COSMOLOGY

A Dark Matter Recipe Is Tested—And Found Wanting

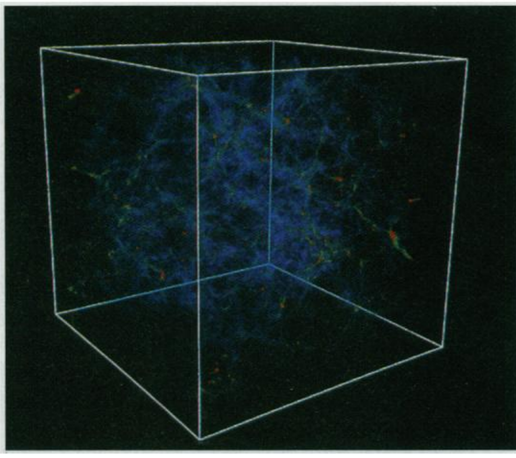
Any cook knows that while a recipe may be mouth-watering to read, the dish itself won't necessarily turn out well. Now cosmologists are facing the same gap between theory and practice: A massive computer simulation is hinting that their favorite recipe—for the universe itself—may cook up something inedible.

The problem lies in one ingredient that most cosmologists insist on: just the right density of matter for gravity to bring the expansion of the universe to a gradual halt. This predisposition for a universe in balance is partly aesthetic. But it's also based on a popular scenario for the first moments of the universe, a scenario known as inflation, which implies that the universe was born with exactly the right amount of mass to achieve that state of balance.

Cosmologists believe that ordinary matter, including stars and gas, can account for only a few percent of what's needed for equilibrium. More than 90% of the mass would have to take the form of invisible "dark" particles. But when Renyue Cen and Jeremiah Ostriker of Princeton University tested the latest version of this dark-matter recipe in a supercomputer, the recipe didn't come out well: It couldn't reproduce the lumpy stew of galaxies and clusters of galaxies seen in the real universe.

To Cen and Ostriker, the result implies that they and their colleagues may have to write a new recipe—and go a lot easier on the dark matter. "It may be that [the results] are pushing us firmly towards a serious consideration of open models" of the universe, containing less dark matter than is needed to halt cosmic expansion, they write in a paper to appear in the 20 August issue of the *Astrophysical Journal.* Some of their colleagues still hold out hopes for the latest dark-matter recipe, pointing to another computer simulation that has lent tentative support to it. But even they are taking Cen and Ostriker's result seriously. It's "an important contribution," says Marc Davis of the University of California, Berkeley.

Computer models of cosmic evolution can test these recipes because the universe's starting ingredients are thought to have shaped its large-scale structures. Dark matter would have speeded up the process of structure formation by clustering around tiny fluctuations in the newborn universe, amplifying the gravitational pulls that generate structure. The specific properties of the dark matter would also have left their signature. Until recently, many theorists thought "cold" dark matter (CDM), made up of hypothetical massive, slow-moving particles, could do the best job of explaining the observed structures, but lately many theorists have pinned their hopes on "mixed" dark matter (MDM): mainly cold dark matter with a dash of "hot" (fast-moving) dark particles.



GREG BRYAN AND MICHAEL NORMAN/NCSA

A model universe. In this computer simulation, the gravitational pull of hot and cold dark matter organizes ordinary matter into filaments and galaxy clusters within a region 500 million light-years on a side.

Accordingly, Cen and Ostriker simulated the evolution of a universe containing 64% cold dark matter, 30% hot dark matter, and 6% ordinary matter. Their model represented a block of universe about a billion light-years on a side—enough to hold hundreds of galaxy clusters—in enough detail that it took several days to run on a powerful supercomputer at the National Center for Supercomputing Applications in Urbana, Illinois. As the simulation progressed, Cen and Ostriker monitored how galaxies and clusters grew as matter clumped under gravity.

The results matched the actual universe better than earlier, simpler simulations based on CDM. But MDM still fell short. In the simulation, galaxies were born later in cosmic history than recent observations suggest, and they formed with much higher velocities relative to one another than are seen the real universe. What's more, the galaxy clusters that took shape in the simulation were more massive than their real counterparts.

Changing the starting mixture of hot and cold dark matter wouldn't help, say Cen and Ostriker. More hot dark matter would delay galaxy formation even further; more cold dark matter would generate even larger velocities. "It seems to us that no successful mixed dark matter model can or will be found," they conclude. Based on earlier, simpler simulations, they argue that the only way to mimic the structure and history of the real universe is to reduce the amount of dark matter, both hot and cold—and thus the total density of the universe. Some observations, Ostriker notes, suggest that the true cosmic density may be only about a third of what's needed for equilibrium.

Some cosmologists are ready to embrace that radical conclusion. "I agree with their claim," says Princeton's P.J.E. Peebles. Recent observations of very distant gas clouds that may be galaxies taking shape provide "reasonably good" evidence, Peebles says, that galaxies formed much earlier in the real universe than they do in the simulation.

But others aren't sure the simulation was a fair test of the model. "Reports of the demise of the cold-plus-hot dark matter model are greatly exaggerated," says Joel Primack of the University of California, Santa Cruz. He takes issue with the technique Cen and Ostriker used to measure the velocities of their simulated galaxies. A less stringent criterion, he says, might open the way to adjusting the simulation until it matches reality.

MDM is also gaining a measure of support from another large computer simulation, reported on 1 June in Minneapolis at a meeting of the American Astronomical Society. In it, Greg Bryan and Michael Norman of the University of Illinois at Urbana-Champaign and Anatoly Klypin of New Mexico State University in Las Cruces simulated the evolution of a chunk of universe 500 million light-years on a side, containing enough matter—ordinary and dark—to come to equilibrium. The simulation modeled the distribution of hot, x-ray emitting gas, which is thought to trace the overall distribution of mass. The modelers compared their results to observations from the x-ray satellite ROSAT and found, says Norman, that "a mix of cold with some hot dark matter seems to match the x-ray properties of the universe."

But Norman and his colleagues caution that the simulation wasn't a perfect match to some observations; its galaxy clusters contained only about a third as much hot gas as real clusters may. As a result, Norman says, their simulation doesn't guarantee MDM is correct. "Cen and Ostriker have raised a serious problem [for] MDM," he concedes. "Whether it will wriggle out is still an open question." If not, cosmologists may have to contemplate a recipe that calls for much less invisible filling.

–Ray Jayawardhana

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