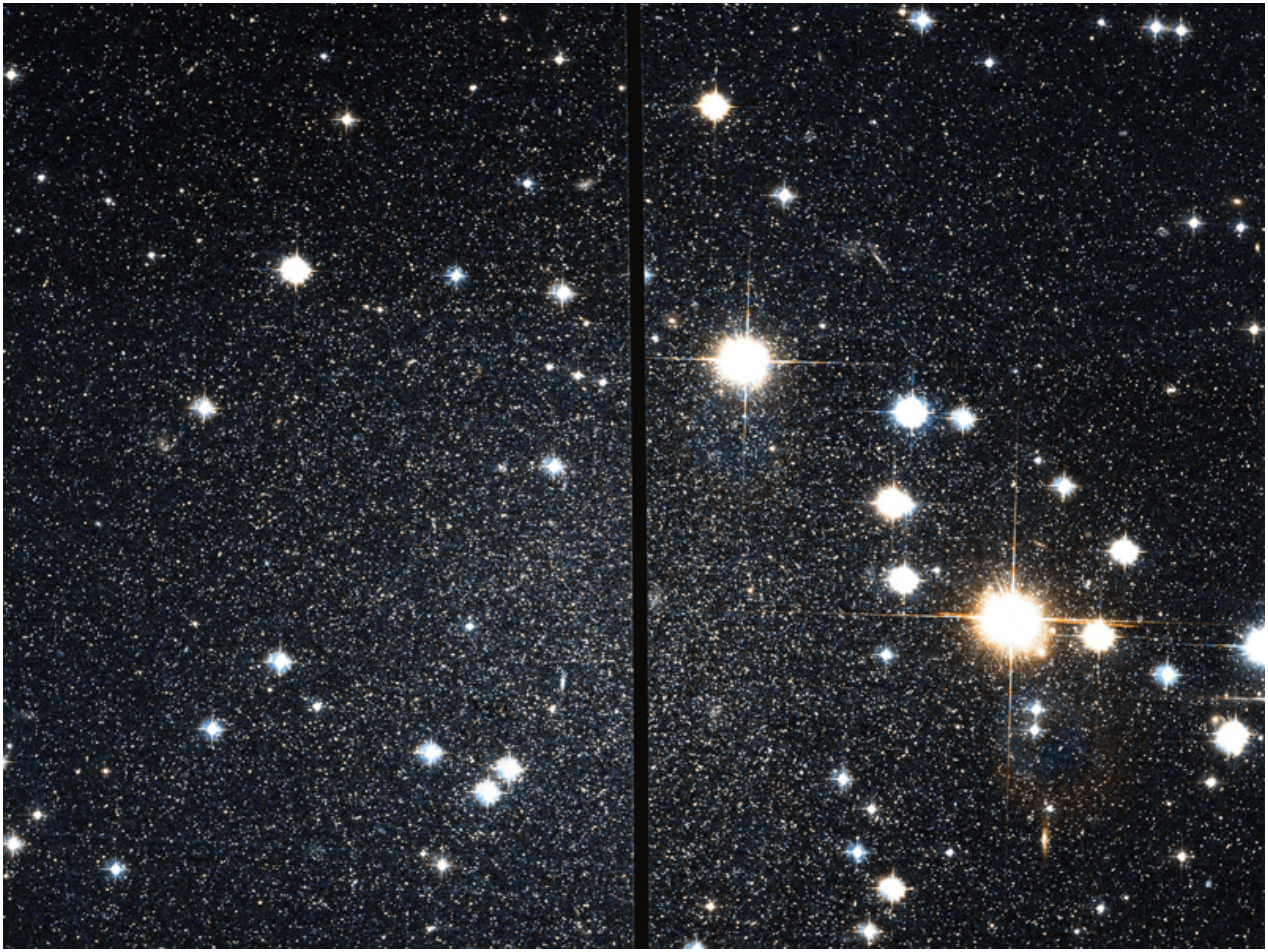
And that’s exactly how McGaugh responded. He first heard about MOND while he was a postdoctoral fellow at the University of Cambridge in 1995, when Milgrom came to speak. McGaugh almost skipped the lecture because he didn’t want to waste his time on “crazy talk” about overthrowing the known laws of gravity.

But he went anyway, and his interest picked up when Milgrom discussed “low surface brightness” galaxies — ones with much lower concentrations of stars than normal spiral galaxies like the Milky Way. These galaxies are smaller, stretched-out versions of spirals, with stars spread so thin — and gravity, accordingly, so weak — that they pose a good test of MOND. Milgrom used the MOND equation to predict stellar rotation speeds in these galaxies.

McGaugh, who was studying low surface brightness galaxies at the time, already had data in hand that he assumed would “falsify this stupid idea, once and for all.” He compared Milgrom’s predictions with his data, “and darned if they didn’t all come true.” That finding stunned McGaugh.

The self-professed “true believer” in dark matter could barely sleep as he tried to figure out how MOND’s wacky predictions could have possibly been confirmed when there seemed to be so much evidence for dark matter. It took him nearly a week of soul searching before he overcame his shock and accepted the fact that MOND’s success in this instance may not have been a fluke.

Since then, McGaugh has resolved to test MOND under various astronomical and cosmological conditions to find out, as rigorously as possible, how well Milgrom’s ideas hold up. “My role has been the objective observer to his theorist,” McGaugh says.


