Dwarf galaxies pose new questions about dark matter and the early universe that models are struggling to answer

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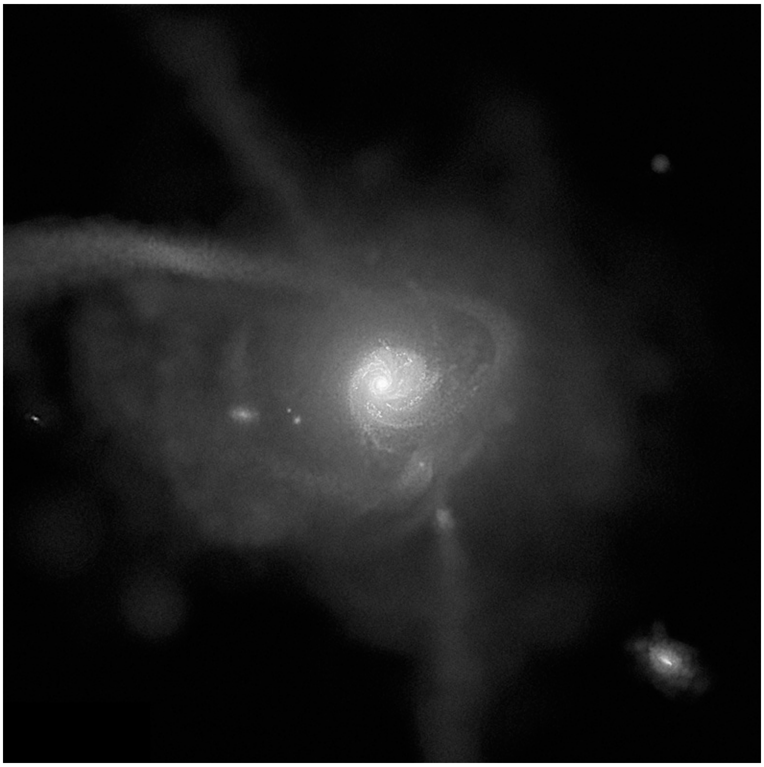
Late one night in October 2015, Andrew Wetzel was fretting. For 15 days, his cosmological models had been swirling virtual dark matter around cybernetic gas and dust and slowly generating a synthetic galaxy approximately the size of our own Milky Way, and Wetzel was about to receive the results. "I finally got the plot up to compare our simulation with the Milky Way," recalls Wetzel, an assistant professor of physics at the University of California, Davis. "I went to bed very happy that night."

That's because, for the first time, a simulation had accurately reproduced a realistic population of dwarf galaxies near the Milky Way. These small companions orbit larger galaxies like planets around a star, and for a decade and a half, they had presented astronomers with a big problem. Simulations suggested that thousands of companion galaxies should surround the Milky Way, but telescopes had seen only a handful. Researchers seemed to be in the dark about some important aspect of the cosmos.

With the latest simulations from Wetzel and his team, the mystery of the missing satellites might appear to be explained (1). But more questions are emerging, with newly discovered galaxies more diverse than anyone predicted, and simulations, as yet, unable to recreate their richness. There may even turn out to be too many dwarfs for simulations to contend with. Future supercomputer models and next-generation telescopes will address these conundrums, potentially illuminating a critical stage in the growth of the universe.



Cosmological simulations such as this one have gotten better at reproducing dwarf galaxies, but questions remain. This simulation shows a Milky Way-like galaxy at the center surrounded by a realistic population of satellite dwarf galaxies and a stellar halo. Image credit: Andrew Wetzel (University of California, Davis, CA) and Phil Hopkins (California Institute of Technology, Pasadena, CA).

Satellite Swarm

In 1999, computers had finally grown powerful enough to model the birth and evolution of an entire universe, including dark energy, the mysterious phenomenon accelerating the expansion of space-time, and dark matter, a still-unknown substance outweighing luminous material by a factor of five. Starting at the Big Bang, these simulations use the laws of gravity to show matter interacting with itself and coalescing into a web-like network of galaxies, exactly like the one astronomers see. Researchers can also use the computer models to zoom in on a particular galaxy and observe its growth in detail. By doing so for a virtual Milky Way, two separate teams noticed a curious incongruity—matter around an object like our galaxy should clump into hundreds or even thousands of satellites (2, 3). At the time, scientists knew of only 11 dwarf galaxies within a million light-years of the Milky Way.

Those early simulations tracked only dark matter because computers did not yet have the processing power to include the complex behavior of ordinary matter. And it seemed possible that many more dwarf galaxies were hiding just below the threshold of detection. Still, one troubling explanation for the size of the discrepancy was that physicists were missing some crucial knowledge about dark matter.