The dwarf galaxy Andromeda VII (diffuse, centered), also known as PGC 2807155, is an example of a low surface brightness galaxy ideal for assessing MONDian predictions. (The vertical bar is an imaging artifact.)

NASA/STSCI

Not There Yet

Based on the evidence collected so far, “MOND can claim an impressive number of correct predictions regarding the dynamics of galaxies,” says Anthony Aguirre, a cosmologist at the University of California, Santa Cruz. But there’s a reason it’s still not the prevailing theory.

MOND has not fared so well in describing the universe on larger scales, such as galaxy clusters, and particularly “rich clusters” that consist of dozens of bright galaxies and hundreds of fainter ones. The predictions MOND makes for rich clusters are off by a factor of 2, McGaugh concedes, meaning that you need twice as much mass as you see to explain galaxy motions.

To make up the deficit, one idea is that the clusters may harbor unexpectedly large quantities of neutrinos — another type of elusive invisible particle. But unlike dark matter particles, neutrinos are ordinary matter, known to exist in great numbers. The universe has enough concealed, ordinary stuff in it to potentially solve this problem without resorting to unknown dark matter, McGaugh says.

Another shortcoming of MOND is that, unlike general relativity, it offers no compelling physical reason as to why MONDian effects occur. There are theories explaining why MOND works, but no one yet knows which, if any, may be correct. Milgrom, for one, would like to see this deficiency addressed through the development of a broader theory of gravity that incorporates aspects of both general relativity and MOND while eliminating dark matter altogether. He came up with a relativity-friendly version of MOND in 2009, even though another such theory — called TEVIS — was devised five years earlier by Jacob Bekenstein of the Hebrew University in Jerusalem. "TEVIS works pretty well," Bekenstein says, but like MOND, it can't explain the behavior of truly large structures. "Maybe some smart guy will come along who can succeed, but that hasn't happened yet."

It's a "really hard problem," McGaugh acknowledges. "I can at least imagine a more general theory that encompasses general relativity and MOND, with MOND applying in one special case and general relativity applying for the rest." He's tried a hand at this himself but hasn't gotten far, noting that "some people don't think of it as a valid problem to work on." Unfortunately, among cosmologists, that attitude extends to pretty much anything involving modified gravity.

Outside the Mainstream

McGaugh's investigations of the countercultural MOND have exposed him to professional hardship and a barrage of criticism. "I've forgotten more slights than most people suffer," he quips. "A new generation of students raised to believe in dark matter often assumes I must be some kind of crackpot."

Still, he and Milgrom are not alone in taking MOND seriously. Other respected physicists have signed on, too, among them contemporary researchers in Belgium, France, the Netherlands, the U.K., the U.S. and elsewhere. All told, more than 100 astronomers have published scientific papers on the subject.

McGaugh is also buoyed by the fact that, unlike other alternative theories that have come and gone, MOND has held up surprisingly well. No one has unequivocally disproven it, despite concerted efforts over the past 30 years to do so. But McGaugh also recognizes that in the end, popular opinion — even among scientists — is largely irrelevant. "Ultimately," he says, "science is not a consensus endeavor. The data rule."

And that is what he has focused on — the data. He goes where it leads him, even though it has carried him on an unexpectedly tortuous journey. The majority of his research pertains to galaxies, which happen to be his specialty. He broadened his studies of low surface brightness galaxies to include "basically all kinds of galaxies," he says, such as denser, high surface brightness galaxies, even more star-rich spirals and irregular galaxies — those that don't come in spiral or ellipsoidal shapes. His conclusion? MOND works well in each of these cases.

On to Andromeda

McGaugh's most recent research, undertaken with Milgrom and other collaborators, has focused on the undersized ("dwarf") galaxies of Andromeda, the nearest large galaxy to the Milky Way. Astronomers have spotted among the outer fringes of Andromeda a few dozen small and roughly spherical galaxies with stars orbiting in random directions. The dwarfs' low stellar densities (and correspondingly low gravitational forces) make them especially good places to look for MONDian effects.

The Pan-Andromeda Archaeological Survey (PANDAS) is exploring Andromeda in unprecedented detail, using the Canada-France-Hawaii Telescope in Hawaii. Shortly after the survey discovered and analyzed 10 new dwarf galaxies, McGaugh and Milgrom predicted in a 2013 paper how fast the stars should be moving, according to MOND. The stellar velocities were later measured, and their predictions were right on the mark for nine of the 10 (with the last one having too few stars to support a velocity measurement). Predictions for two additional nearby dwarf galaxies made by McGaugh and his postdoc Marcel Pawlowski, published in 2014, were also correct.

“When you make predictions and they come out right, that's about as good as it gets,” McGaugh says. “As the Andromeda measurements have shown us, as the data improve, the agreement with MOND seems to keep getting better.”

He accepts the fact that MOND still faces many challenges. There is the cluster problem, which has not gone away, and the difficulty of tying in MOND with a broader description of gravity. Dark matter models, on the other hand, have not fared well in explaining star motions in galaxies, either, and in some cases the models are off by a factor of 100. McGaugh agrees with Bekenstein, who maintains that “dark matter models have problems of the same magnitude [as MOND].”

As to exactly where that leaves us, McGaugh is unsure, though he's more convinced than ever that MOND warrants further investigation. “The formula has predictive power,” he says, “so it's got to be telling us something.” If he's right, other astronomers might find it worth their while to listen.