As supercomputing power improved, researchers could finally simulate the evolution of ordinary gas and dust alongside that of dark matter. In models created by Wetzel and his team, the gravity of our galaxy's disk pulls in and shreds many dwarf galaxies. Supernovas drive out their gas and dust, lowering their mass and making them easier for the Milky Way to catch and destroy. At the end of the simulations, only 13 virtual dwarf galaxies with 100,000 solar masses or more remain, closely recreating the true satellite population for objects that size.

"Rather than a missing satellites problem, it's like a found satellites problem."

—James Bullock

Other teams have performed similar modeling, some yielding results that agree with observational data and some that still show tension; the details generally depend on the specific physics of ordinary matter included. Yet, with the numbers from computer simulations and those from telescope observation finally showing some agreement, many astronomers consider this a done deal. "The missing satellites problem is not something that keeps me up at night anymore," says astrophysicist Alex Drlica-Wagner at the Fermi National Accelerator Laboratory near Batavia, IL.

Ghost Galaxies

But new surprises have sprung up since. In 2005, the Sloan Digital Sky Survey (SDSS)—which uses the Apache Point Observatory in Sunspot, NM, to repeatedly image the entire night sky in supreme detail—uncovered the first ultra-faint dwarf galaxy (4). These wispy objects are less than 100,000 solar masses and hold far fewer stars than those found in the previously known satellites. SDSS and other sky surveys have since increased the number of known Milky Way companions to more than 50. "They were like ghosts all around us," says astrophysicist Elena D'Onghia of the University of Wisconsin–Madison.

Even state-of-the-art simulations still can't get below the 100,000-solar mass limit, but theory says that the Milky Way should have preferentially destroyed such lightweight objects with its tidal gravitational forces. This has cosmologist James Bullock of the University of California, Irvine wondering if there is an opposite problem brewing. "Rather than a missing satellites problem, it's like a found satellites problem," he says.

Another reason to suspect this possibility is a bizarre beast named Antlia 2. Uncovered last November (5), this is one of the largest satellites ever seen around the Milky Way, yet its stars are so thinly spread out that they almost blend in with the background. Theorists suspect it was once a smaller dwarf that got puffed up by internal supernova explosions and then strung out further by tidal interactions with the Milky Way. Bullock and others believe that if one such hidden giant exists, there could be more out there—an entire population of diffuse ultra-faint companion galaxies that were not predicted.

Any new discrepancies could help illuminate the nature of dark matter. The usual assumption is that dark matter particles barely interact with one another, but if they interact more strongly through new fundamental forces, that may affect how they clump together and how many dwarf galaxies they seed.

Both observations and simulations will need to improve before any lingering satellite problems are entirely resolved. Many theorists are now working toward forming ultra-faints in their next-generation models. Wetzel's latest models of the Milky Way galaxy can produce objects 10 times smaller than previously possible, which should be able to resolve ultra-faint galaxies for the first time, he says. Astrophysicist Coral Wheeler of the California Institute of Technology in Pasadena and others are working from a different direction, bringing all of a supercomputer's power to bear on simulating a single dwarf galaxy. This could give astronomers a better idea of how they form, as well as their expected population.

Even if theory and observation match in the Milky Way's near neighborhood, that is only part of the story. Many more ultra-faint satellite galaxies are likely to exist too far away for today's telescopes to detect. For now, astronomers use statistical modeling to infer how many more they might uncover with better instruments. A 2008 study estimated 300 to 600 within 1.3 million light-years of our galaxy (6). That will be tested by the Large Synoptic Survey Telescope (LSST), an observatory on the mountain Cerro Pachón in Chile, which should begin making scientific observations early next decade. With its huge 8.4-meter mirror, LSST will be able to see much fainter objects than its predecessors, potentially capturing hundreds of new dwarf galaxies and testing the latest simulations.

First Light

LSST will also help identify the smallest dwarfs, which could illuminate another mystery of the universe—the end of the cosmic dark ages. Shortly after the Big Bang, dark matter is thought to have begun collapsing into clumps. Ordinary gas and dust would have been pulled in to form protogalaxies. Next came the epoch known as reionization, when the first stars turned on. Their light ionized and heated hydrogen throughout the universe, increasing its pressure. The strong gravity of massive protogalaxies could overcome this and retain the material needed to make new stars, but low-mass protogalaxies couldn't hold on to the energetic, high-pressure hydrogen, essentially snuffing out star formation inside them.

The ultra-faints bear witness to this period in cosmic history. The theory is that they formed before reionization really got going and then shut down star formation when the gas got too hot. "These are the fossils of reionization," says Wheeler. The stars in these dwarf galaxies are all old, which fits this view. Discovering the minimum mass of dwarf galaxies that survive the process would help researchers pin down the timing of reionization as well as potentially what drove it—was it mostly heftier galaxies or their lighter siblings?

The missing satellites problem is now 20 years old, but it is still helping reorient astronomers' thinking. Some of the smallest cosmic objects have a great deal left to teach about the larger universe. "This is how science works," says Wetzel. "You claim victory but you're always looking for where there are tensions. It's exciting and pushing us to where to go next."

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